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The New Demosponges, *Chaunactis olsoni* and *Haplistion nacoense*, and Associated Sponges from the Pennsylvanian Naco Formation, Central Arizona

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ABSTRACT

Several complete specimens and many fragments of the new haplistiid demosponge *Chaunactis olsoni* have been collected from the Pennsylvanian Naco Formation in central Arizona, along with *Haplistion nacoense* n. sp., a new monaxonid genus and species, *Nacospongia radiata,* and a possibly related monaxonid sponge. Heteractinid sponges are represented in the collection by a single isolated sexiradiate spicule. The new *Chaunactis* species is a disc-shaped to broad open funnel-shaped sponge with radial skeletal tracts of dendroclones cored by oxeas and united into a firm net by other tracts and isolated dendroclones. Tracts are separated by relatively large canals that are normal to the gastral surface, but which do not open as distinct large ostia through the dense dermal and gastral layers. The new *Haplistion* species is a relatively fine-textured digitate form, and the new monaxonid sponge is a disc-shaped form with radiate internal architecture. These are the first sponges reported from the Naco Formation and they occur in an alternating red mudstone and argillaceous lime mudstone to wackestone/packstone sequence.

INTRODUCTION

The Naco Formation contains an abundant fauna of brachiopods, bivalves, gastropods, bryozoans, corals, crinoids and other echinoderms (Brew and Beus, 1976; Webster, 1981; Sumrall, 1992; Webster and Olson, 1998). Sponges have not been reported previously from the formation. The present paper documents the occurrence of a new haplistiid rhizomorine sponge and of heteractinid sponges, represented by a single spicule, in the formation. Specimens were collected from near the small community of Pine, located in Gila County, in central Arizona (Figure 1). Most specimens from the formation are fragments found scattered within mudstone layers, but whole demosponges do occur and are best preserved in limestone beds.

The Pine sponge locality is located in road cuts and associated exposures a few meters north of the junction of Control Road and Arizona State Highway 87 (Figure 1), approximately 2 miles southeast of Pine. The locality is in sec. 4, T. 11 N., R. 9 E, (unsurveyed) on the Buckhead Mesa 7.5-minute quadrangle.

The Naco Formation ranges from Middle through Late Pennsylvanian age and unconformably overlies the Mississippian Redwall Limestone. Huddle and Doborovoly (1945, 1952) and Brew (1970) reported that the Naco Formation was deposited in a marine transgression over a Late Mississippian-Early Pennsylvanian karst topography. The Naco Formation thins and eventually pinches out westward where it grades into the Pennsylvanian-Permian Supai Formation (Jackson, 1951; Brew, 1970; Brew and Beus, 1976).

Brew (1965) subdivided the formation into three members, the Alpha, Beta, and Gamma Members. The sponges described here are most likely from the Beta Member, which is composed of fossiliferous interbedded sequences of mudstone and limestone (Figure 2). The Pine locality is probably age equivalent to the Kohl Ranch locality described by Brew and Beus (1976) and is Desmoinesian. Exposures of the Naco Formation at the Pine locality consist of interbedded thin units of argillaceous limestone, mudstone, and wackestone/packstone. A detailed measured section of bed 8 (Figure 2B), from approximately 8.5 meters up to 10 meters above the base, illustrates those interbedded relationships. Specimens of sponges were collected from mudstone layers as associated float of this unit.

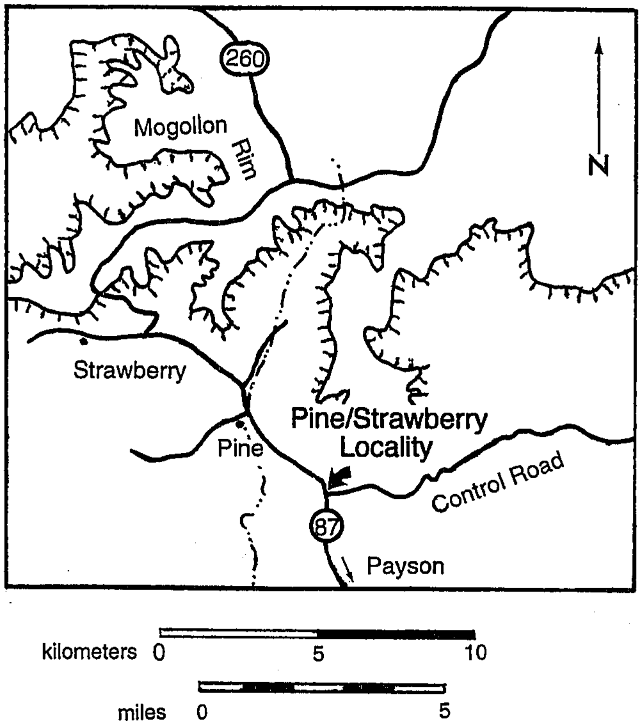

Figure 1. Index map to the sponge locality near Pine, along Arizona State Highway 87, on the Buckhead Mesa 7.5-minute quadrangle, Gila County, central Arizona.

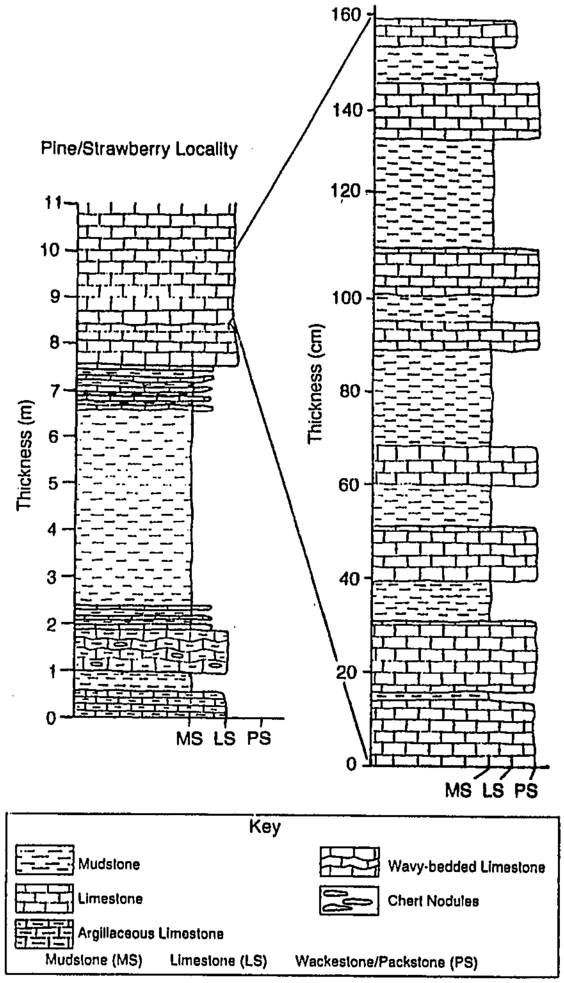

Figure 2. Stratigraphic sections of part of the Naco Formation exposed at the sponge locality near Pine. A, section exposed at the locality; B, detailed section of the 1.6 m of sponge-bearing beds in the upper part of the sequence.

All the specimens utilized in the study are deposited in collections of The Museum of Northern Arizona (MNA).

SYSTEMATIC PALEONTOLOGY

Class DEMOSPONGEA Sollas, 1875
Order LITHISTIDA Schmidt, 1870
Suborder RHIZOMORINA Zittel, 1878
Family HAPLISTIIDAE de Laubenfels, 1955

Diagnosis.—"Massive to foliate sponges with radial architecture; skeletal net regular and open, composed of radial spicule tracts connected by horizontal tracts; tracts composed of rhizoclones, together with dendroclones and smooth monaxons, in parallel orientation; tracts may be hollow or may be cored with smooth monaxons; a specialized dermal net of smooth monaxons may be present" (Finks, 1960, p. 86–87).

Type genus.—Haplistion Young and Young, 1877.

Genus HAPLISTION
Young and Young, 1877

Diagnosis.—"Form of sponge spherical to lobate, digitate, or irregular; surface hispid because of projecting ends of radial tracts; point of origin of radial tracts commonly eccentric to peripheral, new tracts added by intercalation; spicule tracts compact to hollow but apparently not cored, and composed of rather straight rhizoclones, with stubby or warty lateral processes, dendroclones, strongyles, and oxeas; the smooth monaxons may be concentrated on the outside of the tracts in some species; no distinct dermal net apparent, but surface may have borne strongyles and oxeas in tangential orientation, or outermost horizontal tracts may expand and fuse laterally on parts of the surface; a few large circular canals may be present, parallel to the radial tracts." (Finks, 1960, p. 87).

Type species.—Haplistion armstrongi Young and Young, 1877.

HAPLISTION NACOENSE n. sp.
Plate 2, figures 4, 6

Diagnosis.—Stalked erect lobate to incipiently digitate bladed sponge with both horizontal and vertical tracts commonly 0.4–0.5 mm in diameter, and skeletal pores between mostly 1.0–1.2 mm in diameter or across, with a few ostia of canals to 2.0 mm in diameter; tracts composed of rhizoclones with nodose shafts approximately 0.02 mm in diameter and to 0.5 mm long.

Description.—The holotype and only known specimen of the species is a stalked, erect palmate to incipiently digitate sponge 77 mm high, but broken at the base. It expands upward from an elliptical stalk 13 x 27 mm across at the broken base, to 14 x 33 mm at the top of the stalk, 25 mm above the base and at the bottom of the abruptly expanding upper part of the sponge. The upper part widens to over 80 mm wide and it is 18–23 mm thick on crests of the three, vertical, thickened finger-like lobes. Those lobes are laterally attached and separated by thin areas only 13–15 mm thick.

The dermal surface is generally formed by an irregular reticulate grid of tangential tracts, but locally with preserved pointed tips of radial tracts. These skeletal tracts range 0.3–0.6 mm in diameter, although most are 0.4–0.5 mm in diameter. Tracts swell to 0.6–0.7 mm across where horizontal and vertical ones merge so that individual tract segments appear I-shaped, with a narrow central shaft and expanded ends in the zone of merging. They are generally separated 1.0–1.2 mm apart around circular to subquadrate skeletal pores. Ostia of coarser canals, up to 2.0 mm in diameter, are locally evident in the skeleton. Tracts appear to lack coring spicules and to be hollow, although dense chalcedonic silicification has obscured internal structure in most tracts.

Tracts are composed of small rhizoclones that have straight to gently curved, double tapering, shafts 0.015–0.02 mm in maximum diameter and up to 0.5 mm long. They are sculptured with small nodes or points, up to 0.015–0.02 mm in diameter, which are distributed irregularly along the shaft, but are commonly 0.04–0.05 mm apart where most apparent on spicules exposed on tract surfaces around skeletal pores. These elements are fused to adjacent spicules in the skeleton and produce rigid tracts. There are approximately 3 parallel spicules per 0.2 mm, measured laterally around the circumference of characteristic tracts. This would indicate approximately 25–30 spicules in a single layer, and that there may be a hundred spicules per transverse section, even if the tracts are hollow.

Discussion.—Finks (1960) subdivided the then known species of *Haplistion* into subgroups based upon dimensions of the mesh spaces and diameters of the skeletal tracts. The species here is most similar to those species of his Subgroup A, of Group 2, which have mesh spaces of 1.0 mm or more and radial tracts mostly 0.5–1.0 mm in diameter. Most of these species are spheroidal and are clearly different from the palmate-digitate species described here. *Haplistion artiense* Tschernyschew, 1898, is lobate or digitate but has coarse canal openings and skeletal tracts, considerably coarser than in the Naco species. The Leonardian *H. aeluroglossa* Finks, 1960, is also a lobate to subdigitate species, but it has skeletal tracts only 0.15–0.30 in diameter and canal openings that are also smaller than in the species described here. *H. verrucosum* Dunikowski, 1884, is a flattened starlike lobate sponge with a distinctive, coarsely nodose, dermal layer and with mesh spaces less than 0.5 mm across. Dimensions of tracts in this Permian species from Spitzbergen are unknown, but it clearly is a different species.

A Visean lobate to subdigitate species, *Haplistion mega* Rigby and Mundy, 2000, has been recently described from North Yorkshire, England. That species has mesh spaces 1.8–2.8 mm across, which are considerably coarser than in the Naco species. It also has radial tracts that are coarser than in the new species described here, but its concentric tracts are smaller and range 0.5–0.7 mm in diameter, similar to those of the New Mexico species.

Material.—The holotype, MNA N9482, from the Naco Formation at the Pine locality, is the only known representative of the species.

Etymology.—*Nacoense*, named for the Naco Formation from which the holotype was recovered.

Genus CHAUNACTIS Finks, 1960

Diagnosis.—"Foliate or flabellate sponges with differentiated incurrent and excurrent surfaces; radial tracts originating at base of sponge and dichotomizing upward; tracts loose and open, composed chiefly of irregular rhizoclones in non-parallel orientation, and either hollow or cored with long, smooth monaxons; specialized dermal layer present, which may be composed of a rectangular net of bundles of parallel monaxons; prosochetes and apochetes parallel to horizontal tracts and differentiated from each other by size, shape, or spacing." (Finks, 1960, p. 93).

Type species.—*Chaunactis foliata* Finks, 1960

CHAUNACTIS OLSONI n. sp.
Plate 1, figures 1, 3–5,
Plate 2, figures 1, 3

Diagnosis.—Circular to ellipsoidal discoidal sponges; central juvenile area of disc thin and thickness increases radially outward to ramped or beveled edge of disc; skeletal tracts radiate from the center of the sponge and are cross-connected by concentric tracts; those of the principal endosomal skeleton are predominantly 0.5–0.7 mm in diameter, separating circular to elliptical vertical exhalant canals 0.5–0.8 mm wide and up to 1.6 mm high, radially; thin dense dermal and gastral layers with radial and concentric tracts up to approximately 0.10 mm in diameter, generally with ostia 0.20–0.30 mm in diameter, smaller than major canals of interior; tracts of both endosomal and outer skeleton cored by oxeas and coated with rhizoclones and less common dendroclones.

Description.—Sponges in the collection range from distinctly circular to elliptical discoidal, with diameters that range from 2.7 to 13.5 cm. A typical cross section is thin in the center, increases in thickness toward the outer rim, but then decreases abruptly to a rounded or ramped edge. Central areas range from 3 to 5 mm thick, and increase in thickness radially to 8–9 mm in smaller and intermediate sponges, to 13–18 mm in larger sponges with a distinct outer rim.

Radial tracts diverge from the center of the sponge and with cross-connecting concentric tracts form a moderately regular radially expanding gridwork in the endosomal skeleton. Both types of tracts are expressed as low ridges on upper and lower surfaces. Radial tracts are relatively straight and diverge from the center of the sponge, with additional tracts inserted to keep moderately uniform spacing as the skeletal structure expands. Radial tracts average 0.5 mm in diameter but may reach up to 1.1 mm in diameter in more robust specimens. Distances between radial tracts range 0.4 to 1.6 mm, and approximately 8 tracts occur per 10 mm, laterally. Tracts are traceable over the relatively flat dermal and gastral surfaces and over the rim to the outer ramp. Details of their spicule composition is usually obscure because of coarse chalcedonic replacement of nearly all specimens, although a few specimens do locally show tracts cored by doubly tapering oxeas and coated by irregularly oriented rhizoclones and possible dendroclones.

Concentric endosomal tracts are transverse to radial ones and are less continuous, usually bridging only between adjacent radial tracts, although some concentric arc segments apparently parallel the outer rounded margins of the sponges and may be at the same general level between three or four radial tracts. Such concentric tracts range from single rhizoclone or dendroclone spicules to spicule clusters that range 0.2 to 1.0 mm in diameter, but average approximately 0.5–0.7 m in diameter or wide.

Adjacent radial tracts are separated by radially aligned series of vertical exhalant canals that may be circular and up to 0.8 mm, or radially ellipsoidal and range 0.4 to 1.6 mm high and 0.5–0.8 mm wide. These canals are commonly of smaller diameter in central parts of discoidal sponges but increase in diameter outward in the radial skeleton. Smaller probably inhalant canals, 0.3–0.4 mm in diameter, occur locally within concentric tracts, between the larger exhalant openings.

Vertical sections of the sponges show moderately well-defined upper and lower "layers" of skeleton in which numerous, uniformly spaced, vertical exhalant canals are well developed. Average thickness of these relatively uniform "layers" is approximately 2 mm. Inner parts of the skeleton have less obvious structure and may appear as openings in some preservations, but with vertically and radially divergent spicule tracts in other sponges that are better preserved. These more interior, less obviously canalled, parts of the skeleton increase in thickness radially. That interior "layer" may expand from only 1 mm thick near the center of small sponges to 4–8 mm thick in the outer ramp or rim of larger ones.

Vertical sections through parts of several discoidal sponges show iron-stained red impressions of thin divergent skeletal tracts, which may be traceable for 15–20 mm in the massive chalcedonic replacements. These tracts are horizontal at mid-height, but lower ones arch gently downward to meet the presumed lower dermal surface at angles of 15–20 degrees. Other tracts arch more abruptly upward to meet the probable upper gastral surface at angles of 30–45 degrees. These tracts include oxeas that are 0.04–0.05 mm in diameter. Lengths are unknown because of obscure preservation in the heavily silicified interiors of all the sectioned samples. More complex spicules have not been identified in the thin sections and nature of spicules in tracts between canals is uniformly obscure because of massive replacement.

Thin, dense, dermal and gastral layers are locally well preserved on several specimens. These layers are composed of radial and concentric tracts that are smaller and more closely spaced than those in the endosomal part of the skeleton. Typical radial dermal tracts are approximately 0.10 mm in diameter and occur 4 radial tracts per 1 mm parallel to the disc margin. Such tracts are separated by ostia that range 0.20–0.25 mm wide and 0.25–0.30 mm long, radially. Such openings occur approximately 10 per 5 mm in single radial series.

Dermal and gastral tracts are commonly cored by 4–6 oxeas per section, although some have only a single oxea inside the rhizoclone- and dendroclone-coated rods. Oxeas are up to 5 mm long and 0.06 mm in maximum diameter, although most are only fragments of spicules approximately 0.02 mm in diameter and to 1 mm long. Dendroclones in these outer tracts are commonly X-shaped forms, with central shafts 0.2 mm long and 0.02–0.03 mm in diameter. Rays 0.015–0.02 mm in diameter extend to 0.04 mm long beyond shaft ends before their tips are lost in the siliceous replacements. Some more robust, but shorter, I-shaped dendroclones also occur in these thin dermal-gastral tracts and have shafts only 0.10 mm long but which are up to 0.04 mm in diameter. Their ray tips are usually obscured in their silicified common junctions. Rhizoclones in the dermal and gastral layers have main shafts 0.015–0.02 mm in diameter and short branching rays that diverge from along the main shaft to articulate with other spicules. They are commonly curved around margins of ostia but may be more irregular in others parts of the dermal-gastral tracts.

Two sizes of oxeate spicules occur on outer and ramp surfaces of specimens, or in associated irregular spicule occurrences. Largest of these spicules may have been parts of foreign root tufts and commonly appear transported where they are irregularly strewn over sponge and matrix surfaces. They have diameters of up to 0.2 mm and lengths greater than 1 cm, but they are rare. Most specimens with more *in situ*-appearing concentrations are locally covered with finer spicules, which have diameters of approximately 0.1 mm or less and lengths of up to 5 mm. Such spicules are not preserved on some specimens, but on others they form a dense thatch more-or-less aligned parallel to the radial tracts, or they may form a layer of irregularly oriented spicules. A number of specimens have distinct separate clusters of parallel monaxial spicules on ramp surfaces or other clusters that splay out from a tract axis. Both occurrences may represent distal continuations of ends of radial tracts.

Discussion.—Finks (1960) described three species of the genus *Chaunactis,* including the Pennsylvanian type species, *C. foliata,* and two other unnamed Permian species designated as *C.* species 1 and *C.* species 2. Both of the latter are considerably coarser textured than these Naco sponges and therefore are clearly different. The type species *C. foliata* is finer textured than the Permian forms and is most similar in skeletal and canal dimensions to the new species described here. However, *C. foliata* is an asymmetrical ear-shaped to palmate sponge that apparently grew vertically, in contrast to the more likely horizontal living position of the flat, radially discoidal, Naco species.

Both Pennsylvanian species have thin dense dermal and gastral skeletal layers of relatively fine radial tracts and cross-connecting concentric or horizontal tracts. Radial and concentric dermal-gastral tracts in both species are thin, averaging approximately 0.10 mm thick in the new Naco species, but only 0.02–0.05 mm in the type species. Isolated single spicules may also occur in positions of concentric tracts in the new Naco species. Radial tracts are spaced 0.2–0.3 mm apart, laterally, in both species, and concentric tracts in the outer thin skeletal layers are 0.2–0.4 mm apart

Most of the skeleton is considerably coarser textured than that in the outer layers in all four species of the genus. Radial tracts average 0.5 mm and range up to 1.1 mm in diameter in the Naco species, but range 0.2–0.6 mm in diameter in *Chaunactis foliata.* Radial and concentric tracts are separated by arched canals that may be circular and 0.8 mm in diameter or ellipsoidal and 0.5–0.8 mm wide and 0.4–1.6 mm long in the new species and 0.3–1.2 mm across in the type species. Such minor differences might be results of differential preservation, and were it not for the distinct differences in living habits and growth forms, these two finer-textured species of the genus might be considered as a single taxon.

Etymology.—*Olsoni,* named after Thomas Olson who collected the original sponge material.

Material.—Holotype, MNA N9483A, and paratypes, MNA N9484–N9492, with 60 associated reference specimens, all from the Naco Formation at the Pine locality.

Order MONAXONIDA Sollas 1883
Family Uncertain
Genus NACOSPONGIA n. gen.

Diagnosis.–Discoidal, possible flattened spheroidal, sponge with interior layer of horizontal, weakly radiating to parallel monaxial spicules and upper and lower layers of irregularly spaced and oriented, weakly tufted, oxeas; lacks obvious canals and ostia

Discussion.–Comparisons with somewhat similar sponges are treated in discussion of the type species below.

Type species.–*Nacospongia radiata* n. sp.

NACOSPONGIA RADIATA n. sp.
Plate 1, figure 6

Description.—One nearly complete discoidal sponge, the holotype, and several fragments composed of irregularly oriented to radially arranged monaxial spicules occur in the collection. The nearly complete holotype is ellipsoidal, 28 mm across and 43 mm long, with a maximum medial thickness of approximately 8 mm. The sponge tapers laterally to rounded edges 2–3 mm thick. Both upper and lower surfaces are blanketed with irregularly spaced and oriented, to weakly radially tufted oxeas. A vertical section through the sponge lacks obvious canals and no distinct ostia are evident on either surface.

A vertical section cut near one end shows three generally identifiable skeletal layers within the sponge. An inner layer of horizontal, weakly radiating to parallel spicules is 2–3 mm thick, and upper and lower layers, in which the spicules diverge upward and downward, respectively, at angles of 10–15 degrees from spicules of the inner layer, are of the same general thickness. Spicules in the outermost 0.5–1 mm of both upper and lower layers curve to become tangential to outer surfaces of the sponge.

Spicules on the exterior are oxeas that range up to at least 5 mm long, with most 3.5–4.0 mm long. Maximum lengths are difficult to determine for nearly all exposed spicules have broken tips. Typical spicules have maximum midlength diameters of 0.15 mm, although a few range up to 0.18 mm in diameter. They taper in both directions. Interior spicules cut in the thin section are 0.15–0.18 mm in diameter and many have clearly preserved axial canals that are 0.035–0.040 mm in diameter. Some axial canals are now open, but others are filled with limonite-stained silica.

Discussion.—Original shape of the loosely-spiculed sponge is impossible to determine, for it may have been much more nearly spheroidal than the present elliptical cross-section would indicate. However, there is significant consistency in orientation of interior spicules, which would suggest that the sponge has been only slightly modified and that it probably had an originally ellipsoidal skeletal structure.

Coniculospongia Rigby and Clement, 1995, from the Devonian of Tennessee, is a funnel-shaped to bowl-shaped or discoidal sponge with a radiating skeleton of oxeas, but it lacks the irregular exterior thatch of *Nacospongia,* and is considered to be a different sponge. *Belemnospongia* Ulrich *in* Miller, 1889, is also a radiating, probably discoidal sponge, but it is composed of long oxeas that are more or less fasciculate, in a structure unlike that of *Nacospongia.*

Sphaeriella Rigby and Pollard-Bryant, 1979, from the Mississippian of Alabama, is a spheroidal sponge with radiating skeletal structure of long thin monaxons, but it has distinct canals parallel the unclumped spicules, and is thus different from *Nacospongia.*

Material.—Holotype, MNA N9493, from the Naco Formation, Pine locality.

SPECIES A
Plate 1, figure 2

Description.—A single inverted funnel-shaped small sponge occurs on MNA N9494, attached to a fragment of *Chaunactis.* The small circular sponge is approximately 18 mm in diameter, although partially buried in matrix, and is approximately 2 mm thick in the thickest central part of the skeleton. It consists of distinctly radiating smooth oxeas in an unbundled, uniform-appearing, thatch. Spicules were inserted within the thatch in outer parts of the skeleton to maintain a uniform structure, lacking canals. The skeleton appears interleaved and small- and large-diameter fragments of spicules occur side-by-side throughout the skeleton.

Oxeas are mostly 0.12–0.14 mm in maximum midlength diameter, although a few spicules are up to 0.18 mm in diameter. They are at least 3 or 4 mm long, but how much longer is impossible to tell because tips are broken or buried. Microscleres are unknown in the siliceous preservation.

Discussion.—This small sponge has a distinctly radiating fabric, much more regular-appearing than that of *Nacospongia,* and because of that they are separated here. However, the small sponge could be an immature representative of the interior part of that species, where the skeletal structure is more likely radiating than is seen in the outer irregularly spiculed exterior. It is difficult to evaluate that possible relationship because the interior structure of *Nacospongia* is not well known. Neither species has distinct canals in their radiate skeletal structures. Oxeas are major spicules in both sponges and are of similar diameters. Incomplete spicules in both make lengths difficult to compare.

Material.—The single representative of the species occurs on MNA N9494, Naco Formation, Pine locality.

Class Uncertain
ROOT TUFTS
Plate 2, figure 5

Description.—Fragments of root tufts occur in the collection as parallel tracts of monaxons. One larger fragment is composed of two layers, or tufts, 2–5 mm thick, in a stratified sequence of siliceous reddish mudstone. Spicules are parallel to each other and to stratification within each of the layers, but spicule fabrics of the two layers are at angles of 60–70 degrees to each other. Individual spicules in both layers range to 0.25 mm in diameter, although most are 0.15–0.20 mm in maximum diameter, and they taper in both directions, presumably to sharp tips. Longest fragments preserved are up to 14 mm long, but these probably represent only small parts of the complete spicules, for the amount of taper in the fragments is not great. In any section, numerous smaller diameter spicules occur between the coarser ones and have diameters of 0.10 mm or less. These could be only distal tips of the coarse spicules, but some appear to be parts of small spicules, based on their double taper.

Numerous spicules in the tufts have preserved axial canals, some as openings and others as limonite-stained siliceous fillings. In common spicules, 0.15 mm in diameter, such canals are 0.07–0.08 mm in diameter, but in some larger spicules, 0.18 mm in diameter, axial canals may be only 0.04–0.06 mm across. Some spicules 0.16 mm in diameter have obviously secondarily enlarged, open, canals 0.10 mm across, in the silicified preservation.

Discussion.—Relationships of the root tufts to taxa identified in the Naco Formation are unknown. These tufts are probably not related to the rhizomorine *Chaunactis olsoni* n. sp., although thatches of small short monaxons do occur in the dermal layer of that species. The coarse tufts are probably not related to the small discoidal monaxial demosponge either, and are also unlikely parts of the heteractinid sponges, represented by the single isolated sexiradiate spicule in the collection. These root tufts may be from sponges otherwise not yet discovered in the Naco Formation.

Material.—Figured fragment, MNA N9495, Naco Formation, Pine locality.

Class HETERACTINIDA de Laubenfels, 1955
Order OCTACTINELLIDA, Hinde, 1887
Family WEWOKELLIDAE King, 1943
Genus and species uncertain
Plate 2, figure 2

A single isolated sexiradiate spicule occurs associated with numerous irregular monactine spicules in one fragment in the collection. The spicule is a small element with six slightly reflexed tapering rays that radiate at equal angles from a central "disc" 0.16 mm in diameter. These rays have basal diameters of 0.05–0.06 mm and taper distally so that 0.2 mm out from the disc they are approximately 0.03 mm in diameter. On none are distal tips exposed so full ray lengths are not known, but one ray is traceable for 0.3 mm before being covered with matrix.

Discussion.—Although the isolated spicule cannot be even generically identified, it does document the occurrence of heteractinid sponges in the Naco Formation in central Arizona.

Material.—Figured specimen, MNA N9496.

ECOLOGICAL IMPLICATIONS

Brew (1965) concluded that sediments of the northwestern wedge of the Naco Formation accumulated in a shallow shoreward facies. Abundant clastic material and the dominance of reddish and reddish-brown sediments are evidences used by him to determine the depositional environment of the Beta Member in its northwestern extent. However, lack of great lateral continuity of individual beds may suggest that the sediments possibly accumulated in local restricted shallow basins.

Most specimens of the common demosponge were found in isolated mudstone layers. A few specimens are preserved on surfaces of less terrigenous limestone layers. Though the sponges are thought to have lived on muddy substrates, the influx of large quantities of mud may have caused the death of many of the sponges. The occurrence of sponges within the mudstones suggest that some may have been washed into depressions by the currents that brought in the mud that buried them. Other evidence that the sponges were buried quickly by muds include: 1) great number of sponges; 2) lack of superficial spicules on some specimens; 3) preservation of spicules that seem to have been washed off upper surfaces onto the sponge ramps; and 4) the associated dispersed spicules also found in mounds. Terrigenous influence on the quiet waters may have generated the influx of mud into the environment.

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PLATE 1

Sponges from the Naco Formation of central Arizona.

Figures *1, 3–5. Chaunactis olsoni* n. sp., *1,* two well-preserved, nearly complete, sponges on a slab of limestone include the holotype (A) and a paratype (B), MNA N9483, X1; *3,* clusters of monaxial spicule thatch on the outer ramp at the margin of a fragment of the discoidal sponge, MNA N9489, X3.5; *4,* vertical section through a paratype showing extent of exhalant canals and the divergent skeletal structure of the interior of the sponge, MNA N9488, X3.5; *5,* large discoidal paratype with prominent radial skeletal structure as exposed on the gastral surface, MNA N9485, X0.6.

Figure *2.* Sponge species A, with radiating skeletal structure of smooth oxeas, MNA N9494, X3.5.

Figure *6. Nacospongia radiata,* n. gen, n. sp., holotype, irregularly arranged oxeas of discoidal sponge, MNA N9493, X 3.5.

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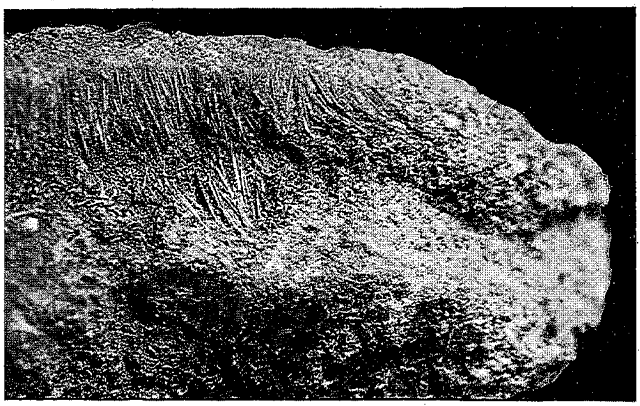

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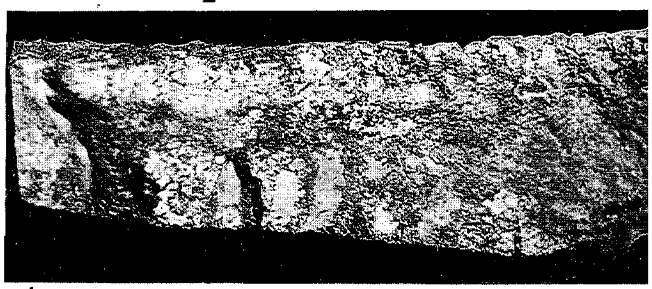

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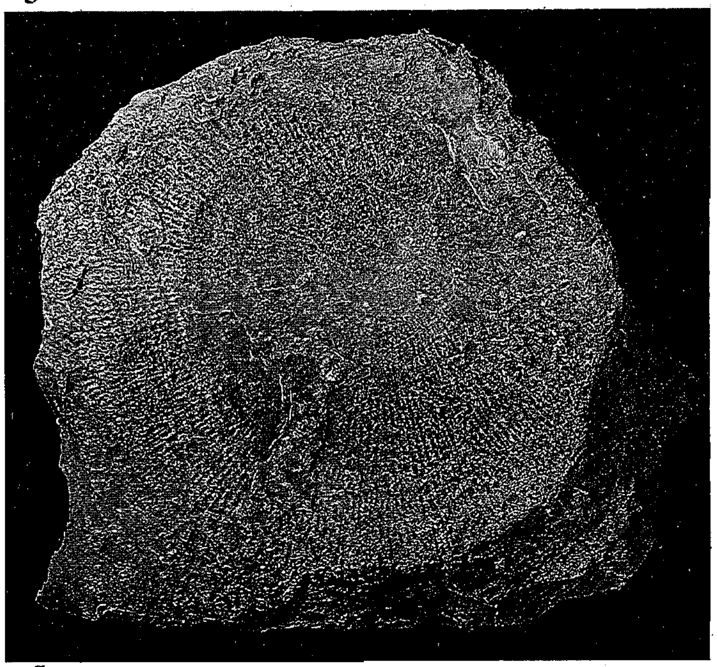

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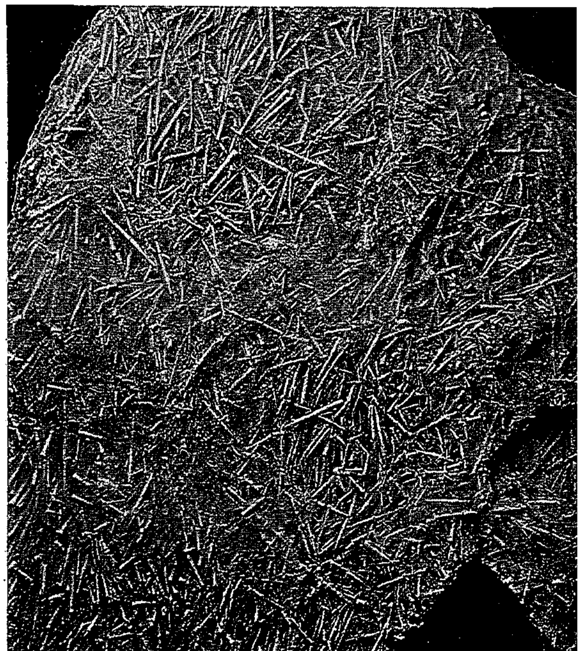

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PLATE 2

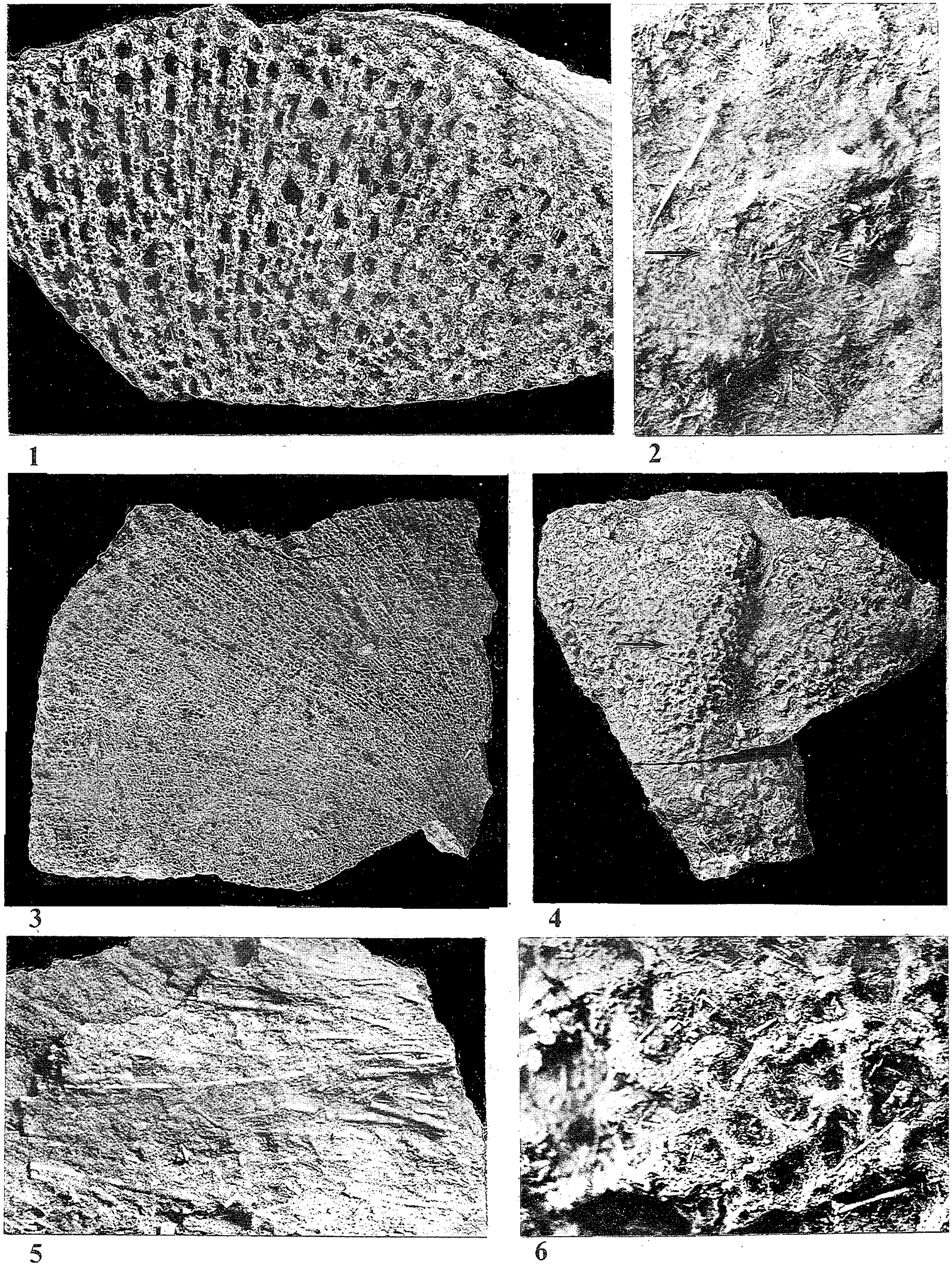
Sponges of the Naco Formation of central Arizona.

Figures *1, 3. Chaunactis olsoni* n. gen, n. sp., *1,* isolated paratype fragment with prominent radial structure of the skeleton and canal development on the upper gastral surface, dendroclones are rung-like spicules bridging radial elements, MNA N9484, X3.5; *3,* calcareous paratype fragment in red mudstone showing fine-textured gastral layer and interruptions of radial skeletal structure by exhalant canals, MNA N9486, X2.

Figure 2. Isolated sexiradiate heteractinid spicule (arrow) associated with probably unrelated fragments of monactine spicules, MNA N9496, X8.5.

Figures *4, 6. Haplistion nacoense* n. sp., holotype, MNA N9482, *4,* side view of stalked, erect lobate sponge with irregular skeletal grid of tangential tracts of rhizoclones, arrow marks location of tracts shown in Figure 6, X1; *6,* photomicrograph showing tracts of bundled small elongate rhizoclones, X20.

Figure 5. Root tuft fragment of aligned monaxial spicules in reddish mudstone, MNA N9495, X 3.5.



Taphonomy and Paleoecology of a Microvertebrate Assemblage from the Morrison Formation (Upper Jurassic) of the Black Hills, Crook County, Wyoming

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ABSTRACT

The Little Houston Quarry in northeastern Wyoming preserves a diverse assemblage of vertebrates in an abandoned channel deposit in the Upper Jurassic Morrison Formation. Along with dinosaurs, the site contains abundant microvertebrate fossils in two thin layers within one of the excavations at the quarry (and in pockets of the other excavation). The quarry serves as a model defining one of two microvertebrate taphofacies for the Morrison Formation. A survey of the microvertebrate elements and taxa collected from the site indicates that the deposit likely represents a broad local community and is only moderately time-averaged. There is a higher diversity of terrestrial taxa than of aquatic or semi-aquatic forms, though, probably for taphonomic reasons, semi-aquatic taxa are more abundant. Larger taxa are also more abundant, though, as in most modern communities, the smaller mass categories contain the most diverse assemblage of animals. Feeding mode guilds are fairly evenly filled, though the highest diversities occur among invertivore/carnivores and omnivores, and omnivorous turtles dominate numerically. This microvertebrate fauna provides a basis for comparison with other small-vertebrate faunas of the Morrison Formation and, in conjunction with other Morrison sites, with those of Late Jurassic deposits in Europe, Asia, and Africa.

INTRODUCTION

The Little Houston Quarry in the Morrison Formation of the Black Hills in northeastern Wyoming has produced a variety of Late Jurassic dinosaur genera. During quarry operations over the past several field seasons, however, many specimens of small, non-dinosaurians have been recovered. Most small bones from the quarry are fragmentary and not diagnostic, but the good specimens demonstrate that this locality is the most diverse vertebrate paleofauna in the Jurassic of the Black Hills region. Non-dinosaurian vertebrates from the site include: actinopterygian fish, lungfish, a frog, two types of turtles, a lizard, a sphenodontian, a choristodere, a crocodilian, and four types of mammals. Dinosaur genera that have been found at the Little Houston Quarry include the theropod *Allosaurus,* the sauropods *Apatosaurus, Camarasaurus,* and *Diplodocus* (or *Barosaurus*), the ornithopods *Othnielia* and *Dryosaurus,* and the thyreophoran *Stegosaurus.*

The first reported occurrence of Late Jurassic vertebrates in the Morrison Formation of the Black Hills was Marsh's (1890) description of the sauropod *Barosaurus.* This type specimen was found near Piedmont, South Dakota, in 1889. In 1935, several partial sauropods were collected from a quarry high in the Morrison northeast of Spearfish, South Dakota. During a stratigraphic survey of the western Black Hills in Wyoming, Loomis (1902) noted fragmentary dinosaurian remains in the Morrison Formation. Since the mid-1970's several additional dinosaur localities in the Morrison Formation of both South Dakota and Wyoming have been found by crews from the Museum of Geology at the South Dakota School of Mines & Technology in Rapid City. The most productive of these localities is the Little Houston Quarry, which was first excavated in 1991 (Foster and Martin, 1994).

The Morrison Formation at the site lies above the Upper Jurassic marine Sundance Formation and below the Lower Cretaceous fluvial deposits of the Lakota Formation. Almost 14 meters of the Morrison Formation are exposed at the Little Houston Quarry, and most of the rock consists of gray, brown, maroon, and green-gray non-smectitic mudstones. Two thin, crossbedded sandstone units occur in the middle of the exposure. The quarries are located in a two-meter-thick unit just above the lower channel sandstone. The bone-bearing lithosome is a light greenish-gray, finely laminated siltstone with thinly interbedded claystones.

The Morrison Formation in the northwestern Black Hills is fairly thin compared to other regions (Mapel and Pillmore, 1963). Stratigraphic correlation with other areas is very difficult due to the apparent pre-Lakota erosion of the upper parts of the Morrison in northeastern Wyoming, the lack of the clay change boundary used to position quarries further south, and the distance of the Black Hills from other Morrison outcrops (Turner and Peterson, 1999). Recent work on the relative stratigraphic positions of Morrison dinosaur quarries indicates, however, that the Little Houston Quarry may be at a level approximately equivalent to the lower Brushy Basin Member near the contact with the underlying Salt Wash Member (Turner and Peterson, 1999). If this relative stratigraphic position is correct, then the quarry would be slightly older than the Dry Mesa Quarry and the Marsh-Felch Quarry, both in Colorado.

Though several of the Black Hills localities have produced non-dinosaurian vertebrates, none yielded the numbers or diversity of the Little Houston Quarry. The taphonomic characteristics of the quarry were studied during field excavation and are described in this paper. The taphonomy of the site is of interest because of the paucity of microvertebrate quarries in the formation, and description of this site allows comparison with the other sites. A survey of all sites in the Morrison Formation has already indicated some possible trends in the microvertebrate deposits (Foster, 1998; Foster and Trujillo, 2000), and these will be discussed in a following section.

In addition to the taphonomic description, a survey of approximately 400 microvertebrate elements and paleoecological categorizations of the represented taxa are used here to determine the relative abundance and diversity of different vertebrate guilds. These are compared with another microvertebrate locality in the Morrison Formation (Quarry 9 at Como Bluff), and the taphonomy of the Little Houston Quarry site is examined to determine the nature of its microvertebrate accumulation. The composition of the microvertebrate fauna from the Little Houston locality is important for comparison with other Morrison Formation microvertebrate localities such as Quarry 9, as well as others such as the Fruita Paleontological Area in Colorado, and Rainbow Park in Dinosaur National Monument, Utah.

With an understanding of the paleoecology of the microvertebrate fauna of the Morrison Formation, we can compare the range of paleoecological characteristics to those represented in the Late Jurassic vertebrate faunas worldwide. There are vertebrate genera common to the Late Jurassic vertebrate faunas of North America, Europe, and Africa, as well as taxa unique to each region. The variation in paleoecological characteristics of the microvertebrate faunas between these regions may lead to a better understanding of the global history and biogeographic distribution of vertebrate feeding mode, locomotion, and body mass guilds during the Late Jurassic. The paleoecological part of this study, then, begins to characterize the paleoecology of the microvertebrate fauna of the Morrison Formation in North America, as represented by one locality.

The term "microvertebrates" for this study will include medium-sized animals such as turtles, crocodilians, and small dinosaurs, as their remains are small, individual bones preserved alongside the truly microscopic elements of very small animals.

Specimens from the Little Houston Quarry are part of the collections of the Museum of Geology, South Dakota School of Mines & Technology, Rapid City. Abbreviations used include: AMNH–American Museum of Natural History, New York; CMNH–Cleveland Museum of Natural History, Cleveland; DNM–Dinosaur National Monument, Jensen; FMNH–Field Museum of Natural History, Chicago; LACM–Natural History Museum of Los Angeles County, Los Angeles; SDSM–Museum of Geology at the South Dakota School of Mines & Technology, Rapid City; USNM–National Museum of Natural History, Washington, D.C.; YPM–Yale Peabody Museum, New Haven.

LOCALITY

The Little Houston Quarry lies approximately 20 km west of the town of Sundance in southern Crook County, Wyoming, just north of Little Houston Creek (Fig. 1). The Little Houston Quarry locality actually consists of two separate but neighboring excavations, both in the same bone-bearing channel deposit: the Main Quarry (SDSM locality V9138) and the Mammal Quarry (V941), the latter of which will be the main focus of this study. The Main Quarry contains remains of numerous individual dinosaurs. The Mammal Quarry is located approximately 75 m north of the Main Quarry. The Mammal Quarry (LHMQ) has been known and worked occasionally since 1991 but was only excavated extensively beginning in 1994. During the 1994 season, it was discovered that in addition to many small bones, the Mammal Quarry contained an articulated to partly disarticulated series of caudal and dorsal vertebrae of the sauropod dinosaur *Camarasaurus*.

METHODS

Collection of Specimens

The taxa considered in this study include fish, a frog, a lizard, a sphenodontian, the choristodere *Cteniogenys*, and several mammals, but also larger vertebrates such as crocodilians, turtles; small theropods, and the small ornithopods *Othnielia* and *Dryosaurus*. These taxa are all included because the taphonomic mode of preservation for all these forms is similar; all are represented by isolated, disarticu-

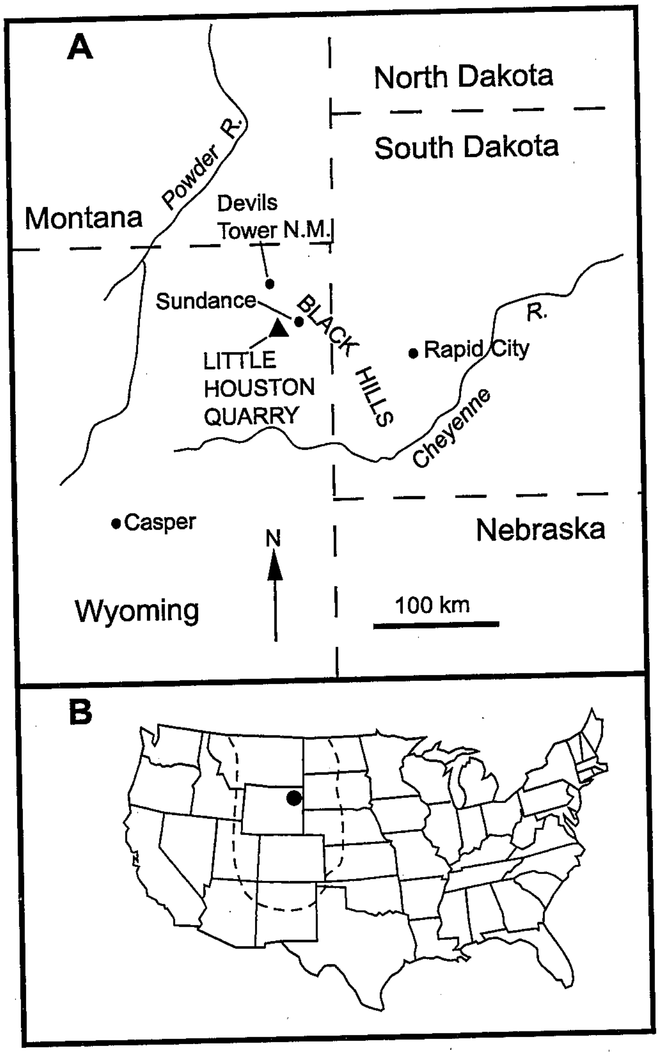


Figure 1. (A) Location of the Little Houston Quarry in northeastern Wyoming, west of the town of Sundance and south of Devils Tower National Monument. (B) Site in relation to the known distribution of the Morrison Formation (dashed line).

lated, individual elements in a high-density deposit of small bones. In addition, all theropod and ornithopod elements pertain to small individuals.

Specimens were collected by hand quarrying of siltstone matrix. In some cases, concentrated pockets of small bones were worked with needles, and occasionally, very small specimens were found via microscopic examination of the matrix. The matrix was not screen-washed because the matrix softens but does not completely breakdown in water, and because the bones were significantly more fragile than the matrix. Most specimens were prepared under a microscope, using a needle to remove matrix and small amounts of glue to repair cracks. Many specimens were particularly delicate and thus were prepared as far as possible but left in the matrix.

Larger bones in the quarry were mapped and photographed before removal, and some particularly important specimens (e.g. mammal jaws) that were too small to be drawn on the map simply had their approximate areas of collection mapped to within ~10 cm. Taphonomic notes on specimens and quarry layers were recorded in the field as well.

All but two specimens included in this study were from the LHMQ; jaw fragments of a multituberculate and a sphenodontian, taxa not known from the LHMQ, were found in the Main Quarry. Other Main Quarry microvertebrate material was not included in this study because the specimens have not been identified nor prepared from the blocks in which they were collected. Most Main Quarry microvertebrates occurred in pockets among the dinosaur material.

Specimen Counts

Badgley (1986) reviewed common methods for counting relative numbers of individuals for mammalian assemblages. Regardless of the method used, there are always difficult aspects of the counting process for fossils that cannot always be entirely solved (e.g. Gilinsky and Bennington, 1994; Blob and Fiorillo, 1996; Blob, 1997). Among the methods reviewed by Badgley (1986) are minimum number of individuals (MNI), number of identified specimens (NISP), and minimum number of elements (MNE). For reasons discussed later, the number of indentified specimens is nearly equal to the minimum number of elements at the LHMQ. Thus, the main counting methods to be chosen between in this case are MNI and NISP. Badgley (1986) indicated that the MNI method is best suited to deposits in which there has been limited transport and in which the probability of association of elements is medium to high. The NISP method, on the other hand, works best for sites that show evidence of current transport of bones prior to burial and where the probability of association of elements is low. Nearly all microvertebrate specimens from the quarry are isolated individual elements, and there is very little association and no articulation; the quarry is also in a channel deposit. The material appears to have been transported at least a short distance, and, from the disarticulation of the material, the probability of association of the elements is considered low. Thus, the relative abundances of taxa were estimated using the NISP method. Specimens rather than elements are counted in the study (cf. Lyman, 1994); complete elements are less common in the LHMQ and tallies of these would limit the size and diversity of the dataset.

In using the NISP method, it is valuable to have a similar possibility of preservation of the included taxa (J. Damuth, pers. comm., 1997). For this reason, larger taxa (medium and large dinosaurs) were not included in the analysis. Most small taxa from the quarry are assumed to have had an equal chance of preservation, except for the turtles and crocodilians, whose shell material and teeth, respectively, are probably more resistant to destruction during transport than most other elements. Crocodilian teeth are harder than bone and turtle shell fragments are generally thicker and less delicate than many microvertebrate elements.

Teeth are the most common remains of theropod dinosaurs and crocodilians in the sample. These elements were included in the count although one animal produces and sheds many teeth in its lifetime. Furthermore, these animals have substantially more teeth per individual than mammals. It is assumed, however, that few of these teeth belonged to the same individual. Counting all teeth may overestimate the abundances of theropods and crocodilians, but exclusion of teeth entirely would underestimate the abundances. Similarly, it was felt that doing a MNI count for turtle shell material would underestimate abundance more than including the material would overestimate it.

Ecological Categorizations

The specimen counts were used to determine relative abundances of the taxa, and each taxon was categorized by main habitat, feeding mode, and approximate weight in order to facilitate comparisons of the relative abundance of each group. Relative abundances and diversities of the ecological categories are compared with those of Morrison Formation microvertebrates in general. The likelihood of preservation of each species in the deposit is assumed to be roughly equal, and the accumulation appears to be in an abandoned channel. This paleoenvironmental interpretation suggests that the relative abundance counts would be dominated by aquatic and semi-aquatic species and by lighter-weight species (< 1 kg).

Habitat—Aquatic species are those that spend their lives entirely within bodies of water. Semi-aquatic species are those which either spend much of their time in water and some of it on land or are dependent on water sources for reproductive parts of the life cycle. Species in the terrestrial category are not dependent on water except for drinking and include all theropod and ornithopod dinosaurs, as well as mammals and lizards. This category does not differentiate scansorial, fossorial, or arboreal forms, which may have existed at least among the mammals and lizards.

Feeding mode—For the purposes of this study, species of the carnivore category are those that eat mainly other vertebrate forms. The herbivorous species possess teeth specialized for feeding on plants. The invertivore/carnivore category consists of small species that needed high-energy food and were small enough to feed mainly on adult insects and larvae, worms, and other soft-bodied invertebrates. Most of these species probably also fed on other microvertebrates occasionally, as some modern insectivorous and even herbivorous lizards and salamanders sometimes ingest other small vertebrates (Evans, pers. comm., 1999). Omnivorous species fed on plant material as well as invertebrates and possibly vertebrates.

Mass—The mass categories are here defined for animals <1 kg, 1–10 kg, and 10–100 kg. In this quarry, most of the larger species are represented by individuals under 100 kg. Weights of ornithopod dinosaurs and crocodilians and turtles were partly based on estimates in Dodson et al. (1980). Most other taxa are, based on size, similar to modern species that weigh less than 1 kg.

TAPHONOMY

The microvertebrate material is in a laminated siltstone. The siltstone occurs just above a convex-bottomed channel sandstone, which contains rounded bone fragments and calcium carbonate clasts, particularly at the base. To the south, the channel cuts into and across several layers of gray to red mudstone on either side. The fossiliferous unit consists of light greenish-gray, finely laminated siltstone beds 3–20 cm thick, thinly interbedded with dark greenish-gray to grayish-olive claystones 1–4 cm thick (Fig. 2). Some layers within the siltstones contain abundant rounded, green mudclasts up to about 10 mm in diameter. The matrix is interbedded with, and is eventually overlain by, green claystone and higher up is overlain by another channel sand. The siltstone quarry matrix often is laminated and consists of light gray silt and green clay layers, most less than 1 mm thick. Abundant carbonized plant material occurs in some layers, mostly within the siltstone beds. Invertebrates collected from the quarry include common casts and impressions of bivalves and gastropods. In addition, several charophyte gyrogonites were found in the Main Quarry.

To the south of the LHMQ, at the Main Quarry, the rocks demonstrate the same fining-upward trend, and the overlying sand can also be seen. About 1 m above the top of the bone layer, in the claystone, a single root cast was observed.

Quarrying operations at the mammal excavation demonstrate that the microvertebrate material occurs in two layers, each approximately 10 cm thick, separated by 10–15 cm. The thickness of each layer varies and is as thin as 1 cm. The top of the deposit is undulatory, sometimes dropping or rising 5–7 cm in the space of less than a meter laterally.

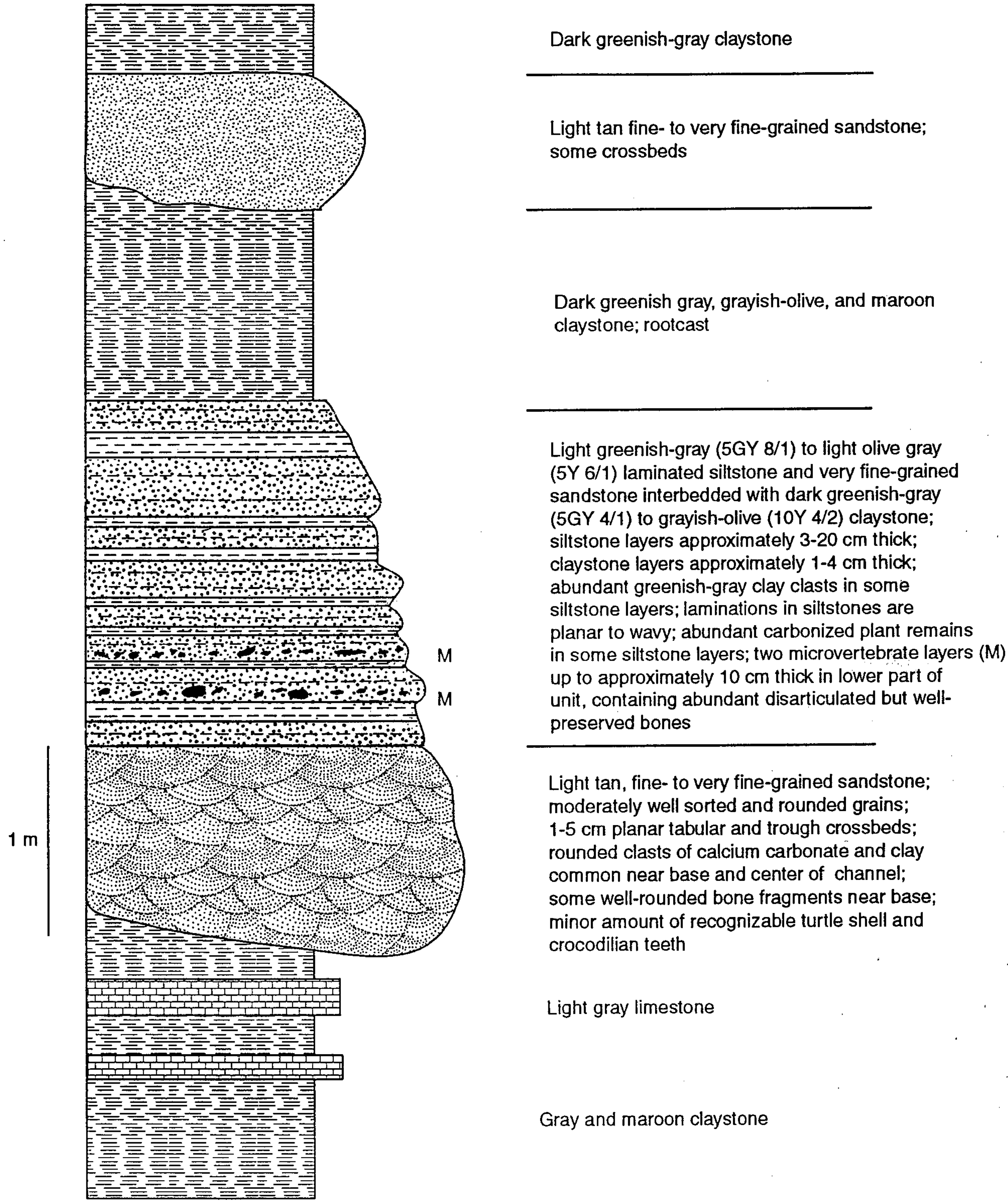


Figure 2. Generalized stratigraphic section of the Little Houston Quarry exposure showing position of the microvertebrate layers (M) in a unit of interbedded siltstones and claystones above a channel sandstone. Section covered above and below; quarry is in the upper middle part of the Morrison Formation.

The microvertebrate remains are abundant in the fossiliferous layers, with up to several thousand bones and bone fragments per square meter (Fig. 3). Most are tiny, indeterminate fragments. The 400 or so bones from the LHMQ surveyed in this study were collected from an area of approximately 17 m^2 and thus had an approximate bone density in the quarry of $24/m^2$ (for elements that can be identified at least to a major taxonomic vertebrate group).

Almost all elements of microvertebrates are completely disarticulated, and there are few occurrences of associated elements. Remains of animals from all habitat modes (terrestrial, semi-aquatic, and aquatic) are equally disarticulated; fish and turtle remains are disarticulated just as are terrestrial animals. The small bones do not show any preferred orientation. Although many bones are fragmented, few are worn or polished, and many preserve delicate laminae, processes and spines. Some bones are complete and undistorted, such as small hypsilophodontid femora with intact fourth trochanters, but there are also rare occurrences of highly worn and rounded, unrecognizable, fragments of larger bones. The amount of wear and rounding on most bones is low, although the degree of fragmentation is high, and few bones are entirely complete. The partial sauropod specimen from the LHMQ is articulated except for the distal parts of the tail and some of the anterior dorsal vertebrae (Fig. 4).

Behrensmeyer (1975) proposed a tooth/vertebra ratio as an index of fluvial winnowing for mammalian deposits. Since the tooth/vertebra ratio in a live mammal skeleton is often close to 1 (Badgley, 1986), the higher the ratio is, the more winnowed the deposit. Because vertebrae are easily transported and teeth difficult to move, the teeth would represent a lag deposit. Badgley (1986) found that Miocene channel deposits from Pakistan had ratios of about 3.3 and floodplain facies about a 1.7 ratio. With a greater component of reptilian taxa in a Jurassic deposit, the expected ratio should be somewhat different. The number of vertebrae in most small Jurassic reptiles would probably be somewhat greater than in many Cenozoic mammals, but the number of teeth would likely be much greater. Not only do many reptiles have more teeth per jaw than mammals, but they also continuously shed and replace teeth so that each individual can contribute many teeth to a deposit. We would thus expect the unwinnowed tooth/vertebra ratio of a Jurassic deposit to be somewhat higher than 1.

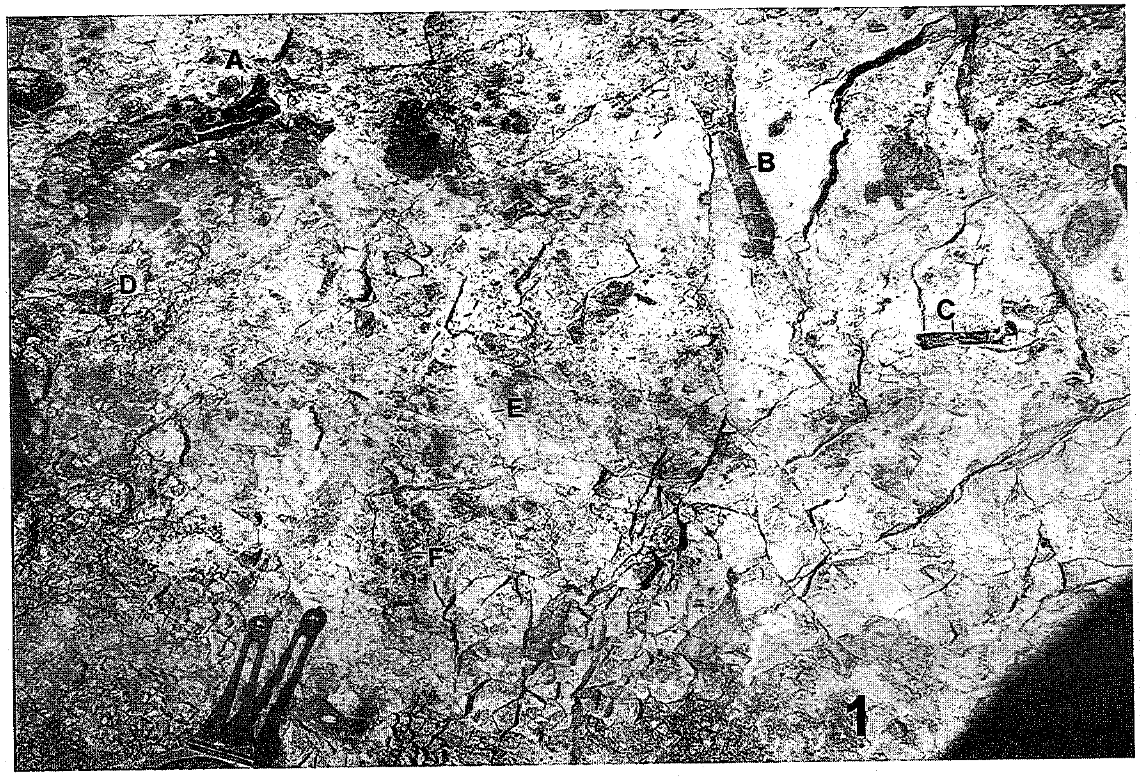
Interestingly, the ratio for the LHMQ is in fact lower. There are 88 vertebrae of microvertebrates in the sample and 53 isolated teeth (excluding a single very small fish tooth). This gives a tooth/vertebra ratio of 0.602. Including the 13 jaw fragments in the tooth sample, the ratio is 0.795. This suggests that the deposit is relatively unwinnowed.

Behrensmeyer (1988) described the taphonomic characteristics of two different modes of channel deposits for vertebrates; these are the channel-lag and channel-fill modes. Channel-lags accumulate near the bases of active channels, while channel-fill deposits occur in abandoned channels. A range of intermediate types of deposits occurs between these two. Based on the characteristics for each listed by Behrensmeyer (1988), the Little Houston Quarry appears to represent an abandoned channel-fill deposit. Channel-fill deposit characteristics of the Little Houston Quarry are: occurrence in the upper part of the channel, above basal lags; lithology of mudstone, silt, clay, and fine sands; edges of bones usually fresh; fairly complete bones; wide range of body sizes preserved; and variable alignment of bones. The rareness of associated skeletal parts is more characteristic of channel-lag deposits, and even though some sauropod partial skeletons are articulated in both the Main and Mammal quarries, many of the bones of the smaller dinosaurs are disarticulated and unassociated.

The fact that the siltstone is laminated, and that the microvertebrate remains occur in two distinct layers of disarticulated elements within the siltstone, may indicate that the deposit was an abandoned, but occasionally reactivated, channel and that the bones were deposited during major flooding events. Features of the deposit indicate an abandoned channel, but not the extreme case in which the channel is cut off suddenly and gradually infilled with fine-grained sediments and buries articulated skeletons from nearby. Rather, the channel appears to have been gradually abandoned and to have gone through a period of reactivation during several flooding events before finally being completely cut off and eventually infilled. This would account for the bone deposit having some characteristics of a channel-lag. Similar conclusions about the nature of the Little Houston Quarry deposit were reached in a preliminary study of the Main quarry by Pagnac and DiBenedetto (1998).

A comparison of quarries containing microvertebrates in the Morrison Formation indicates some trends in the taphonomic preservation and that at least two microvertebrate taphofacies can be preliminarily defined (Table 1). These taphofacies are defined by the characteristics of the

Figure 3. (3.1) Photo of the Little Houston Mammal Quarry with bone layer exposed; bones and carbonaceous plant material are black to dark gray; unfossiliferous underlying layer is visible in lower right of photo above shadow; compass in lower left points north; labeled bones are of small ornithopod or theropod dinosaurs: (a) femur; (b) tibia; (c) metatarsal; (d) caudal vertebra; (e) phalanx; (f) small serrated, unrecurved theropod tooth. (3.2–3.6) Specimens of microvertebrates from the Little Houston Mammal Quarry: (3.2) Actinopterygian fish, skull fragment (maxilla?); (3.3) Frog, distal half of humerus; (3.4) Scincomorph? lizard, right dentary; (3.5) Othnielia, *tooth; (3.6) Dryolestid mammal, left dentary with six teeth.*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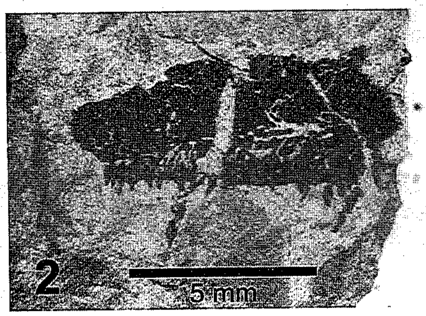
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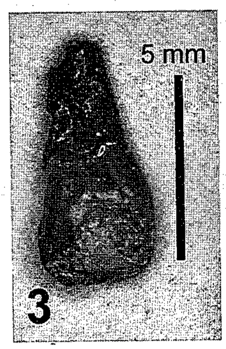
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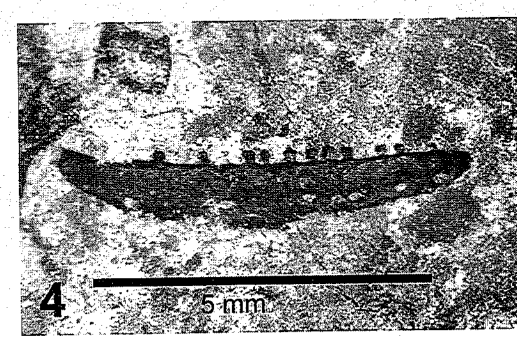
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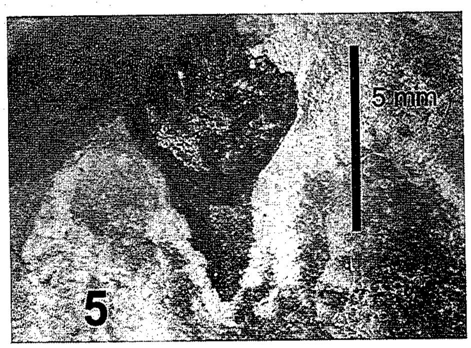
5 mm
5


10 mm
6

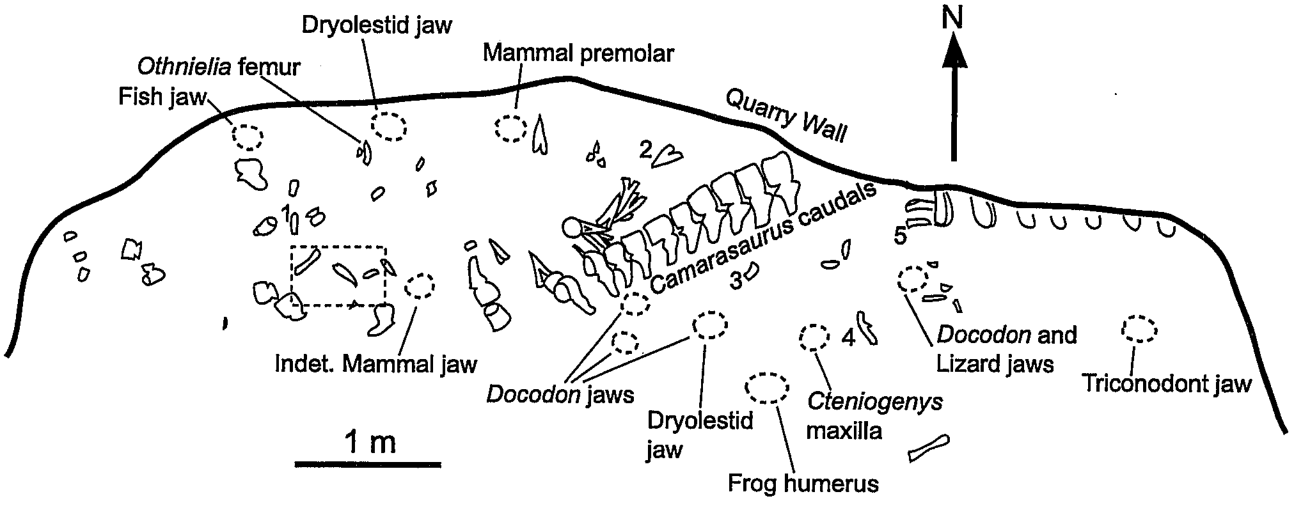

Figure 4. Map of the Little Houston Mammal Quarry as of 1996, showing Camarasaurus *vertebrae and distributions of other material; dashed circles indicate approximate positions of microvertebrate material as labeled. Numbered specimens are as follows: (1) ornithopod dinosaur humerus; (2)* Camarasaurus *chevron; (3) proximal half of ornithopod dinosaur femur; (4) complete femur of* Othnielia*; (5) ornithopod dinosaur metatarsal. Dashed rectangle indicates area of quarry shown in Figure 3.1.*

vertebrate fossil preservation and sedimentology of the quarries and are independent of the types of taxa they preserve. The Type I microvertebrate taphofacies is typified by the LHMQ deposit and this section has provided a description of its characteristics. The Type II taphofacies is based on sites at the Fruita Paleontological Area, in western Colorado, and differs from the LHMQ deposit in that the matrix is often slightly finer, rarely laminated, and more gray in color; it is also different in that microvertebrate remains are less densely accumulated than at the LHMQ and include articulated skeletons and partial skeletons. The LHMQ also preserves more aquatic and semiaquatic taxa than do the quarries at Fruita, which include mainly terrestrial animals. The Fruita sites have been interpreted as overbank crevasse-splay deposits (Kirkland et al., 1990) and this probably accounts for many of the differences between these quarries and the abandoned channel LHMQ deposit.

AUTECOLOGIES OF TAXA

The following section details which taxa have been identified at the Little Houston Mammal Quarry and the characteristics of each regarding habitat, food preference, and weight category.

OSTEICHTHYES
ACTINOPTERYGII

Fish are represented in the Little Houston Mammal Quarry mainly by scales and jaw fragments, and occasional skull fragments and teeth (Fig. 3.2). Fish known from the Morrison include Palaeonisciformes, Leptolepididae, Halecostomi, Pycnodontoidea, and Amiiformes (Kirkland, 1998). The identities of the fish from the LHMQ are unknown, but they are relatively small and most do not appear to be amioids.

All actinopterygian fish in the quarry were aquatic, and though some forms or individuals may have grown larger, the remains found here indicate that most were small and weighed <1 kg. Their small size suggests the fish ate invertebrates such as surface insects and worms as well as smaller fish. Modern freshwater fish sometimes ingest plant material, but since this is unlikely to be a major source of energy for fish of this size, the Morrison actinopterygians are classified as invertivore/carnivores.

DIPNOI
Ceratodus sp.

Lungfish are represented in the quarry by two tooth plates. The lungfish were probably several tens of centimeters long and weighed at least 1–2 kg but probably not more than 10 kg, based on comparisons with a modern lungfish with similar skull size. Some specimens of *C. robustus* weighed considerably more, but their tooth plates are much larger than those at the quarry. *Ceratodus* is assumed to have been fully aquatic, though it may have aestivated during dry periods. The teeth of lungfish from the Morrison indicate that the animals probably ate soft-bodied invertebrates when young and clams and other

Table 1. Characteristics of Taphofacies I and II for microvertebrate assemblages within the Morrison Formation of the western United States. Example quarries include main ones, on which characteristics are based, and other sites that are similar in parentheses.

Taphofacies	Lithology	Taphonomy	Example Quarries
Type I	Siltstone, claystone, fine sands; some lamination of siltstones; often green-gray; some small clay clasts; often just above or below channel sands	Relatively abundant disarticulated remains of small vertebrates; often in thin, distinct, high-density accumulations	Little Houston Mammal Quarry (Quarry 9; Small Quarry)
Type II	Siltstone, claystone, very fine sands; rare lamination; often gray; sometimes associated laterally with channel sands	Less abundant articulated to disarticulated remains of small vertebrates; low-density accumulations; less distinct bone layers than Type I	Quarry 4 and Tom's Place at Fruita Paleo Area (Wolf Creek Quarry)

harder shelled animals as adults (Kirkland, 1987). They may also have eaten some aquatic plant material and, when larger, some small fish and other vertebrates, as modern lungfish sometimes feed on these items. Thus, the *Ceratodus* specimens from the Little Houston Mammal Quarry are categorized as invertivore/carnivores.

AMPHIBIA
Anura indet.

A single frog specimen has been found in the quarry; it consists of the distal half of a humerus (Fig. 3.3). Evans and Milner (1993) noted that there were at least two families of frogs represented in the Morrison Formation, the Discoglossidae and the Pelobatidae, but that most material from the formation is undiagnostic below family level. Henrici (1998), however, documented pipoid frogs at Dinosaur National Monument in Utah. The new species *Enneabatrachus hechti* (Evans and Milner, 1993), a discoglossid, and *Rhadinosteus parvus* (Henrici, 1998), a pipoid, are currently the only valid species, as *Eobatrachus agilis* (Marsh, 1887) and *Comobatrachus aenigmatis* (Hecht and Estes, 1960) are considered *nomina dubia* (Evans and Milner, 1993). Humeri in particular are difficult to identify due to ontogenetic changes in the features of these elements; thus, the Little Houston Quarry specimen is simply identified as Anura indeterminate.

The small size of the humerus, and most Morrison frog material, indicates that the animals were less than 1kg in weight. Many small frogs are invertivores and eat mainly ants, termites, beetles, snails, and worms, most of which appear to have been present during Morrison times (Evanoff et al., 1998; Hasiotis and Demko, 1998). Jurassic frogs may have eaten some vertebrate material as well and are here considered as invertivore/carnivores. The mode of life classification used for this study will be semi-aquatic, due to the frogs' dependence on water sources and because many modern species live near lakes, swamps, marshes, and streams. Modern discoglossids and pelobatids, however, have varied habitat preferences ranging from aquatic environments, to near ponds and streams, to rather arid regions (Mattison, 1987).

REPTILIA
CHELONIA
Glyptops plicatulus

This species is represented entirely by carapace and plastron fragments. Other turtle elements could not be distinguished from *Dinochelys* and are thus identified as Chelonia indeterminate. The sculpted and ridged shell of this species is similar to *Uluops uluops* (Bakker et al., 1990) but is unlikely to belong to that form, as *Uluops* is so far only identified from two sites in the upper part of the Morrison. *Glyptops* is a semi-aquatic species and, based on its relatively small size probably weighed 1–10 kg. This species, along with all Morrison turtles, is classified as an omnivore, as modern chelonians eat insects, small fish and other vertebrates, as well as plant material, and vary their diet seasonally and/or as they grow (Alderton, 1988).

Dinochelys whitei

This turtle species is distinguished from *Glyptops* by its relatively smooth, unsculpted shell surface (Gaffney, 1979). It is more common at the quarry than *Glyptops*, and is also only represented by carapace and plastron fragments. *Dinochelys* is similarly semi-aquatic, omnivorous, and approximately 1–10 kg in weight.

SPHENODONTIA
Opisthias?

A single sphenodontian jaw fragment was found in the Main Quarry. The fragment consists of a section of the posterior part of the dentary with three teeth. *Opisthias* was a small reptile, most likely weighing less than 1 kg, and was terrestrial and mainly insectivorous. The *Opisthias* feeding mode is here considered to be invertivore/carnivore, as the modern *Sphenodon* occasionally consumes small vertebrates.

SQUAMATA
Scincomorpha? indet.

The single lizard specimen from the quarry is a tiny (6 mm) right dentary with several relatively blunt teeth (Fig. 3.4). Generic identification is difficult, but the teeth are too blunt to be from an anguimorph (Hoffstetter, 1967; Evans, 1996). It is not referrable to either of the known Morrison scincomorphs, *Paramacellodus* or *Saurillodon* (Evans, pers. comm., 1996), but that lacertilian group may be the best tentative identification. The specimen is considered to represent a terrestrial form weighing less than 1 kg and is categorized as an invertivore/carnivore, as most small, modern skinks and anguids are largely insectivorous (Mattison, 1989) but some lizards may occasionally feed on small vertebrates (Evans, pers. comm., 1999).

CHORISTODERA
Cteniogenys sp.

This species was named by Gilmore (1928) as a probable lizard, based on elements from Quarry 9 at Como Bluff, but additional material from Europe has indicated that it is actually a small, early choristodere (Evans, 1989). It is represented at the quarry by vertebrae and dentary and maxilla fragments (Foster and Trujillo, 2000). It is a small animal, approximately 25 cm long (Evans, 1991), and weighed considerably less than 1 kg. Like turtles and crocodilians, it was probably semi-aquatic (Evans, 1990). Based on its small size, it probably ate insects and other small invertebrates, as well as small fish.

CROCODYLIA INDET.

Crocodilians are represented mainly by teeth, scutes, and a few jaw fragments that are too incomplete to allow more detailed identification. These crocodilians were semi-aquatic forms of moderate size, most likely *Goniopholis* or *Eutretauranosuchus*, traditionally referred to as goniopholids. The material is not identified here as belonging to that family, as *Eutretauranosuchus*, though related to *Goniopholis*, may be closer to the Dyrosauridae and Thalattosuchia than to *Goniopholis* (Clark, 1994). Additionally, there may be yet unidentified elements of cursorial crocodilians in the collection. Long-limbed cursorial crocodilians are known from the Morrison Formation in Utah and Colorado (Clark, 1985; Kirkland, 1994), but no positively identifiable elements of these taxa have been found in the Little Houston Quarry.

Preserved elements indicate animals of relatively moderate size and most probably weighed less than 100 kg. Dodson et al. (1980), based on Mook's (1925, 1942) descriptions, estimated the weight of *Goniopholis* as being up to 50–60 kg. *Eutretauranosuchus* (Mook, 1967) probably had a similar mass, as the type specimen (CMNH 8028) is slightly smaller than most known *Goniopholis* specimens and appears to be a relatively young individual. Although young crocodilians may feed largely on insects (Pooley, 1989), animals of the lengths indicated by the material from the quarry probably fed primarily on fish, but also on some small vertebrates. The modern crocodilian *Crocodylus niloticus*, at lengths similar to Morrison crocodilians (~2.5–3 m), feeds mostly on fish as well as some small mammals and reptiles, and occasionally ingests snails and shellfish (Pooley, 1989).

REPTILIA? INDET.

Most of the specimens from the Little Houston Quarry are bones, mostly vertebrate and limb elements, probably of small indeterminate reptiles. Many probably belong to turtles, crocodilians, and lizards.

DINOSAURIA
SAURISCHIA
Theropoda

Theropod dinosaurs are represented at the site mainly by teeth and some vertebrae and limb elements. Most of the specimens appear to be of small theropods, including juvenile *Allosaurus* and an unidentified form with laterally compressed but unrecurved teeth. The small theropods are included in this study because the size of their remains indicates that few were much larger than the ornithopod dinosaurs in the collection, and because the taphonomic mode of their preservation is similar to the other animals.

The theropods from the site are carnivorous. Based on their relatively small size, they fed on small reptiles and mammals and other small dinosaurs. Theropods are terrestrial, and those at the site were 100 kg or less.

It should be noted that while the remains from the LHMQ indicate relatively small theropods, the Main Quarry 75 m to the south does contains elements of larger theropods, including adult *Allosaurus*.

ORNITHISCHIA
ORNITHOPODA
Othnielia rex

This small ornithopod, named by Galton (1977), is represented in the LHMQ mainly by teeth (Fig. 3.5) and several femora. The LHMQ teeth include specimens with accessory ridges similar to *Drinker nisti* (Bakker et al., 1990), although these ridges are known from teeth of some specimens of *Othnielia* as well (R. Scheetz, pers. comm., 1998). The teeth of *Nanosaurus agilis* (Marsh, 1877) appear to be slightly different from those of *Othnielia*, but preservation of the dentary and teeth as an impression in matrix in the type specimen of *Nanosaurus* makes it difficult to satisfactorily compare the two. *Nanosaurus*, though considered valid by Galton (1983), is among the *nomina dubia* listed by Sues and Norman (1990), and that classification is followed here. The teeth in the Little Houston Quarry collection are referred to *Othnielia*.

Othnielia was a small ornithopod weighing between 3 and 30 kg, with a modal adult weight of approximately 12 kg (Dodson et al., 1980). It was undoubtedly terrestrial and a low-browsing herbivore that orally processed its food (Sues and Norman, 1990).

Dryosaurus altus

This species is represented by a small pubis of a juvenile. Interestingly, none of the ornithopod teeth in the quarry belong to this species. Dodson et al. (1980) gave the range of weights of *Dryosaurus* as less than 10 kg to about 300 kg with a modal size of 100 kg. The juvenile found at the LHMQ was less than 100 kg as a living animal. Like *Othnielia*, *Dryosaurus* was a terrestrial, low-browsing herbivore and probably possessed more efficient oral processing, because of its more advanced teeth.

Several elements of indeterminate ornithopods have been found in the deposit also, and these most likely belong to one of the two above species.

MAMMALIAFORMES
Docodon victor

This docodont is represented by five jaw fragments and one partial molar. Though several species of *Docodon* have been named, Gingerich (1973) noted that all are probably referrable to *D. victor*. This species was less than 1 kg and terrestrial. Docodonts are believed to have been omnivorous (Simpson, 1933) but may have relied more on small invertebrates than on plant material. The multiple cusps of docodonts have numerous shearing surfaces, which would be useful in processing small, soft-bodied invertebrates and adult insects, but the teeth overall have relatively shorter, blunter cusps and greater occlusal surface area than most other Jurassic mammals, other than multituberculates. These features probably allowed for docodonts to include small seeds and other plant material in their diet.

MAMMALIA
Multituberculata
Psalodon marshi

This plagiaulacid multituberculate was found in the Main Quarry 75 m south of the LHMQ and near a series of *Camarasaurus* caudal vertebrae. *Psalodon marshi* was named by Simpson (1929) for lower jaws and teeth that were larger than the other Morrison multituberculate known at the time, *Ctenacodon*. Simpson (1929) noted that this form probably belonged to *Psalodon potens*, which is based on upper teeth and maxillae, but that he could not be certain. The specimen from the Little Houston Quarry (SDSM 26912) is referred to *P. marshi*, as it consists of a dentary fragment with p4 and m1 that is closer in size to the type specimen of that species (USNM 2684) than to lower jaws and teeth of *Ctenacodon* (Martin and Foster, 1998).

Morrison multituberculates were small and almost certainly weighed less than 1 kg. Though some multituberculates may have been scansorial, there is no evidence of any being fossorial or aquatic (Clemens and Kielan-Jaworowska, 1979), so those of the Morrison are classified as terrestrial, with no differention made for further specializations. The diet of multituberculates has been debated, though it is generally agreed that they were herbivorous to some degree. Simpson (1926) concluded that plagiaulacoid and ptilodontoid multituberculates were largely herbivorous, while Clemens and Kielan-Jaworowska (1979) preferred an omnivorous interpretation of the multituberculate diet. Krause's (1982) study of *Ptilodus* indicated that this genus (and ptilodontoids generally) was probably omnivorous. *Ptilodus* is not much larger than the Morrison multituberculate taxa, and though it has a single, larger blade-like p4, *Ptilodus* has a fairly similar lower dention to *Ctenacodon* and *Psalodon*, which have four, smaller, interlockling blade-like premolars. Krause (1982) also noted that ptilodontoids were probably too small to be entirely folivorous. It is likley, then, that *Psalodon* and other Morrison multituberculates were omnivorous and ate a variety of plant material and seeds as well as insects and other small invertebrates.

Triconodonta indet.

A single, poorly preserved maxilla fragment with one molar is the only evidence of this group found at the LHMQ. The specimen may belong to either *Priacodon* or *Trioracodon*. Triconodonts were most likely terrestrial and weighed less than 1 kg. Early triconodonts were probably insectivorous and later forms most specialized to become partly carnivorous (Jenkins and Crompton, 1979). Since almost no contemporaneous vertebrates were smaller than the mammals, it is likely that the diet of the triconodonts of the Morrison Formation consisted of insects, soft-bodied invertebrates such as slugs and grubs, and possibly small vertebrates.

Dryolestidae indet.

This family is represented by two specimens at the Little Houston Mammal Quarry. The first is a partial jaw with six teeth (Fig. 3.6); it is closest in molar morphology to *Dryolestes priscus* but has a reduced number of molars and may be a juvenile (see T. Martin, 1999). The second Little Houston specimen is a jaw fragment of an indeterminate form, and, as no teeth are preserved, it is identifiable as a dryolestid only because of the characteristically unequal root structure of the alveoli.

Dryolestids had high, pointed cusps and were best suited for feeding on insects and other small invertebrates (Simpson, 1933). The dryolestids were, like the other mammals mentioned here, small and terrestrial. A postcranial skeleton of a paurodontid from Portugal, however, suggests that some members of the order Dryolestida may have been arboreal (Krebs, 1991).

RESULTS AND DISCUSSION

The numbers of elements of each taxon observed in the survey are summarized in Table 2. The habitat, feeding mode, and weight category distributions are summarized in Tables 3–5. The terrestrial habitat category is most diverse, along with the <1kg weight category. Fairly high diversities occur within the invertivore/carnivore feeding mode guild, although the distribution among the other three guilds is fairly even; a relatively even diversity across guilds is a pattern common to many modern communities as well (Gotelli and Graves, 1996). The high diversities in the terrestrial, <1 kg, and invertivore/carnivore ecological categories appear to be significant, even considering the numbers of specimens of each guild in the sample.

Approximately one-third of the specimens in the sample belongs to indeterminate vertebrates (Fig. 5A). Almost all of these are small elements, mainly vertebrae and limb elements, probably belonging to turtles, small crocodilians, lizards, amphibians, and small archosauromorphs such as *Cteniogenys*. Another third of the sample is composed of turtles and crocodilians. The turtle sample consists of *Glyptops*, *Dinochelys*, and indeterminate turtle remains. Turtles and more specifically *Dinochelys* are the most common identifiable taxa preserved. Ornithopods, theropods, and actinopterygian fish are all roughly similar in abundance and together comprise about a quarter of the sample. Rarer elements of the fauna include mammals, *Cteniogenys*, *Ceratodus*, frogs, sphenodontians, and lizards. Among these, mammals are represented by the most elements (17), and *Cteniogenys* specimens (6) outnumber the single specimens of frogs, sphenodontians, and lizards.

A census of collections of microvertebrates from other Morrison sites (at the YPM, AMNH, USNM, FMNH, LACM, and DNM) demonstrates that in Quarry 9 at Como Bluff, *Cteniogenys* and sphenodontian specimens each outnumber the lizards significantly (nearly twice and three times as many specimens as lizards, respectively), whereas at the Dinosaur National Monument sites (including Rainbow Park), lizards and sphenodontians are nearly equally common and there is only a single *Cteniogenys* jaw fragment (Chure and Evans, 1998). At the Fruita Paleontological Area in western Colorado, lizard specimens outnumber sphenodontians 3:2 (Foster, 1998), but no specimens of *Cteniogenys* are known, and at Ninemile Hill, north of Como Bluff, *Cteniogenys* specimens are relatively common among a collection also including mammals, lizards, and fish (Trujillo, 1999). These data suggest possible biogeographic patterns in the microvertebrate faunas of the Morrison Formation, particularly the more abundant occurrence of *Cteniogenys* in, and perhaps its restriction to, northern areas of Morrison distribution, (Chure and Evans, 1998; Foster and Trujillo, 2000). Also, the sample from Quarry 9, along with those from Dinosaur National Monument and Fruita, indicates that sphenodontians may have been more common relative to lizards in northern areas; thus, more data are needed from other microvertebrate sites in northern areas.

The occurrence of *Docodon* as the most common mammaliform genus at the Little Houston Quarry is also interesting in that this genus still seems to be restricted mainly to eastern localities (Engelmann and Callison, 1998). It is also known from Quarry 9, Ninemile Hill, and from the Marsh-Felch Quarry and the Small Quarry at Garden Park, Colorado. At all but one of these sites, *Docodon* is the most common mammaliform genus in the sample (the Marsh-Felch Quarry produced one jaw each of *Docodon* and *Kepolestes* [= *Amblotherium* in T. Martin, 1999]), but it is still unknown from western sites such as Rainbow Park and the Fruita Paleontological Area. The occurrence of

Table 2. Specimen counts by taxon and element for the Little Houston Quarry assemblage.

Actinopterygii	Jaw fragments	12
	Skull fragments	5
	Scales	14
	Teeth	1
	Total:	32
Ceratodus sp.	Tooth plates	2
	Total:	2
Anura	Humeri	1
	Total:	1
Glyptops plicatulus	Shell fragments	7
	Total:	7
Dinochelys whitei	Shell fragments	45
	Total:	45
Chelonia indet.	Shell fragments	25
	Limb elements	14
	Vertebrae	1
	Pect/Pelv girdle elements	11
	Total:	51
Opisthias?	Jaw fragments	1
	Total:	1
Scincomorpha?	Jaw fragments	1
	Total:	1
Cteniogenys sp.	Jaw fragments	3
	Maxillae	1
	Vertebrae	2
	Total:	6
Crocodylia	Teeth	11
	Scutes	21
	Jaw fragments	3
	Limb elements	3
	Total:	38
Theropoda	Teeth	19
	Vertebrae	12
	Limb elements	4
	Total:	35
Dryosaurus altus	Pubes	1
	Total:	1
Othnielia rex	Teeth	11
	Femora	3
	Total:	14
Ornithopoda indet.	Teeth	3
	Limb elements	4
	Vertebrae	14
	Pect/Pelv girdle elements	2
	Total:	23
Reptilia? indet.	Limb elements	66
	Ribs	11
	Vertebrae	59
	Total:	136
Psalodon marshi	Jaw fragments	1
	Total:	1
Docodon victor	Jaw fragments	5
	Molars	1
	Total:	6
Triconodonta	Maxilla fragments	1
	Total:	1
Dryolestidae	Jaws	1
	Jaw fragments	1
	Total:	2
Mammalia indet.	Jaw fragments	1
	Premolars	3
	Molars	1
	Canines	1
	Incisors	1
	Total:	7
	Total Sample:	410

Docodon in a variety of lithologies suggests that this distribution is not necessarily a result of paleoenvironmental or preservational bias.

More than half of the identifiable microvertebrate specimens from the Little Houston Quarry are semi-aquatic forms (Fig. 5B). Together, semi-aquatic and aquatic taxa make up about two-thirds of the sample, the remaining third being composed of various terrestrial forms (indeterminate reptiles? were not included). Behrensmeyer (1975) noted that aquatic depositional environments increase the abundance of aquatic and semi-aquatic taxa relative to terrestrial taxa, but that the numerical representation of terrestrial taxa should be similar to what would be seen in terrestrial deposits. That terrestrial forms are less common in a channel deposit is not surprising. Fully aquatic species, however, seem to be less common than expected.

Table 3. Habitat category assignments for taxa known from the Little Houston Quarry.

Aquatic	Semi-Aquatic	Terrestrial
Actinopterygii	Anura	Scincomorpha?
Ceratodus sp.	*Glyptops plicatulus*	Theropoda
	Dinochelys whitei	*Othnielia rex*
	Chelonia indet.	*Dryosaurus altus*
	Cteniogenys sp.	Ornithopoda indet.
	Crocodylia	*Psalodon marshi*
		Docodon victor
		Triconodonta
		Dryolestidae
		Mammalia indet.
		Opisthias?

This may be a result of a truly more diverse and numerous population of semi-aquatic forms in the region or of a taphonomic bias against the preservation and/or easy recognition of aquatic forms. The relative rareness of *Ceratodus* tooth plates may stem from a low population density in the original environment, but actinopterygian fish elements, which are much smaller and more easily destroyed, are less likely to be preserved or are not easily recognized. On the other hand, Dodson et al. (1980) noted that the microvertebrate component of the Morrison, particularly aquatic forms, was low-density and "background" in nature, perhaps a result of the seasonal to semi-arid climate that appears to have been prevalent. A number of newly-found microvertebrate sites in the Morrison, which contain abundant remains of fish and other aquatic taxa, suggest, however, that these forms were not as rare as previously supposed.

The relative abundances of taxa in each feeding mode category (Fig. 5C) indicate that the omnivores (turtles and two types of mammals) and carnivores (crocodilians and theropod dinosaurs) dominate, comprising two-thirds of the sample. The next most-common group (invertivore/carnivores) in the sample includes the two types of fish, the dryolestid and triconodont mammals, frogs, lizards, sphenodontians, and *Cteniogenys,* while the herbivores were ornithopod dinosaurs. The invertivore/carnivore category is the most diverse feeding mode (Table 4). The omnivores are fairly common and also reasonably diverse (Table 4). This is unusual, as most food webs have relatively few omnivorous species (Rosenzweig, 1995). Conceivably, the sampled community may have been significantly more diverse than is currently apparent, the omnivorous species may have been drawn from separate communities, or the assignment of some of the species to omnivorous habits may be mistaken. The fact that the deposit combines taxa from both terrestrial and aquatic environments also probably accounts for some of the diversity and abundance among omnivores.

Dodson (1973) studied the transport potential of elements of microvertebrates and warned that, because of the ease with which these bones are carried downstream, it is risky to make paleoecological conclusions based on assemblages of microvertebrates. Dodson found that vertebrae are particularly quick to move and that jaws remain stationary the longest; he suggested that a common occurrence of vertebrae relative to jaws in a microvertebrate deposit may indicate a lack of selective winnowing. Vertebrae are reasonably common elements in the Little Houston Mammal Quarry sample, with more than three times as many vertebrae as jaws (Fig. 5D) and more vertebrae than teeth, as well. The abundance of vertebrae is a bit surprising, as other taphonomic characteristics of the deposit (layering of two microvertebrate layers; disarticulaton and disassociation; rare rounded bone fragments) indicate deposition during flood events. It is possible, however, that large amounts of bone material were transported a short distance into the abandoned channel rather quickly and little flow occurred after this, allowing the material to settle with no subsequent winnowing removing more easily transported elements. Thus it is possible that the specimens are from a local community. Hanson (1980), however, found little abrasion or other transport-related damage on bones that had been carried 2 km. How much communities on the Morrison floodplain would have varied in this distance cannot be determined.

As the fauna may represent a paleocommunity from the surrounding floodplain and not a mixture of proximal and distal communities, it will be interesting to compare other microvertebrate deposits of the Morrison Formation. A faunally and lithologically comparable site is Quarry 9 at Como Bluff, Wyoming, several hundred kilometers to the southwest of the Little Houston Quarry (see Ostrom and McIntosh, 1966). Quarry 9 also represents a Type I taphofacies (Table 1). All taxa known from the Little Houston site also occur at Quarry 9, but numerous other genera are known at the latter as well. Mammals are particularly diverse at Quarry 9 (Simpson, 1929). A preliminary survey of 870 specimens from Quarry 9 (from the collections at YPM, USNM, AMNH, and FMNH) and 193 from the Little Houston Quarry (excluding sauropods and larger theropods at both) reveals 38 genera from the former and 16 from the latter. Table 6 compares the relative abundance percentages of taxa from the Little Houston Quarry with those of Quarry 9. Some distinct differences are apparent. Fish are the most common taxon at Quarry 9, mainly due to a significant sample of amioid vertebrae, whereas at the Little Houston Quarry the turtle *Dinochelys* is most common.

Table 4. Feeding Mode category assignments for taxa known from the Little Houston Quarry.

Carnivores	Herbivores	Invertivore/Carnivores	Omnivores
Crocodylia	*Othnielia rex*	Actinopterygii	*Dinochelys whitei*
Theropoda	*Dryosaurus altus*	*Ceratodus* sp.	*Glyptops plicatulus*
	Ornithopoda indet.	*Cteniogenys* sp.	*Docodon victor*
		Psalodon marshi	
		Chelonia indet.	
		Anura	
		Scincomorpha?	
		Triconodonta	
		Dryolestidae	
		Opisthias?	

Table 5. Mass category assignments for taxa known from the Little Houston Quarry.

<1kg	1–10kg	10–100kg
Actinopterygii	*Glyptops plicatulus*	Theropoda
Anura	*Dinochelys whitei*	*Othnielia rex*
Cteniogenys sp.	Chelonia indet.	*Dryosaurus altus*
Scincomorpha?	*Ceratodus* sp.	Ornithopoda indet.
Psalodon marshi		Crocodylia
Docodon victor		
Triconodonta		
Dryolestidae		
Mammalia indet.		
Opisthias?		

Dinochelys is more common than *Glyptops* at the LHMQ, but the two turtles are about equally abundant at Quarry 9. Also, crocodilians are abundant at the Little Houston Quarry but are a minor component of the Quarry 9 fauna. Some of the differences in abundances and diversity between the two sites may be due to the drastically different sample sizes. Is the diversity at the Little Houston Quarry lower (or higher) than we should expect for a sample of approximately 190 specimens drawn from the same community as Quarry 9?

Rarefaction curves were calculated for each quarry in order to compare the relative generic diversities. These curves were calculated using the equations of Tipper (1979), which are in turn based on Hurlbert (1971) and Heck et al. (1975). The method of Sanders (1968) is simple to compute but consistently overestimates the expected number of species (Heck et al., 1975). It is important that samples compared using rarefaction are taxonomically similar, are from similar habitats (lithologically and taphonomically similar, in this case), and have been collected using similar techniques (Tipper, 1979; Gotelli and Graves, 1996). As stated above, the faunas, lithology, and taphonomy of the Little Houston Quarry and Quarry 9 are quite similar and both were collected mainly through hand quarrying of matrix. Rarefaction curves based on counts of vertebrates, in which the numbers of preservable elements are not always the same between different taxa, may vary slightly due to the necessarily less-reliable way these animals must be counted. However, this should not present much of a problem as long as the preservation potential of taxa remains the same between localities (e.g. Clyde and Gingerich, 1998).

The rarefaction curves for the LHMQ and Quarry 9 (Fig. 6) suggest that the samples were drawn from communities similar in species richness and that the LHMQ sample is not significantly less diverse than expected for the number of specimens known. The number of genera from the LHMQ is just below the 95% confidence interval of the expected value for a sample of similar size from Quarry 9. A sample of 190 specimens from Quarry 9 would

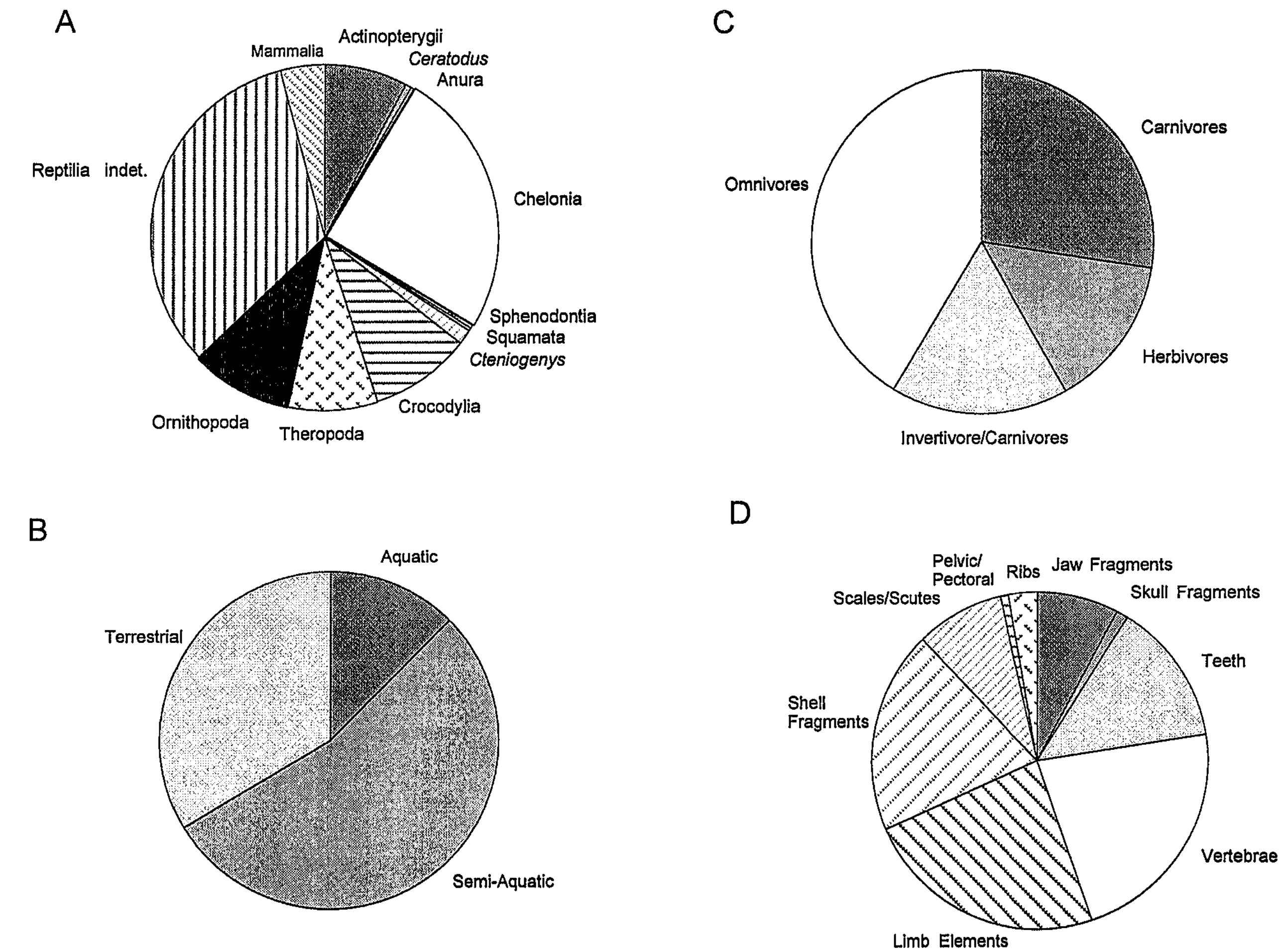

Figure 5. (A) Relative abundances of microvertebrate taxa in the sample from the Little Houston Mammal Quarry. N = 410. (B) Relative abundances of quarry specimens attributed to different habitat categorizations. N = 274. (C) Relative abundances of quarry specimens from each feeding mode category. N = 266. (D) Relative abundances of quarry microvertebrate elements. N = 399.

be expected to have about 24 genera represented, but the confidence interval allows a range of about 16 to 32 genera; the LHMQ has 16 genera known with 193 specimens. For sample sizes smaller than 190, the 95% confidence intervals of the two quarries' samples overlap. Thus, although the LHMQ sample may in fact be drawn from a taxonomically similar but less diverse paleocommunity than Quarry 9, these data cannot confirm that.

Most Morrision high-level vertebrate taxonomic groups are present in the Little Houston Quarry sample. The main groups missing are pterosaurs and symmetrodont and paurodont mammals. Thus, most of the missing generic diversity at the Little Houston Quarry is among these groups and in the range of taxa known among the crocodilians and dryolestid, triconodont, and multituberculate mammals at Quarry 9. Aside from the greater sample size at Quarry 9, the higher diversity there may also result from that deposit perhaps being drawn from a greater geographic area within the Morrison floodplain. Also, it may have been time-averaged over a greater interval than the LHMQ; both of these factors would have increased the chances of preservation of rarer taxa, such as the crocodilian *Macelognathus,* known from a single specimen from Quarry 9 and nowhere else.

The degree to which the LHMQ sample may be time-averaged is difficult to precisely ascertain. Channel-fill deposits like the LHMQ should be drawn from shorter intervals (and from smaller areas) than channel-lags (Behrensmeyer and Hook, 1992). Estimates for the range of deposition of channel-fill accumulations are generally from 10s or 100s to 1000s of years (Kidwell and Behrensmeyer, 1993; Rogers, 1993), and the effects of time-averaging can include distortions of species richness and other characteristics of the fauna (Fürsich and Aberhan, 1990).

Table 6. Comparison of the relative abundances of taxa in the Little Houston Quarry and Quarry 9 microvertebrate assemblages.

Taxon	Little Houston Quarry Percent of Sample	Quarry 9 Percent of Sample
Dinochelys	23.3	8.7
Crocodylia	19.7	3.5
Theropoda	18.1	1.0
Actinopterygii	16.6	29.2
Othnielia	7.3	0.73
Glyptops	3.6	11.5
Cteniogenys	3.1	3.8
Docodon	3.1	6.1
Ceratodus	1.0	3.1
Dryolestidae	1.0	12.7
Dryosaurus	0.5	0.44
Anura	0.5	0.58
Psalodon	0.5	1.5
Triconodonta	0.5	3.4
Scincomorpha?	0.5	1.9
Sphenodontia	0.5	5.3
Ctenacodon	—	2.3
Caudata	—	0.15
Pterosaur	—	0.30
Symmetrodonta	—	2.4
Paurodontidae	—	1.7

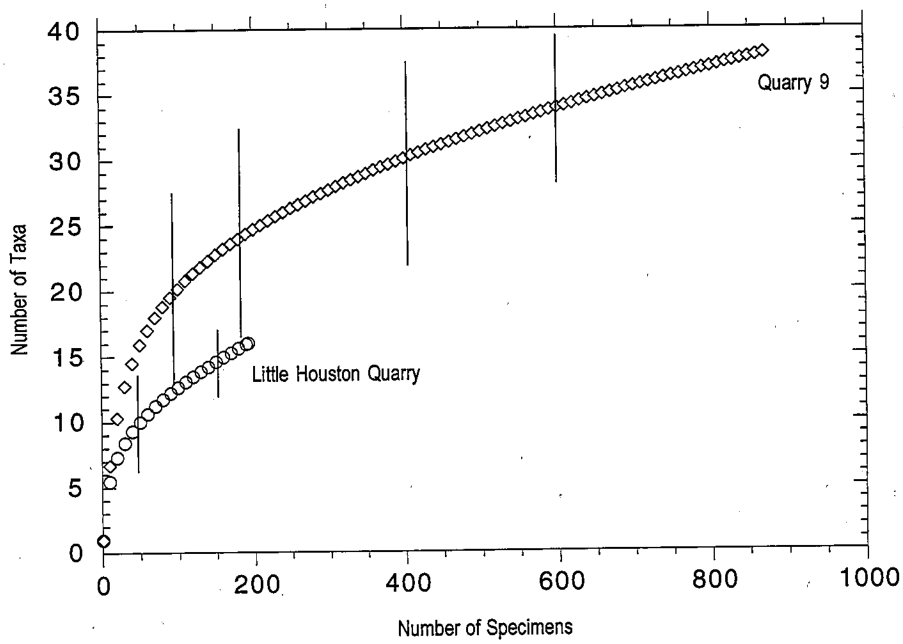

Figure 6. Rarefaction curves for microvertebrate material from the Little Houston Mammal Quarry and Quarry 9, showing expected number of taxa at smaller sample sizes. Vertical lines indicate 95% confidence interval.

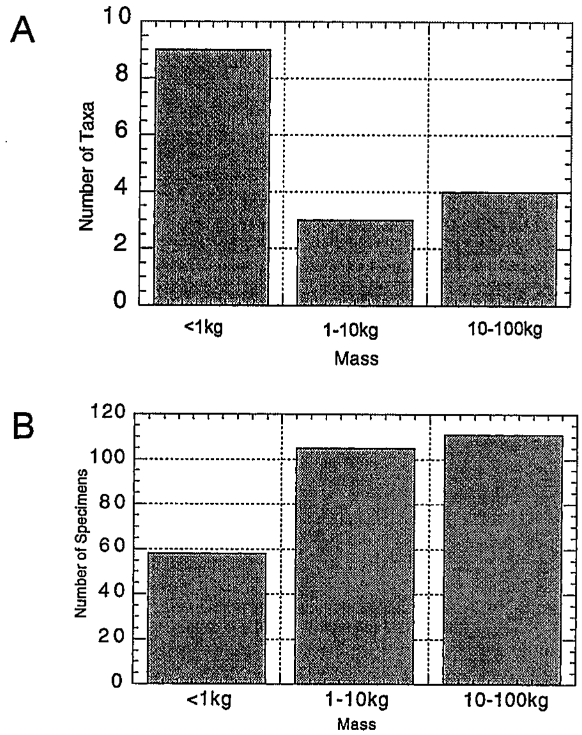

Figure 7. (A) Taxonomic diversity within mass categories for the Little Houston Mammal Quarry sample. (B) Numeric abundance within mass categories.

However, advantages of moderate time-averaging include the filtering out of minor fluctuations in the environment that may affect populations and ecosystem dynamics; this would result in the record reflecting the long-term average composition of the fauna (R. Martin, 1999). Also, analyzing the composition of the fauna through ecological characterizations (e.g. feeding and habitat modes) appears to be less prone to distortion than other attributes (Fürsich and Aberhan, 1990).

The sample from the Little Houston Quarry resembles the Morrison Formation in general, and most modern communities, in preserving a higher diversity of animals of small body size than of larger sizes (Fig. 7A). However, there is still a greater abundance of specimens of larger-bodied animals in the sample (Fig. 7B), indicating that, despite the great range of body sizes preserved at the quarry and the relative abundance of small animals compared to many quarries in the Morrison Formation, there still is a preservational bias in favor of larger skeletal elements. Alternatively, the fact that many of the smallest elements from the quarry are taxonomically indeterminate, and thus cannot be assigned to a specific weight category, may have lowered the abundance of taxa with a body mass less than 1 kg in Figure 7B.

CONCLUSIONS

The Little Houston Quarry microvertebrate fossils are preserved in an abandoned channel deposit. The fossiliferous layers were likely deposited fairly quickly with well-preserved vertebrate material, derived from nearby, mixed with a very minor component of rounded bone fragments, apparently transported a significant distance. Preservation of a wide variety of microvertebrate elements in good condition, including vertebrae and other more easily transported elements, suggests a lack of significant winnowing of the deposit.

The paleofauna represents a mixture of the local aquatic, semi-aquatic, and terrestrial communities. Because of the aquatic environment of deposition, the semi-aquatic taxa are most abundant, though the terrestrial animals have a greater overall diversity. As with most other communities, the smaller-bodied weight categories were more diverse than larger ones and feeding mode guilds were fairly evenly filled. Numerically, however, identifiable small-bodied animals are less abundant, and the omnivore feeding mode (mostly turtles) dominates; both of these abundance patterns are products of the taphonomy of the site and not true paleoecological patterns unique to the area. In fact, these abundance patterns are characteristic of the Morrison Formation as a whole. Smaller-bodied animals must have been far more abundant and ecologically important than their known record indicates.

The microvertebrate fauna at the LHMQ is taxonomically similar to Quarry 9, and the generic-level diversity is apparently within the range expected for its smaller sample size. In addition to its larger sample size, the greater diversity at Quarry 9 may be a result of greater time averaging within the deposit or from having a greater area from which the material was drawn in the original ecosystem. If biogeographic patterns of diversity change within the vertebrate fauna of the Morrison Formation are found, the patterns would not likely be a result of temporal differences between sites, as the expected vertebrate generic diversities for the Morrison Formation as a whole do not seem to have changed significantly through time (Foster, 1998). North-south microvertebrate diversity and biogeographic distribution patterns within the formation, if present, could be related in part to an observed trend toward more humid conditions in the more northern parts of Morrison deposition (Miller, 1987).

Patterns of occurrence and abundance of *Cteniogenys*, lizards, sphenodontians, and other animals at the Little Houston Quarry and other microvertebrate sites in the Morrison Formation suggest biogeographic distributions that are more varied than those of some larger-bodied species (Foster, 2000). The choristodere *Cteniogenys* and the mammaliform *Docodon* are known mainly from northern and eastern localities, respectively, and these distributions seem to be independent of sample size (Chure and Evans, 1998; Engelmann and Callison, 1998; Foster and Trujillo, 2000). Each occurs in its respective region at large and small sites and is nearly absent from other areas even in large sample sizes.

Our understanding of paleobiogeographic distribution and abundance patterns will improve with the discovery and analysis of new microvertebrate sites and with continued analysis of those already known. Comparison of the faunas and collections of the microvertebrate localities will help determine in which groups the differences between the quarries are greatest. Finding whether these differences are due to species biogeography, paleocommunity patterns, or some other factor, will require a better understanding of all microvertebrate localities within the Morrison Formation.

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New Lithostratigraphic Units in the Notch Peak and House Formations (Cambrian-Ordovician), Ibex Area, Western Millard County, Utah

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ABSTRACT

Type areas of the uppermost Cambrian Millardan Series and lowermost Ordovician Ibexian Series are in the Ibex area of Millard County, Utah. The Notch Peak Formation and the House Limestone include this series boundary, which is near the middle of the Lava Dam Member of the Notch Peak Formation, the youngest of its three members. Slightly above the series boundary is the Tank Canyon Bed (new), an ooid grainstone that in most places is less than one meter thick and is 1–2 m above the series boundary. Slightly higher is the Lawson Cove Bed (new), a stromatolite or thrombolite bed 1–1.5 m thick. These beds can be traced from the northern Wah Wah Mountains to the Sneakover Pass area in the central House Range. The Tank Canyon Bed can be traced westward into Nevada. Type sections of both beds are in the Lawson Cove area in the northern Wah Wah Mountains.

The House Limestone is herein divided, in ascending order, into three members, the Barn Canyon, Burnout Canyon, and Red Canyon members. The Barn Canyon and Burnout Canyon members have type sections in the Lawson Cove area, and the type section of the Red Canyon Member is in the Lava Dam area in the southern House Range. These members can be traced throughout the southern and central House Range and into the northern Drum Mountains. The lower two members can be traced westward into Nevada.

INTRODUCTION

Decades of research by many geologists in the Ibex area of western Millard County, Utah have resulted in major advances in understanding the lithostratigraphy, biostratigraphy, and chronostratigraphy of upper Cambrian and lower Ordovician strata exposed there. These strata comprise the North American standard for both the highest Cambrian and lowest Ordovician series. Ross et al. (1997) summarized much of the available data and documented the Ibexian Series as the lowest of four Ordovician series in North America. Those authors divided the Ibexian into four stages, and herein we consider only the lowest, the Skullrockian Stage. Palmer (1998) proposed new subdivisions of the Cambrian System in North America. He recognized four series, the youngest of which is the Millardan Series, named after Millard County, Utah, where the Ibex area is located. Herein we consider only the upper stage of the Millardan Series, the Sunwaptan Stage. These stratigraphic units are summarized on Figure 1.

Authors of this report have studied Millardan and Ibexian strata in the Ibex area for as much as four decades.

*Deceased September, 1999

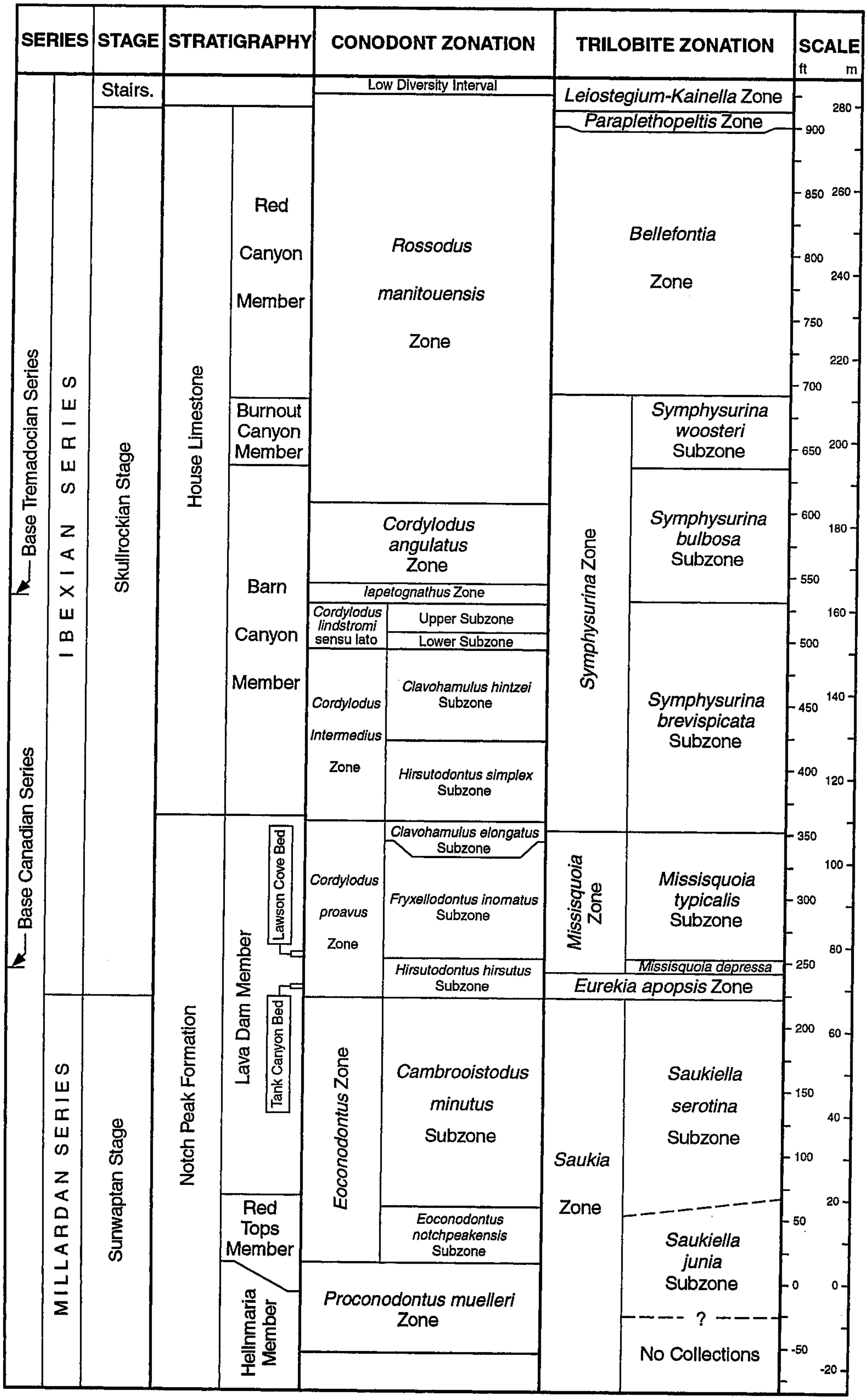

Figure 1. Chronostratigraphic, biostratigraphic, and lithostratigraphic units used in text.

We have measured and studied many sections that have not been described in the literature, and we have restudied and redescribed in more detail some sections that were described in earlier reports. With additional colleagues, we are involved in a comprehensive research program to document more fully the strata that comprise the Millardan and Ibexian series.

In this report our primary objective is to document strata that comprise most of the Sunwaptan Stage and all of the Skullrockian Stage and to name five new lithostratigraphic units. These new units include two formally named beds in the Lava Dam Member of the Notch Peak Formation and three new members of the overlying House Limestone. We present new, more detailed descriptions of four important sections that were described previously in the northern Wah Wah Mountains and in the nearby southern House Range, and we describe one new section in the northern Drum Mountains.

We also provide a conodont and trilobite biostratigraphic framework for these strata (Fig. 1) that is based on extensive fossil collections. Documentation of the biostratigraphy is beyond the scope of this report, and we are preparing a separate report on the biostratigraphy and other aspects of the stratigraphy of these strata. The biostratigraphic units are nearly identical to those used by Ross et al. (1997) in documenting the Ibexian Series in this part of Utah. The basis for the biostratigraphic framework presented herein is considered briefly in a later section of this report.

MEASURED SECTIONS

This report is based on data from measured sections located on Figure 2. Most data discussed are from the Lawson Cove section in the northern Wah Wah Mountains and sections at Steamboat Pass, Lava Dam Five, and Lava Dam North (Fig. 2, locations A–D) in the southern House Range. These sections are described in the Described Sections part of this report. Figure 2 also locates the Sneakover Pass section (location E), which is the Principal Reference Section of the Notch Peak Formation and the type section of each of its three members (Hintze et al., 1988). Location F on Figure 2 is Section A of Hintze (1951), which is the type section of the House Limestone. Location G on Figure 2 is a section in the northern Drum Mountains (Stitt and Miller, 1987), which is the farthest north that we have traced these strata.

Figure 3 is a detailed location map of the Lawson Cove section, where most of the new stratigraphic units are named. It is located in the west end of a northern branch of Lawson Cove, near Middle Pass, in an area known as the Gray Hills. The Lawson Cove section is accessible from the north and east by road. It was measured in three overlapping segments, identified herein as the lower, middle, and upper segments. It is easy to drive to the base of the lower and middle segments in an ordinary automobile. The access road and a dirt automobile track lead to the lower part of the section and end at the Hellnmaria-Red Tops contact. The road over Middle Pass provides access to near the base of the upper segment.

A complete section of the Hellnmaria Member is present in the hills east of the lower segment. Although we did not study these strata, we sampled the top 12 ft (3.7 m) of the Hellnmaria for conodonts at the base of the Lawson Cove section. The base of the measured traverse begins slightly below the base of the Red Tops Member (see described section). The lower segment includes a complete section of the Red Tops and Lava Dam members. The bases of the Ibexian Series and Canadian Series are somewhat above the middle of the lower segment. A total of 360 ft (110 m) of strata was measured in the lower segment. A profile view of the section is shown on Figure 4.

The base of the middle segment of the section is approximately 100 yards (100 m) west of the top of the lower segment; these segments are separated by a small N-S fault. This fault crosses the lower segment less than one meter above the Notch Peak-House contact, and the House Limestone is not exposed in the lower segment. The middle segment includes the upper 79 ft (24.1 m) of the Lava Dam Member; this interval duplicates strata measured in the lower segment. The middle segment includes the type section of the Barn Hills Member (new) of the House Limestone and the lower 35 ft (10.7 m) of the Burnout Canyon Member (new) of the House Limestone. A total of 384.5 ft (117.2 m) of strata was measured in the middle segment.

The upper segment of the Lawson Cove section is ca. 1.6 miles (2.6 km) northeast of the top of the middle segment (Figs. 3, 5). A painted label identifies this as the Lawson Cove North section, but for convenience it is referred to herein as the upper segment of the composite Lawson Cove section. This segment duplicates some strata measured at the top of the middle segment. The lower 53 ft (16.2 m) of this segment constitutes the type section of the Burnout Canyon Member of the House Limestone, and the remaining 106 ft (32.3 m) of the section is assigned to the Red Canyon Member (new) of the House Limestone. We estimate that a little less than half of the Red Canyon Member is present in the upper segment, but younger strata are eroded away in this area. A total of 159 ft (48.5 m) of strata was measured in the upper segment. The section ends at the top of hill 6149, north of the area shown on Figure 5.

The Cambrian-Ordovician stratigraphic succession continues in the southern House Range to the northeast (Fig. 2). The southern part of the House Range is a large syncline, and the southern end of the structure exposes a

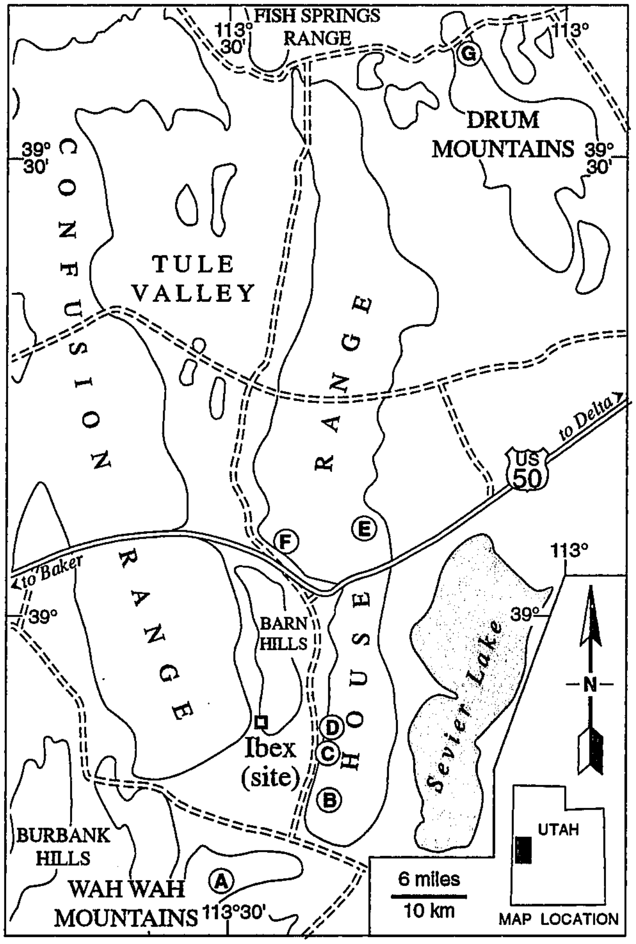

Figure 2. Location of measured sections. A = Lawson Cove (see Figure 3 for more detail). B = Steamboat Pass. C = Lava Dam Five. D = Lava Dam North. E = Sneakover Pass, type section for Hellnmaria, Red Tops, and Lava Dam members of Notch Peak Formation and Principal Reference Section for Notch Peak Formation. F = Section A of Hintze (1951), type section of House Limestone. G = Drum Mountains.

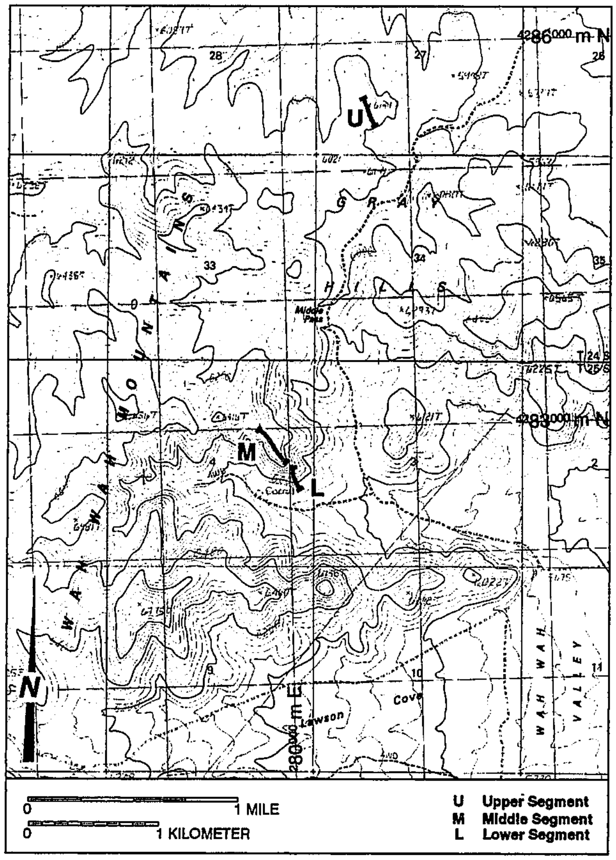

Figure 3. Detailed location map for lower, middle, and upper segments of Lawson Cove section.

complete section of the Millardan Series and most of the Ibexian Series. These strata dip gently north. The sections discussed herein are overlapping increments of this succession. The Steamboat Pass section is near the southern end of the House Range, in an area a little north of a topographic lowland named Steamboat Pass (visible on Fig. 5). The lowland is developed on the shaly Steamboat Pass Member of the Orr Formation. The Steamboat Pass area has a nearly complete section of the overlying Notch Peak Formation, which was described by Hintze et al. (1988). That report showed detailed locations of the measured sections. Included herein is a detailed redescription of the uppermost part of the upper map unit of the Hellnmaria Member, all of the Red Tops Member, and most of the Lava Dam Member of the Notch Peak Formation. The lower 44 ft (13.4 m) of Red Tops strata described in the 1988 report are herein reassigned to the upper Hellnmaria Member. In that report the description of the Lava Dam Member was based on strata in the Lava Dam Five section; herein we describe the Lava Dam Member in both sections. The description includes the upper 457 ft (139.3 m) of Notch Peak strata at Steamboat Pass. Fossils found in this section were reported by Hintze et al. (1988, Tables 2, 4).

Location C on Figure 2 is the Lava Dam Five section in the southern House Range. The section was described by Hintze et al. (1988) and was discussed by Ross et al. (1997) because the base of the Ibexian Series was defined there. A more detailed location of this section is shown in those two reports. The Lava Dam Five section includes most of the Red Tops Member, a complete section of the Lava Dam Member, and the lower 86 ft (26.2 m) of the Barn Canyon Member of the House Limestone. The

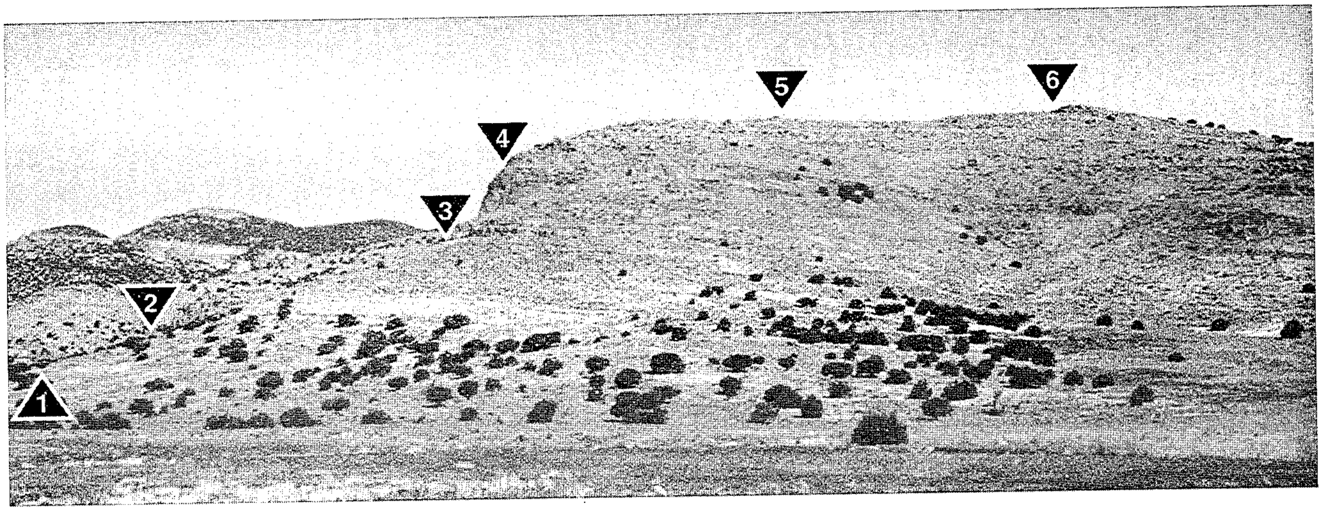

Figure 4. Westward view of profile of lower and middle segments of Lawson Cove section. 1 = base of Red Tops Member. 2 = Red Tops-Lava Dam contact. 3 = base of Ibexian Series near middle of Lava Dam Member. 4 = Notch Peak-House contact; top of Lava Dam Member and base of type section of Barn Canyon Member. 5 = location of olenid trilobite Jujuyaspis borealis, *which indicates the base of the Tremadocian Series. 6 = Barn Canyon-Burnout Canyon contact near top of middle segment of Lawson Cove section. Crest of Wah Wah Mountains in left background.*

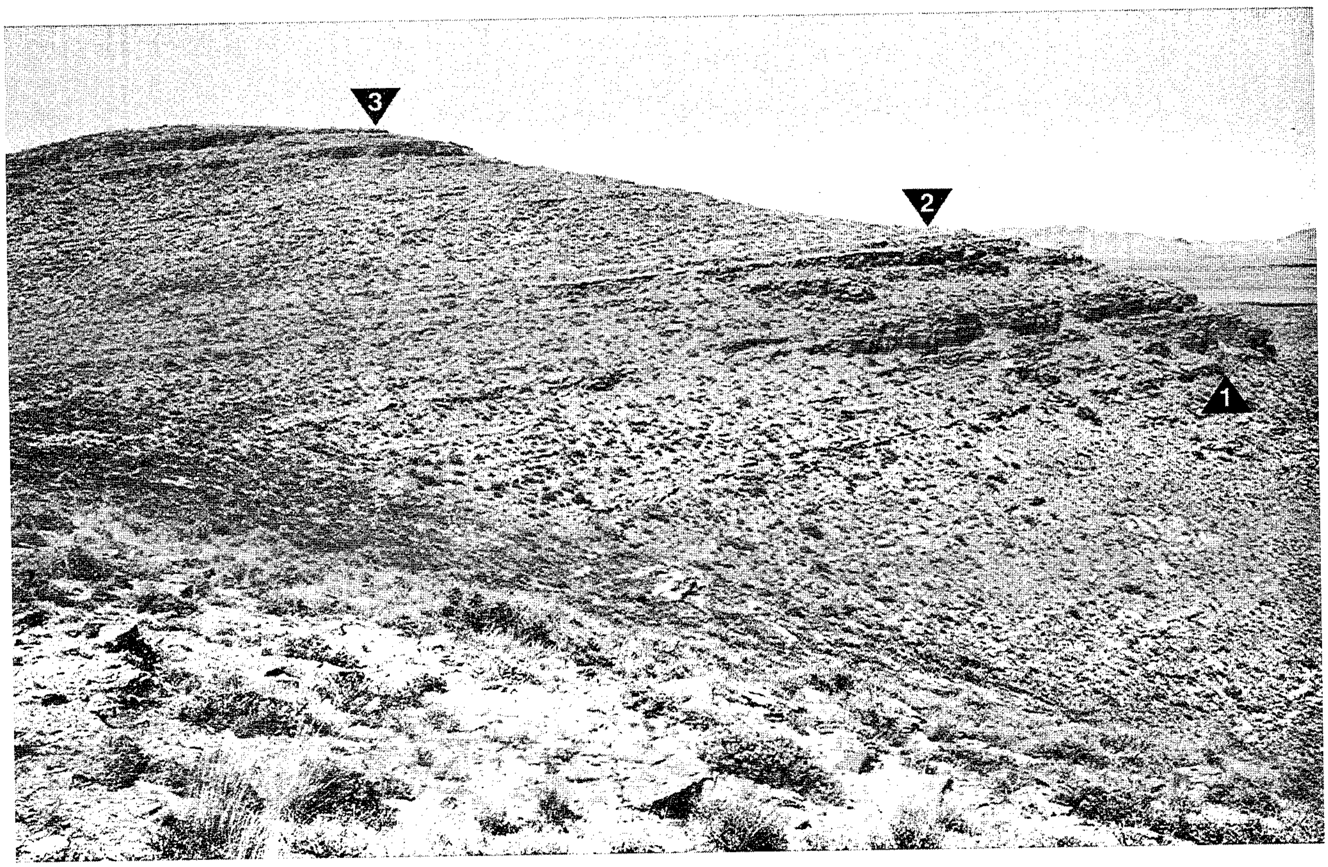

Figure 5. Eastward view of most of upper segment of Lawson Cove section. 1 = base of type section of Burnout Canyon Member. 2 = Burnout Canyon-Red Canyon contact. 3 = top of unit 15 in description of upper segment of Lawson Cove section (see Described Sections). Steamboat Pass area in southern House Range is visible in upper right background.

thickness of these strata is 340 ft (103.6 m), and a detailed description of the Lava Dam Five section is presented herein. Fossils found in this section were reported by Hintze et al. (1988, Tables 3, 4).

The Lava Dam North section (Fig. 2, location D) is ca. 0.7 miles (1.1 km) north of the Lava Dam Five section. This section begins in the upper part of the Lava Dam Member of the Notch Peak Formation and includes the upper 50 ft (15.2 m) of that member. The Lava Dam North section includes a complete section of the House Limestone that was described by Hintze (1973), and this is the type section of the Red Canyon Member (Fig. 6). A total of 607 ft (185.0 m) of strata was measured, and our redescription is presented herein. The section ends at a hilltop where a nearly vertical fault cuts the line of traverse at a horizon that is 5 ft (1.5 m) above the base of the Fillmore Formation.

The Drum Mountains section (Fig. 2, location G) is much farther north than the other sections, and strata there contrast with equivalents farther south. The Notch Peak Formation in this area is mostly dolomite, much of it stromatolitic. This facies may be regarded as transitional between the typical limestone facies of much of the Notch Peak Formation in the House Range and the equivalent dolomites assigned to the Ajax Dolomite, Chokecherry Dolomite, and the Dugway Ridge Dolomite in other mountain ranges to the north. Hintze et al. (1988, Fig. 2) summarized correlations between these stratigraphic units and the Notch Peak Formation. They demonstrated that strata assigned to the Notch Peak Formation in the Fish Springs Range (northwest of the Drum Mountains; see Fig. 2) are almost entirely dolomite.

The Notch Peak Formation in the northern Drum Mountains is overlain unconformably by the House Limestone. This unconformity can be traced through a large region north of the Drum Mountains (Michael Taylor, personal communication, 1988), including areas as distant as the Bear River Range in northern Utah, where this unconformity separates the St. Charles Dolomite and the Garden City Formation (Taylor and Landing, 1982). The presence of this regional unconformity and the regional facies changes probably are related to Cambrian-Ordovician uplift of the Tooele Arch (Hintze, 1988, Fig. 25).

CHRONOSTRATIGRAPHY

The chronostratigraphic classification adopted in this report follows the classification of the Cambrian System proposed by Palmer (1998) and the classification of the Ordovician System proposed by Ross et al. (1997) for strata in the Ibex area (Fig. 1 herein). Upper Cambrian strata are assigned to the Sunwaptan Stage of the Millardan Series. Strata below the Sunwaptan Stage are not considered in this report. Lower Ordovician strata are assigned to the Ibexian Series, the base of which is at the base of the *Cordylodus proavus* Zone. The Ibexian Series is divided into four stages: Skullrockian (oldest), Stairsian, Tulean, and Blackhillsian (youngest). In this report we do not consider strata younger than the Skullrockian Stage, the top of which is less than one meter below the top of the House Limestone.

Figure 1 also shows the position of the bases of two other series that have been used as the base of the Ordovician System. The base of the Canadian Series at the base of the *Missisquoia* Zone is slightly above the base of the Ibexian Series. The base of the Canadian Series formerly was used as the base of the Ordovician System in North America. Current usage in the Ibex area is to place the base of the Ordovician System at the base of the Ibexian Series, slightly below the base of the Canadian Series. The base of the Tremadocian Series, used as the base of the Ordovician System in the Acado-Baltic Faunal Province, is placed at the occurrence of the widespread olenid trilobite *Jujuyaspis borealis* (see Aceñolaza and Aceñolaza, 1992). This species occurs in the middle segment of the Lawson Cove section 1 ft (0.3 m) above the base of the *Symphysurina bulbosa* Subzone of the *Symphysurina* Zone (Figs. 1, 4). This species is also known at comparable horizons at Lava Dam North (at 196–197 ft in the section description), at Section A (Miller and Taylor, 1995), and at the Drum Mountains section (Stitt and Miller, 1987) at 408 ft in the section description.

LITHOSTRATIGRAPHY

Western Utah is a classical area for study of Cambrian and Ordovician strata in North America. Specialists on Cambrian strata generally refer to this as the House Range area, whereas Ordovician specialists refer to it as the Ibex area. Ibex (Fig. 2) was the site of the homestead of Jack Watson, who lived alone in the desert at that location in the late 1800's and in the early decades of the 1900's (V.B. Kelsey, 1992; M.R. Kelsey, 1997). Cambrian and Ordovician strata were deposited on a tropical miogeoclinal carbonate platform near the outboard edge of a passive plate margin that formed by continental rifting in late Precambrian time. This margin subsided rapidly and was the site of deposition of a very thick succession of Paleozoic marine strata. Cambrian strata in the House Range are approximately 10,000 feet (3050 m) thick, and the base of the Cambrian is not exposed (Hintze, 1988, p. 161). Ordovician strata in the Confusion Range are approximately 5000 ft (1525 m) thick (Hintze, 1988, p. 172). A nearly complete sequence of marine sediments from Cambrian through Lower Triassic is present in this area and is approximately 32,000 ft (9.8 km) thick (Hintze, 1988, p. 161, 172).

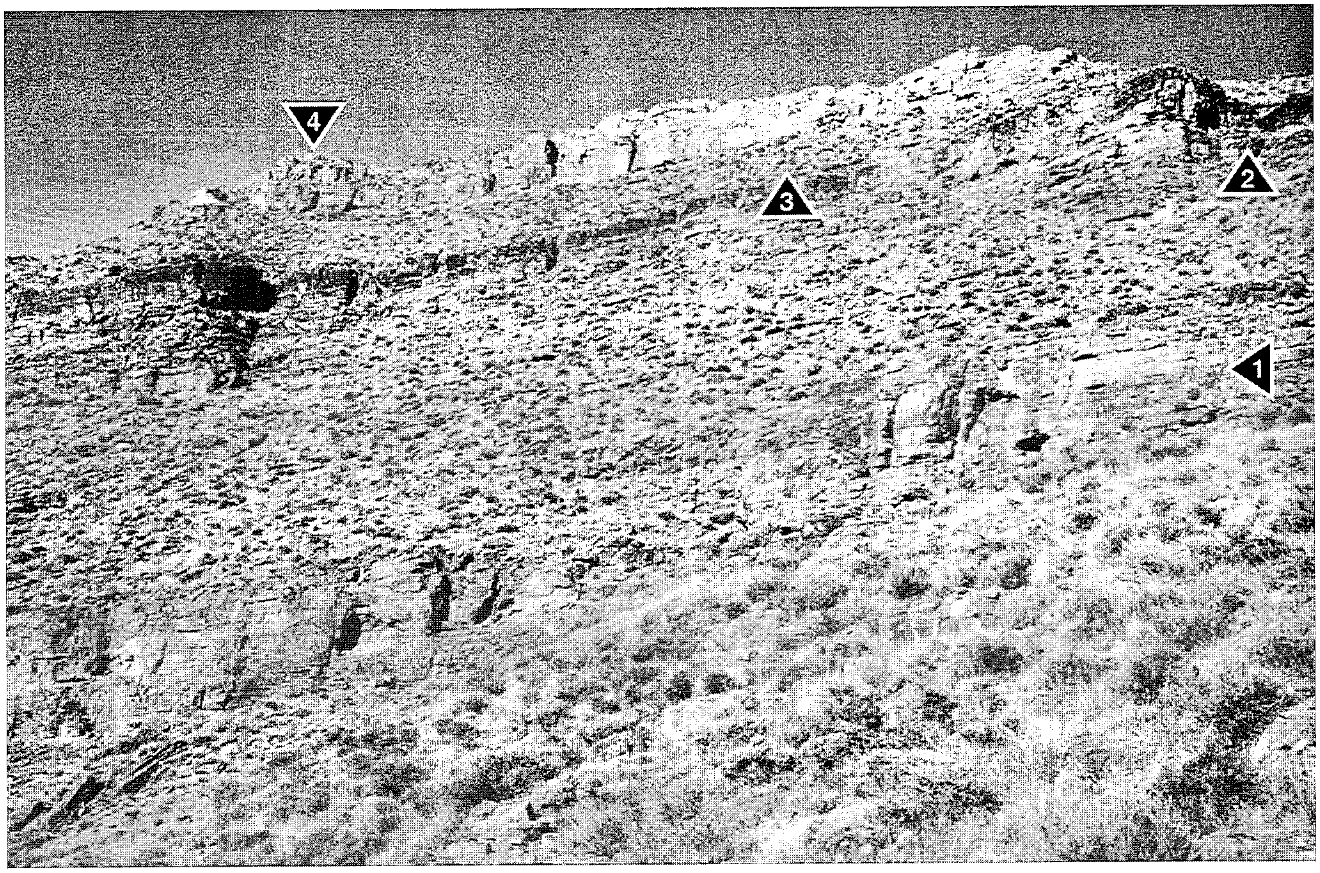

Figure 6. Eastward view of Lava Dam North section. 1 = paint mark at 145 ft in measured section, base of unit 17 in section description (see Described Sections). 2 = base of Burnout Canyon Member. 3 = top of Burnout Canyon Member and base of type section of Red Canyon Member. 4 = top of Red Canyon Member and of House Limestone.

NOTCH PEAK FORMATION

Study of Cambrian strata in this area began early in the last century with two reports by Walcott (1908a, 1908b) from the central House Range. Walcott named the Notch Peak Formation as well as several older formations in these reports. Hintze et al. (1988) divided the Notch Peak Formation (Fig. 1) into the Hellnmaria Member (oldest), the Red Tops Member, and the Lava Dam Member (youngest). These lithologic units were defined in the central House Range at the Sneakover Pass section (Fig. 2, location E). The lithologic character and facies variations of these members were documented in descriptions of this and several other sections in the Wah Wah Mountains, in the House Range (Fig. 2, locations A, B, C, E), and in a section in the Fish Springs Range. Hintze et al. (1988) reported that the Notch Peak Formation ranges in thickness from approximately 1500 ft (ca. 455 m) at the Steamboat Pass-Lava Dam composite section in the southern House Range to approximately 1825 ft (ca. 555 m) at the Lawson Cove section in the northern Wah Wah Mountains.

Strata of the Notch Peak Formation display considerable facies variation within the Ibex area. The discussion presented here is based primarily on the Lawson Cove section and is supplemented by sections in the southern House Range and in the northern Drum Mountains. Hintze et al. (1988, p. 27) reported that the Hellnmaria Member at Lawson Cove consists of 1340 ft (408.2 m) of mostly gray dolomite, much of it stromatolitic. The lithology and thickness of the Red Tops and Lava Dam members shown on Figure 1 are based on restudy of these units at Lawson Cove. The Red Tops Member is 52 ft thick (15.8 m) and consists of rusty brown to gray stromatolitic limestone, flat-pebble conglomerate, and trilobite, ooid, and intraclast grainstone. At the Steamboat Pass section, Hintze et al. (1988, p. 25, unit 27) included in the Red Tops Member a 44 ft (13.4 m) interval of dominantly gray lime mudstone to wackestone and grainstone. Herein we reassign this interval to the underlying Hellnmaria Member. The overlying strata that we assign to the Red Tops at Steamboat Pass are 87 ft (26.5 m) thick. The Red Tops is depicted on Figure 1 so as to indicate the thickness in both the Lawson Cove section (left side of stratigraphic column) and the Steamboat Pass section (right side of column).

The Lava Dam Member at Lawson Cove is 293 ft (89.3 m) thick and consists of different lithologies in three parts of the unit. The lower 154 ft (46.9 m) consists primarily of cherty lime mudstone. The middle 42 ft (12.8 m) is quite diverse in lithology and includes several marker beds that can be traced from the Lawson Cove section to the Sneakover Pass section (locations A and E on Fig. 2). Near the base of this interval is a marker bed of ooid grainstone that is herein named the Tank Canyon Bed. Most of the overlying strata in this middle part of the Lava Dam consist of interbedded lime mudstone to wackestone, as well as trilobite, ooid, and intraclast grainstone. The top 10 ft (3.0 m) of this middle interval contains additional marker beds, including an unusual white to brown to black chert bed that is overlain by edgewise flat-pebble conglomerate, a bed of stromatolitic boundstone that is herein named the Lawson Cove Bed, and by a second unit of intraclast and flat-pebble conglomerate. This succession of strata was reported by Miller (1992, p. 404) in his discussion of the Lange Ranch Eustatic Event, and these strata are described herein. The third part of the Lava Dam Member is 97 ft (29.6 m) thick and consists of a lower portion that is primarily stromatolitic and thrombolitic boundstone and an upper portion that is primarily lime mudstone with subordinate packstone to grainstone. The boundstone is a bioherm 78 ft (23.8 m) thick that is of limited lateral extent. It is present in the lower segment of the Lawson Cove section, but it changes facies to lime mudstone and fine intraclast grainstone in the middle segment of the section (see Described Sections). The two segments of the section are only about 100 m apart.

Tank Canyon Bed (new)

The Tank Canyon Bed is a marker bed that occurs near the middle of the Lava Dam Member, slightly above the base of the Ibexian Series (Fig. 1). The lowermost beds of the Ibexian Series, typically 1–5 ft (0.3–1.5 m) of strata below the Tank Canyon Bed, usually form a covered interval that must be dug out in a trench (Fig. 7). The Tank Canyon Bed often forms the lowest natural exposure of strata assigned to the Ibexian Series. The bed consists of ooid and intraclast grainstone with subordinate bioclasts, and commonly the bed contains intraclasts and grapestone clusters. It is usually mottled light and dark gray (Fig. 8). The unit is named for Tank Canyon, which is located on the Skull Rock Pass 7.5 minute topographic quadrangle in the central House Range. This canyon is 2.9 miles (4.7 km) east-northeast of Skull Rock Pass.

This marker bed can be identified in sections at Lawson Cove, Steamboat Pass, Lava Dam Five, and in other sections as far north as Sneakover Pass, where the Tank Canyon Bed is unit 26 in the description of Hintze et al. (1988, p. 21). Figure 8 shows the lithology of this bed at Sneakover Pass, where it rests on a planar, ferruginous hardground. The Tank Canyon Bed, however, can not be identified in sections in the Chalk Knolls area in Tule Valley nor in sections farther north. Its thickness varies from ca. 1 ft (0.3 m) at Steamboat Pass to 2.5 ft (0.8 m) at Sneakover Pass (Fig. 2). The type section of the Tank Canyon Bed is in the lower segment of the Lawson Cove section (see section description). There this unit is 2 ft (0.6 m) thick and contains both trilobite and gastropod bioclasts. Gastropods have been observed only at this section, although trilobite bioclasts are common at other sections. Hyoliths occur in this bed at Sneakover Pass, and the underlying bed at Lawson Cove is a hyolith coquina (see section description). The Tank Canyon Bed contains fauna diagnostic of the *Hirsutodontus hirsutus* Subzone of the *Cordylodus proavus* Zone and of the *Eurekia apopsis* Zone, which are the lowest biostratigraphic units of the Skullrockian Stage.

A similar ooid grainstone occurs at the base of the Skullrockian Stage in the Whipple Cave Formation at the Sawmill Canyon section in the central Egan Range near Lund, Nevada (Taylor, Cook, and Miller, 1989). Those ooid grainstone strata are ca. 5 ft (1.5 m) thick and occur directly above a planar truncation surface at the top of a thick succession of cherty lime mudstone. This ooid grainstone is coeval with the Tank Canyon Bed. The Whipple Cave Formation in most of the Egan Range is so similar to the Notch Peak Formation in the Ibex area that the term Whipple Cave Formation probably should be abandoned and the strata assigned to the Notch Peak Formation and its various members.

Lawson Cove Bed (new)

The Lawson Cove Bed occurs ca. 25 ft (7.6 m) above the Tank Canyon Bed in the lower segment of the Lawson Cove section (Fig. 1). It is near the middle of the Lava Dam Member and provides another lithologic marker near the base of the Ibexian Series. This bed consists of stromatolitic or thrombolitic boundstone with minor amounts of dark chert (Fig. 9) underlain and overlain by flat-pebble conglomerate beds that grade laterally into skeletal grainstone. Orthid brachiopods, including *Apheoorthis*, often occur in one or both flat-pebble conglomerate beds. The name is derived from Lawson Cove, a reentrant valley along the east margin of the Wah Wah Mountains that is depicted on the Fifteenmile Point and Grassy Cove 7.5 minute top-

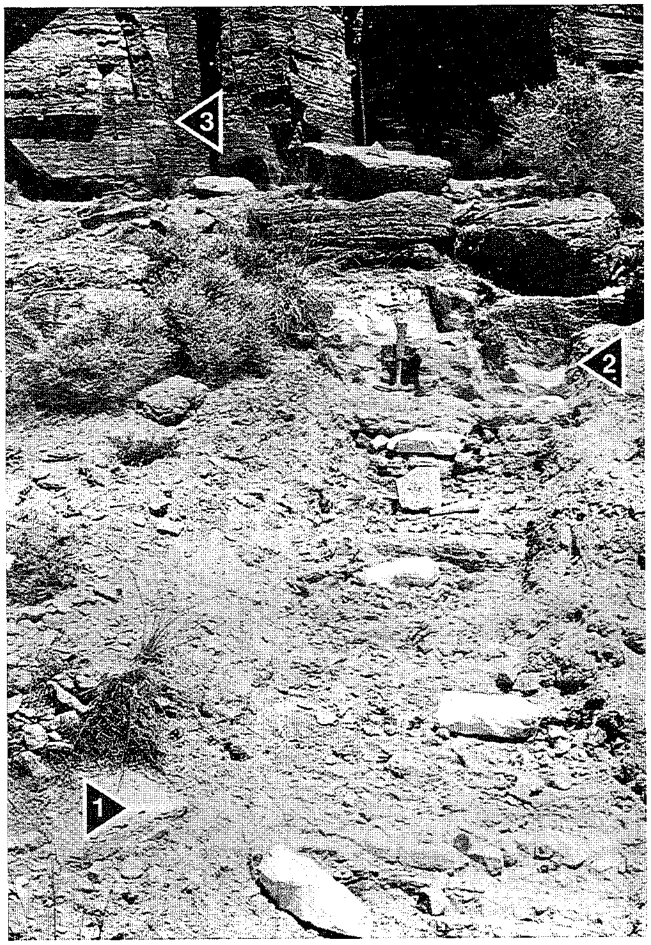

Figure 7. Trench exposing lowest beds of Ibexian Series in lower segment of Lawson Cove section. Base of Ibexian Series is at 158 ft, just below photograph. 1 = 160 ft mark. 2 = level of 165 ft mark (partly hidden by bush at left side of photograph). 3 = 170 ft paint mark. Lowest conodont sample bag is at 159.5 ft; next sample bags are at 160.5, 161.5, and 163 ft. Hammer leans against type section of Tank Canyon Bed, 164.5 to 166 ft (see Described Sections).

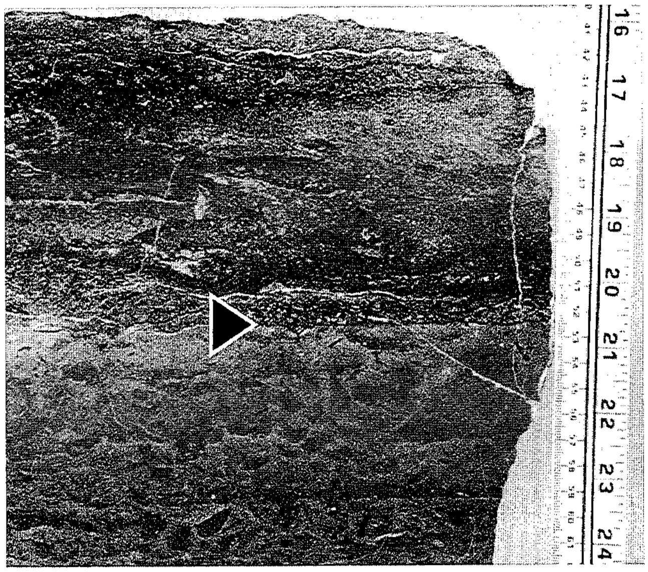

Figure 8. Polished slab of Tank Canyon Bed and underlying burrowed lime mudstone bed. Arrow indicates ferruginous hardground at base of Lawson Cove Bed. Note mottling, intraclasts, and grapestone clusters in ooid Lawson Cove Bed. Sample from 144 ft above base of measured traverse of Lava Dam Member at Sneakover Pass section (see Hintze et al., 1987, p. 21). Scale in inches and centimeters.

ographic quadrangles. The type section for this unit is at the lower segment of the Lawson Cove section (see section description). The thickness of the unit varies from 1.3 ft (0.4 m) at Lava Dam Five to 4 ft (1.2 m) at Lawson Cove.

This marker bed can be identified in sections at Lawson Cove, Steamboat Pass, Lava Dam Five, and in other sections as far north as Sneakover Pass (Fig. 2). The Lawson Cove Bed can not be identified in sections farther north. In those northern sections the stratigraphic position of the Lawson Cove Bed correlates to the base of a very thick interval of stromatolitic and thrombolitic boundstone. At some sections the top of the Lawson Cove Bed is an irregular truncation surface.

The Lawson Cove Bed contains fauna diagnostic of the *Fryxellodontus inornatus* Subzone of the *Cordylodus proavus* Zone. Flat-pebble conglomerate to grainstone beds below and above the Lawson Cove Bed contain trilobites diagnostic of the *Missisquoia typicalis* Subzone of the *Missisquoia* Zone. These biostratigraphic units occur in the lower part of the Skullrockian Stage.

HOUSE LIMESTONE

Several thousand feet of strata above the Notch Peak Formation in the Ibex area are referred to the Pogonip Group. Hintze (1951) divided the Pogonip Group into six formations—the House Limestone (oldest), Fillmore Formation, Wah Wah Limestone, Juab Limestone, Kanosh Shale, and Lehman Formation (youngest). Hintze's report included descriptions of numerous sections in the central and southern House Range and in the southern Confusion Range. These stratigraphic units were redescribed by Hintze (1973). Of the several stratigraphic units in the Pogonip Group, the most important for this report is the House Limestone; its type section is at Section A (Fig. 2, location F). Several of the Notch Peak described sections reported by Hintze et al. (1988) also included descriptions of the lower strata of the overlying House Limestone.

Figure 9. Type section of Lawson Cove Bed in lower segment of Lawson Cove section. Arrow indicates head of sledge hammer that is 26.5 in (67 cm) tall; head is somewhat above base of Lawson Cove Bed.

The House Limestone is divided herein into three members (Fig. 1). The key unit is the middle member, which is the "brown marker bed" described by Hintze (1973, p. 16) at the Lava Dam North section in the southern House Range. Strata below and above this brown-weathering middle member comprise the lower and upper members, respectively. All three members are identifiable by their distinctive lithologies at locations A, D, F, and G (Fig. 2). At least the lower two members can be traced into eastern Nevada.

Barn Canyon Member (new)

The Barn Canyon Member is the lower member of the House Limestone. It is medium to dark gray limestone that crops out as ledges above the bold cliff formed by the top of the Notch Peak Formation. Skeletal, intraclast, and peloid grainstones are abundant. Lime mudstone to wackestone is common. Many of these beds are burrowed. Stromatolitic to thrombolitic boundstone is a minor lithology. All of these lithologies also contain brown to black cherts as burrow replacements, nodules, stringers, and beds. The lower part of the Barn Canyon typically has 30–50 percent white, brown, or black bedded chert, and this abundant chert is useful in recognizing the base of the Barn Canyon Member.

Historically the contact between the underlying Notch Peak Formation and the House Limestone has been drawn at or close to the major lithologic change from stromatolitic boundstone to non-boundstone lithologies. We can demonstrate, however, that some stromatolitic packages in these sections are laterally discontinuous, and stromatolites are absent near this stratigraphic level south of the Skull Rock Pass area. We redefine the base of the House Limestone and its lower Barn Canyon Member to lie at the top of a geographically widespread, 2–5 in (5–13 cm) thick coquina composed almost exclusively of the trilobite *Symphysurina*. The top of the *Symphysurina* coquina is usually overlain by grainstones with 30–50 percent white to brown to black chert. In most sections this modification in definition changes the placement of the formational contact upward by 2–5 feet (0.6–1.5 m). Using this new definition, the Notch Peak-House Formation contact at Lawson Cove is placed 132 ft (40 m) lower in the present report than was stated by Hintze et al. (1988, p. 26–27). This means that a total of 443.5 ft (135.2 m) of the House Limestone, approximately the lower three-fourths of the formation, is exposed at Lawson Cove. The upper contact of the Barn Canyon is at the base of the Burnout Canyon Member.

The Barn Canyon Member is recognizable throughout the Ibex area. Complete sections are exposed at Lawson Cove, Lava Dam North (where it contains several faults), Section A, and in the northern Drum Mountains. At Lawson Cove the Barn Canyon Member is 313 ft (95.4 m) thick (Figure 6), and it varies in thickness from 248 ft (75.6 m) at Lava Dam North to 233 ft (71.0 m) at Section A. In the Drum Mountains section the base of the Barn Canyon is an unconformity, the lower part of the Barn Canyon is condensed, and the lithology of the lower part is unusual compared with southern sections (see described section). A basal chert-cobble conglomerate is overlain by a stromatolite bed and by unusual striped black and white dolomite ("zebra rock") that apparently represents planar microbial mats. The middle to upper parts of the Barn Canyon in the Drum Mountains is similar in lithology and thickness compared with sections farther south. The member is 100.5 ft (30.6 m) thick at the Drum Mountains section. The lower 143 ft (43.6 m) of the House Limestone at the Sawmill Canyon section in the central Egan Range, Nevada is similar to the Barn Canyon Member.

Fossils are abundant in the Barn Canyon Member. A succession of several conodont zones is present in the Barn Canyon Member, including the *Cordylodus intermedius*, *Cordylodus lindstromi* sensu lato, *Iapetognathus*, and *Cordylodus angulatus* zones, as well as the lower portion of the *Rossodus manitouensis* Zone (Fig. 1). The lower part of the Barn Canyon has trilobites diagnostic of the *Symphysurina brevispicata* Subzone of the *Symphysurina* Zone, and the upper part has taxa diagnostic of the *Symphysurina bulbosa* Subzone of the same zone. A single thin bed of brown, graptolitic shale occurs in this member at the Lava Dam North section at 207 ft in the section description. This shale contains the planktic graptolite *Anisograptus matanensis* (Miller et al., 1999) and occurs 6.5 ft (2.0 m) above the olenid trilobite *Jujuyaspis borealis*. Both of these species are index fossils of the Tremadocian Series in the Acado-Baltic faunal province.

The name of this member is derived from Barn Canyon, located in the Barn Hills (Fig. 2) and depicted on The Barn 7.5 minute topographic quadrangle. The type section of the Barn Canyon Member is the middle segment of the Lawson Cove section (see described section).

Burnout Canyon Member (new)

The Burnout Canyon Member is the middle member of the House Limestone and is much thinner than the lower and upper members (Fig. 1). The member usually forms a bold cliff between the ledge-forming strata above and below (Figs. 5, 10) and appears characteristically brown and rusty in color, even when viewed from a distance. Hintze (1973, p. 16) described these beds in the Lava Dam North section as the "brown marker bed" near the middle of the House Limestone. Major lithologies in this unit are fine grainstone, flat-pebble conglomerate, and coarse grainstone. Lime mudstone to wackestone is less common. Quartz sandstone beds occur rarely, although much of the Burnout Canyon has abundant disseminated quartz sand. The fine grainstones are typically finely laminated and have cross-laminated sets, suggesting that these strata were influenced by tidal currents. Flat-pebble conglomerates often contain large clasts made of this laminated fine grainstone. Diagenetic white, brown, reddish brown, and black cherts are common throughout the member. Chert locally replaces the laminae and edges of intraclasts, fractures, burrows, and features that are comparable to siliclastic tepee structures.

The lower contact of the Burnout Canyon is defined at the transition from the gray lime mudstones of the underlying Barn Canyon Member to the overlying brown, laminated, cherty grainstones. The Burnout Canyon Member contains two slightly different parts. The lower part is mostly brown, laminated, fine grainstone with a low proportion of bedded chert. This portion of the member is well developed in the middle segment of the Lawson Cove section. Strata in the upper Barn Canyon Member also contain laminated fine grainstone and flat-pebble conglomerate, but typically these lithologies are interbedded with gray lime mudstone. Significantly, the upper part of the member contains a high proportion of bedded chert and other chert masses. The top of the Burnout Canyon is at the base of the overlying Red Canyon Member.

The Burnout Canyon Member is recognizable throughout the Ibex area. Its thickness ranges from 53 ft (16.2 m) at Lawson Cove, to 64 ft (19.5 m) at Lava Dam North, to 63 ft (19.2 m) at Section A, and 48 ft (14.6 m) in the northern Drum Mountains. A cherty unit within the House Limestone at the Sawmill Canyon section in the central Egan Range, Nevada is similar to the Burnout Canyon Member.

Conodonts and trilobites occur in sufficient numbers for biostratigraphic assignment of strata in the Burnout Canyon. Conodonts indicate that the entire member is to be assigned to the lower part of the *Rossodus manitouensis* Zone, a very thick zone that also includes the entire over-

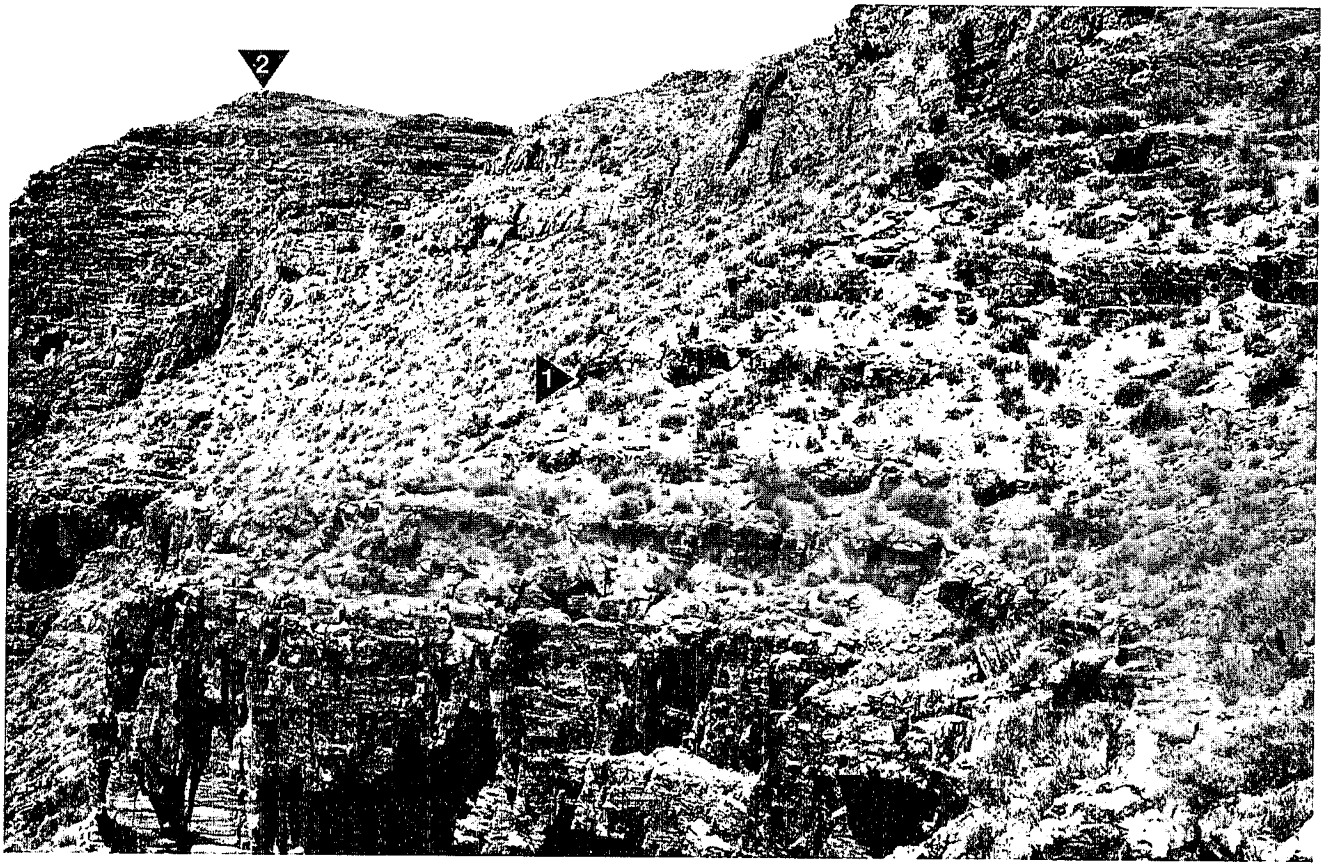

Figure 10. Northeastward view of upper part of Lava Dam North section. Lower dark cliff is upper part of Burnout Canyon Member. 1 = base of type section of Red Canyon Member. 2 = top of Red Canyon Member close to rock cairn near top of measured section.

lying member. Trilobites are assigned to the *Symphysurina woosteri* Subzone of the *Symphysurina* Zone.

The name of this member is derived from Burnout Canyon in the southern House Range. The name is suggested by the dark color of these strata, as though they had been burned by fire. The type section of the Burnout Canyon Member is the upper segment of the Lawson Cove section (see described section).

Red Canyon Member (new)

The upper member of the House Limestone is the Red Canyon Member. The Red Canyon forms a gray, ledge-forming unit above the cliffy, rust-colored exposures of the Burnout Canyon (Fig. 10). Dominant lithologies in the Red Canyon include gray or blue-gray lime mudstone and rarer wackestone, laminated fine grainstone, trilobite grainstone, and flat-pebble and intraclast conglomerate. Some strata have up to 20 (rarely 30) percent brown to black chert nodules, stringers, and thin beds. Some chert forms unusual, vertically oriented bodies that also extend irregularly across bedding surfaces.

The lower contact of the Red Canyon Member is transitional over a thin interval with the underlying Burnout Canyon Member. The contact is drawn at the decrease in slope angle coincident with an increase in the proportion of lime mudstone and a significant decline in siliciclastic material and chert (Fig. 10). The highest strata of the Red Canyon and the top of the House Limestone is a 10-ft (3.0-m) massive ledge of dark gray lime mudstone that can be traced over much of the southern House Range. The top of the Red Canyon Member is placed at the base of the Fillmore Formation. Although the lowest bed of the Fillmore Formation is lithologically similar to the highest ledge of the House Limestone, the strata overlying the ledge weather to a slope. Such a sloping profile is characteristic of the interbedded shales and limestones of the younger Fillmore. Only the lower 5 ft (1.5 m) of the Fillmore is exposed at the type section of the Red Canyon Member at

Lava Dam North. The contact relationships are exposed better at the 1965 C section of Hintze (1973), two miles (3.2 km) north of the Lava Dam North section. At that section the lower 1.5 ft (0.5 m) of the Fillmore consists of dark lime mudstone, and overlying strata include ooid grainstone, skeletal grainstone, and flat-pebble conglomerate.

Only two complete sections of the Red Canyon Member have been measured in the Ibex area. The type section at Lava Dam North is 234 ft (71.3 m) thick. At Section A, the type section of the House Limestone, the Red Canyon Member is 247 ft (75.3 m) thick based on measurement by Hintze (1951). Exposures at Lawson Cove include the lower 106 ft (32.3 m) of the Red Canyon, but the section ends at a hilltop, and younger strata have been removed by erosion. The lower 50 ft (15.2 m) of Red Canyon strata are exposed at the Drum Mountains section. These sections include the complete north-south extent of strata studied in this report, so this member can be recognized throughout the Ibex area.

Trilobites and conodonts are abundant in Red Canyon strata. Conodonts diagnostic of the *Rossodus manitouensis* Zone (Fig. 1) are present throughout the member. Most of the Red Canyon Member contains trilobites diagnostic of the *Bellefontia* Zone, but the 10-ft (3.0-m) ledge at the top of the Red Canyon contains trilobites diagnostic of the *Paraplethopeltis* Zone (Ethington et al., 1987). The top 1–2 ft (0.3–0.6 m) of this ledge and overlying strata contain trilobites diagnostic of the *Leiostegium-Kainella* Zone, which is the basal zone of the Stairsian Stage.

The name of this member is derived from Red Canyon, which is named for exposures of red-brown Oligocene volcanic rocks that mantle the lower Ordovician strata and form the topographic feature named the Lava Dam. The canyon is in the southern House Range and is northeast of the Lava Dam; the Lava Dam and Red Canyon are topographic features that are depicted on the northern part of the Red Tops 7.5 minute topographic quadrangle. The Red Canyon Member crops out extensively along the road in this canyon. The type section for the Red Canyon Member is the Lava Dam North section (see described section), located near the head of Red Canyon (Fig. 10).

The name "Red Canyon" was used as an informal stratigraphic unit in the Permian of Colorado by Duce (1924), who did not name a type section nor indicate the locality from which the name was derived. The term has had no usage since its introduction, so there is little chance of confusion with the Red Canyon Member named herein.

BIOSTRATIGRAPHIC FRAMEWORK

The biostratigraphic framework adopted in this report (Fig. 1) conforms, in general, to current usages for western Utah (see Ross et al., 1997). Although this report does not consider biostratigraphy in detail, brief comments about our use of zonal and subzonal concepts are appropriate. We integrate our data on conodont and trilobite distributions (published and unpublished) with literature sources where appropriate. We have large conodont collections from all of the sections discussed herein. We have trilobite collections from Lawson Cove and Lava Dam North. Additional trilobite collections were reported by Stitt and Miller (1987) from the Drum Mountains and by Hintze et al. (1988) from Steamboat Pass and Lava Dam Five.

The conodont biostratigraphic units in this report generally follow those used in previous reports on these strata, especially the report by Ross et al. (1997). One significant change is in the recognition of two subzones within *Cordylodus lindstromi* s. l. Zone. We are now able to recognize, in some sections, a lower subzone (equivalent to the *Cordylodus prolindstromi* Zone at Black Mountain, Australia) and an upper subzone (equivalent to the lower part of the *Cordylodus lindstromi* s. s. Zone at that section; Nicoll and Shergold, 1991). The *C. lindstromi* s. s. Zone in Australia includes strata equivalent to the *Iapetognathus* Zone of this report, but diagnostic taxa of the *Iapetognathus* Zone have not been found in Australia.

The trilobite biostratigraphic units largely conform to those used by Ross et al. (1997) at the zonal level. Westrop et al. (1993), however, considered *Xenostegium* to be a junior subjective synonym of *Bellefontia.* At this time we accept their opinion and revise the name of the former *Bellefontia-Xenostegium* Zone to simply the *Bellefontia* Zone. The boundaries and characteristic taxa of this interval remain unchanged. Work at the Lawson Cove section has, however, allowed us to apply a more refined subzonal terminology (Loch et al., 1999). Stitt (1983) established three subzones for the *Symphysurina* Zone in Oklahoma. We can now recognize his lower *S. brevispicata,* middle *S. bulbosa,* and upper *S. woosteri* subzones as a complete succession in Utah. Stitt (1983) also established three subzones for the *Bellefontia* Zone in Oklahoma. We are unable to apply this subzonation successfully in the Ibex area. We have recovered trilobites characteristic of only his lower *Bellefontia franklinense* Subzone and upper *Bellefontia chamberlaini* Subzone. Further, we have demonstrated that in Utah *Bellefontia chamberlaini* occurs significantly earlier than in Oklahoma (Loch et al., 1999). We have chosen not to subdivide the *Bellefontia* Zone in this report.

SUMMARY AND CONCLUSIONS

Strata of the upper part of the upper Cambrian Millardan Series and the lower part of the lower Ordovician Ibexian Series are assigned to the Notch Peak Formation and the House Limestone. The Hellnmaria, Red Tops, and Lava Dam members of the Notch Peak Formation are widely distributed and display facies variations in western Utah that were documented previously. These stratigraphic divisions can be traced into the Whipple Cave Formation in the central Egan Range, Nevada. The term Whipple Cave Formation probably should be abandoned and replaced by Notch Peak Formation and its members. The Notch Peak changes facies from limestone in the central House Range to mostly dolomite in the northern Drum Mountains to virtually all dolomite in the Fish Springs Range.

Two new marker beds, the Tank Canyon Bed and the Lawson Cove Bed, occur near the middle of the Lava Dam Member. They are slightly above the Millardan-Ibexian series boundary and help to identify that boundary in the field. These marker beds can be traced from the northern Wah Wah Mountains into the southern House Range and to sections a little north of where U.S. highway 50 crosses the House Range. These beds can not be identified in sections farther north. The Tank Canyon Bed can be identified in the Whipple Cave Formation in the central Egan Range, Nevada.

The contact between the Notch Peak Formation and the House Limestone is placed above a widespread thin trilobite coquina bed with abundant *Symphysurina* at the top of the Notch Peak Formation and below a distinctive interval of limestone that has 30–50 percent white to brown to black chert. This contact is conformable throughout the northern Wah Wah Mountains and the southern to central House Range, but it is unconformable in the northern Drum Mountains. This unconformity is widespread in areas north of the Drum Mountains.

The House Limestone is divided into three members, the Barn Canyon, Burnout Canyon, and Red Canyon members. These members can be traced from the northern Wah Wah Mountains through the House Range and into the northern Drum Mountains. At least the two lower members can be identified in House Limestone exposures in the central Egan Range, Nevada. The lower part of the Barn Canyon Member is condensed and consists of a basal chert-cobble conglomerate and dolomite in the northern Drum Mountains.

APPENDIX

Described Sections

LAWSON COVE SECTION

Northern Wah Wah Mountains, Utah

This section is located in the northwestern end of Lawson Cove, in the northern part of the Wah Wah Mountains, Millard County, Utah, in an area known as the Gray Hills. The measured traverse is similar to that of Hintze et al. (1988), which was measured and described by L. F. Hintze. That traverse was not marked with paint and so could not be recovered for the present study. The section was remeasured and painted for biostratigraphic study by Miller on June 5–7, 1989 and June 15, 1992; the upper segment was measured by Miller and Evans in early June, 1996. Only the Red Tops and Lava Dam members of the Notch Peak Formation and the overlying House Limestone were studied. The Hellnmaria Member of the Notch Peak is well exposed east of the section described here, but only about the upper 75 ft (25 m) of this member is exposed below this measured traverse.

The section was measured in three segments referred to as the lower, middle, and upper segments (Fig. 3). The lower segment exposes the Notch Peak Formation, including the upper part of the Hellnmaria Member, the Red Tops Member, and the Lava Dam Member, including the type sections of its Tank Canyon Bed and Lawson Cove Bed. A north-south high-angle fault separates the lower and middle segments. The middle segment includes the upper beds of the Lava Dam Member, the type section of the Barn Canyon Member of the House Limestone, and most of the Burnout Canyon Member of the House Limestone. The upper segment includes the type section of the Burnout Canyon Member and approximately the lower half of the overlying Red Canyon Member of the House Limestone. The upper segment ends at the highest exposures of House Limestone in this part of the Wah Wah Mountains.

The entire Lawson Cove section is located on the Grassy Cove 7.5 minute topographic quadrangle and on a geologic quadrangle map by Hintze (1974b). The measured traverse trends north and northwest. The base of the lower segment is located in the NE1/4 SW1/4 NE 1/4 sec. 4, T. 25 S, R. 15 W, at UTM zone 12 coordinates 280103 m E, 4282490 m N. The top of the lower segment is in the SW corner, SE 1/4 SE 1/4 NE 1/4 sec. 4, T. 25 S, R. 15 W, at UTM coordinates 280006 m E, 4282748 m N. The base of the middle segment is in the NE 1/4 NW 1/4 NE 1/4 SE 1/4 sec. 4, T. 25 S, R. 15 W, at UTM coordinates 279965 m E, 4282632 m N. The top of the middle segment is at a rock cairn in the NE 1/4 SW 1/4 NE 1/4 sec. 4, T. 25 S, R. 15 W, at UTM coordinates 279789 m E, 4282994 m N. The base of the upper segment is in the NW 1/4 SE 1/4 SW1/4 sec. 27, T. 24 S, R. 15 W, at UTM coordinates 2800743 m E, 4285355 m N. The top of the upper segment is at the hilltop in the NE 1/4 NW 1/4 SW 1/4 sec. 27, T. 24 S, R. 15 W, at UTM coordinates 280597 m E, 4285755 m N.

The section was marked every 5 ft (ca. 1.5 m) with yellow paint, and the footage was marked every 10 ft (ca. 3.0 m). Many painted numbers are abbreviated, so that, for example, the number 3 may indicate 30 ft, 20 may indicate 200 ft, and 55 may indicate 550 ft. The measured traverse began at what was thought to be the base of the Red Tops Member in the lower segment. Subsequently, small exposures of Red Tops lithology were discovered below this horizon; these exposures were measured in negative numbers and are included in the description. Renumbering with zero feet begins at the base of the Lava Dam Member, but a fault was crossed at 5 ft (1.5 m), so that 0 ft and 5 ft are the same horizon. In the middle segment, numbers in the House Limestone are continuous with those in the Lava Dam Member of the Notch Peak Formation. Numbers in brackets within and after unit descriptions, such as [581–586], correspond to the painted numbering system.

An error in making an offset in the section was noted in June, 1990. The lower and middle segments of the section constituted a single section originally, and there was an offset at 212 ft between what is now the lower and middle segments. The error was corrected by measuring 16 ft (5.5 m) of strata missed originally at the base of the middle segment, and the description was corrected to include this interval. A second error in numbering beds occurred in that the number 310 ft was marked on the rock at 315 ft, so that strata above 305 are actually 5 ft (1.5 m) higher than indicated by the numbers appearing on the outcrop. A small high-angle fault with ca. 2 ft (0.6 m) of offset crosses both the lower and middle segments of the section, and in each case the reported thickness of the strata was increased to correct for this offset. All of these corrections are noted in the descriptions, and thicknesses have been corrected so as to report the correct stratigraphic thicknesses.

There is a difference between the present description and that of Hintze et al. (1988) in placement of the Notch Peak-House formational contact. In the 1988 report the contact was placed so that all stromatolitic limestones were assigned to the Notch Peak Formation. In this report the base of the House Limestone is placed about 132 ft (40.2 m) lower, and this contact is more consistent with its placement in sections measured in the type area of the formation in the central House Range. The higher placement of the contact was used by Hintze (1974b) for mapping the base of the House Limestone within the Wah Wah Summit Quadrangle.

The thicknesses of stratigraphic units in the Lawson Cove composite section are:

Formation	*Member*	*Segment*	*Thickness*
House	Red Canyon	upper	106 ft (32.2 m); upper part eroded
House	Burnout Canyon	upper	53 ft (16.2 m)
House	Barn Canyon	middle	277 ft (84.4 m)
Notch Peak	Lava Dam	lower	293 ft (89.3 m)
Notch Peak	Lawson Cove Bed	lower	4 ft (1.2 m)
Notch Peak	Tank Canyon Bed	lower	1.5 ft (0.5 m)
Notch Peak	Red Tops	lower	52 ft (15.8 m)
Notch Peak	Hellnmaria	lower	not measured; but Hintze et al. (1988) reported 1340 ft (408.4 m) of Hellnmaria strata slightly east of the measured section

UPPER SEGMENT OF LAWSON COVE SECTION

HOUSE LIMESTONE [part]
Red Canyon Member [part, 106 ft (32.3 m) measured]

Unit	*Description*	*Thickness (feet) Unit*	*Cumulative*
17	Lime mudstone, fine grainstone, with minor flat-pebble conglomerate near base of unit; medium gray to brownish gray; some beds with orange burrow mottling; 5 percent brown to black chert nodules; good bedding plane exposures with silicified trilobite debris, black lingulids on surface of top bed exposed at [159]. Unit forms low ledges at hill top. [147–159]	12	106
16	Mostly lime mudstone with some interbeds up to 1 in (2.5 cm) of laminated trilobite grainstone, a thin bed of intraclast grainstone to flat-pebble conglomerate at [128] with clasts up to 1 in (2.5 cm) wide, matrix supported; medium gray (blue gray); some beds burrowed, some burrows replaced by brown chert; 5 percent black chert nodules and stringers; medium to thick bedding. Unit forms step ledges. [120–147]	27	94

OFFSET MEASURED TRAVERSE ca. 200 m to north-northwest along top of unit 15. Top of unit 15 is at UTM coordinates 280682 m E, 4285503 m N; base of unit 16 is at UTM coordinates 280630 m E, 4285705 m N; both coordinates are in UTM zone 12.

15	Mostly lime mudstone, a bed of grainstone and flat-pebble conglomerate [113–114], clasts up to 3 in (8 cm) wide, grain supported; medium gray (blue gray); up to 10 percent black chert nodules in upper half of unit, a thick ledge [116–120] has black vertical chert bodies that cut through bedding. Unit forms two ledges. [113–120]	7	67
14	Lime mudstone; medium gray (blue gray); burrowed in lower 1 ft (0.3 m); some layers appear graded, with fine grainstone overlain by mudstone topped by burrowed mudstone; very few black chert nodules; thin to medium beds. Unit forms low ledges. [109–113]	4	60
13	Lime mudstone, fine skeletal grainstone in thin layers interbedded with mudstone [102–103]; medium gray (blue gray); 5 percent black to brown chert nodules and stringers, some vertical chert bodies; thick to massive bedding. Unit forms a cliff. [100–109]	9	56
12	Lime mudstone; medium gray (blue gray); argillaceous partings; 20 percent black chert nodules with minor white chert bands, beds, and stringers, and as abundant vertical chert bodies that cut 1.5 ft (0.5 m) of strata and disrupt bedding. Unit forms low ledges and slopes. [90–100]	10	47
11	Covered. [88.5–90]	1.5	37
10	Fine grainstone, lime mudstone, and flat-pebble conglomerate; light medium gray; some beds burrowed; 20–30 percent white to brown to black laminated chert nodules up to 3 in (8 cm) thick, some forming vertical bodies that disrupt bedding. Unit forms ledges. [86–88.5]	2.3	35.5
9	Mostly lime mudstone, some lenses of silicified trilobite debris, intraclast conglomerate [77], clast-supported framework, some clasts round and up to 1.5 in (4 cm) across, some clasts truncated by fine grainstone; medium gray (blue gray); some beds burrowed, burrows may be silicified; 3 percent black chert nodules and stringers, beds [73–76 and 80–82] have 20 percent black chert, many lingulids [74.5]; medium beds. Unit forms step ledges alternating with covered slopes. [68–86]	18	33
8	Alternating thin covered slopes and thin ledges of lime mudstone with a 6 in (15 cm) bed of flat-pebble conglomerate [63], clast supported, clasts up to 2 in (5 cm) across; medium gray (blue-gray); black chert bands. [58.5–68]	9.5	15
7	Lime mudstone and skeletal packstone with abundant silicified trilobites of *Bellefontia* Zone in thin interval [58]; medium gray (blue-gray); one black chert band. Unit forms a continuous ledge. [57–58.5]	1.5	5.5
6	Mostly covered; one bed of fine grainstone and flat-pebble conglomerate [54], clast supported, clasts up to 5 in (13 cm) across, one bed [56] has black chert at top; light to medium gray; burrowed. [53–57]	4	4

Contact conformable and placed above brown, very cherty, cliff- to ledge-forming strata (referred to Burnout Canyon Member) and below slope- and ledge-forming gray limestones, most of which consists of lime mudstone (referred to Red Canyon Member).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Burnout Canyon Member (Type Section) [53 ft (16.2 m) measured]

Unit	Description	Thickness (feet) Unit	Cumulative
5	Fine and coarse grainstone and flat-pebble conglomerate, clasts range from 0.25–2 in (0.6–5 cm) wide, abundant quartz sand; brown to medium gray; laminated and with low-angle cross-stratification of sets; some beds burrowed, many laminated, abundant dark brown chert replaces lamination, producing a rough weathered surface, 30–40 percent white, brown, and black chert beds, some chert bodies vertical and disrupt bedding and lamination as much as 2 ft (0.6 m) thick, forming features that resemble tepee structures and may be compaction features. Unit forms step ledges. [23–53]	30	53
4	Fine grainstone and flat-pebble conglomerate; light to medium gray; grainstone strongly laminated and with cross-stratified sets; very minor brown chert replacing some laminae; medium to thick beds. Unit forms a break in slope. [18–23]	5	23
3	Mostly fine grainstone, some intraclast to flat-pebble conglomerate, abundant quartz sand; brown to light gray; beds laminated and with cross-stratified sets, many laminae replaced by brown chert, producing a very rough weathered surface; 20 percent white to brown chert beds and stringers, chert is 40 percent in top 4 ft (1.2 m) of unit; some chert nodules oriented vertically disrupt laminae and bedding, showing compaction of carbonate host rock; laminated to thin beds. Unit forms a brown-weathering cliff. [5.5–18]	12.5	18
2	Mixed lithology; fine and coarse grainstone and 1 in (2.5 cm) beds of black chert; light gray; thin to very thin beds; some beds burrowed. Unit is recessive and is part of a break in the cliff formed by units 1–3. [4–5.5 ft]	1.5	5.5
1	Fine grainstone; brown to gray; laminated and with cross-stratified sets, many laminae replaced by brown chert; 15–20 percent white to brown to black chert, some laminated, some as nodules up to 3 in (8 cm) thick. Unit forms prominent ledge within this cliff-forming member. [0–4]	4	4

Conformable contact placed above gray limestones (referred to Barn Canyon Member) and below brown-weathering grainstones that are cliff-forming and have abundant white, brown, and black laminated chert (referred to Burnout Canyon Member).

RESET NUMBERING SYSTEM TO ZERO AT BASE OF UPPER SEGMENT.

Barn Canyon Member [only top ~3 ft (1 m) studied]

Unit	Description	Thickness (feet) Unit	Cumulative
0	Fine grainstone, minor wackestone, and intraclast and flat-pebble conglomerate; light gray; abundant burrows, laminated to thin beds strongly influenced by currents. Unit forms base of a cliff together with overlying beds.	~3	~3

MIDDLE SEGMENT OF LAWSON COVE SECTION

HOUSE LIMESTONE [part]

Burnout Canyon Member [part; lower 35 ft (10.7 m) measured

Unit	Description	Thickness (feet) Unit	Cumulative
30	Fine grainstone and chert; grainstone is light brown, chert is white to brown, occurs as irregular vertical bodies which distort some lamination and as argillaceous partings in the grainstone that produce very irregular weathered surfaces; grainstone has some silicified burrows. Description ends at rock cairn, but the member continues northwest to top of hill. [581–586]	5	35
29	Intraclast grainstone to flat-pebble conglomerate with clasts up to 3 in (8 cm) across, most clasts supported by fine grainstone matrix; medium gray; brown chert as beds and stringers; appears to grade laterally into lithology of unit 28. Unit forms a slope near hilltop. [579–581]	2	30
28	Fine grainstone and intraclast to flat-pebble conglomerate; gray to light brown; mostly finely laminated and with low-angle cross-stratified sets; brown silicified argillaceous partings and silicified burrows; thin brown to black chert stringers; thin to medium beds. Unit forms top of a ledge and an overlying slope near the hilltop. [576–579]	3	28
27	Fine grainstone and flat-pebble conglomerate; brownish gray fine grainstone [567–569.5], finely laminated and with cross-stratified sets, 30–40 percent white to brown chert nodules, stringers, and irregular vertical bodies; medium gray fine grainstone [570.5–574.5], beds 0.5–1 in (1–2.5 cm) thick, burrows, some silicified, some silicified argillaceous partings; flat-pebble conglomerate beds [566–567, 569.5–570.5, 574.5–576] with clasts up to 5 in (13 cm) across, tops of beds with silicified *Thalassinoides* burrows. Unit forms a slope with a ledge at the top. [566–576]	10	25
26	Fine grainstone, some beds of intraclast grainstone and flat-pebble conglomerate, quartz sand mixed with fine grainstone locally; light brown; finely laminated with low-angle cross-stratified sets, clasts in conglomerate up to 4 in (10 cm) across are made of laminated fine grainstone; much of unit with silicified burrows, argillaceous partings, and stylolites that produce a rough weathered surface; 5–10 percent brown to white chert stringers and discontinuous beds; beds medium to massive. Unit forms two thick ledges. [551–566]	15	15

Contact conformable and placed above gray limestones with relatively small amounts of chert (referred to the Barn Canyon Member) and below brown laminated fine grainstone and flat-pebble conglomerate strata with large amounts of white to brown chert (referred to the Burnout Canyon Member).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Barn Canyon Member (Type Section) [277 ft (84.4 m) measured]

Unit	Description	Thickness (feet) Unit	Thickness (feet) Cumulative
25	Lime wackestone and minor fine grainstone, abundant silicified trilobite fragments; light to medium gray (blue gray); many brown silicified burrows; argillaceous partings; 1 in (2.5 cm) black chert band [549.5]; beds 1–6 in (2.5–15 cm) thick; forms base of thick ledge continuous with beds above. [547–551]	4	277
24	Covered. [543–547]	4	273
23	Skeletal and intraclast grainstone, flat-pebble and intraclast conglomerate (more conglomerate than in unit 22), some beds and irregular stringers of brown fine grainstone, some lime mudstone beds with argillaceous partings, some with flat-pebble conglomerate at top, grainstones with trilobite fragments and fine, well rounded, red intraclasts to peloids; conglomerates with pebbles up to 4 in (10 cm) across, usually brownish gray, such a bed up to 1 ft (30 cm) thick [518] with clasts of laminated fine grainstone; a 1 ft (30 cm) bed [535] of fine grainstone with ripples 3 in (8 cm) high and 10 in (25 cm) between crests, brown silicified argillaceous partings above, lime mud covers ripples, contact is stylolitized; unit is medium gray to brown; some beds with *Thalassinoides* burrows, some burrows replaced by dark brown chert. Unit has thin to medium beds and forms low ledges with covered intervals. [510–543]	27	269

CROSS A FAULT within unit 23 between [530 and 535]; 6 ft (1.8 m) of strata are repeated. Thickness of unit 23 is reduced to account for repeated strata.

OFFSET MEASURED TRAVERSE along bed at top of unit 22 about 75 ft (25 m) to the northwest. UTM coordinates at top of unit 22 are 279823 m E, 4282913 m N, UTM zone 12.

Unit	Description	Thickness (feet) Unit	Thickness (feet) Cumulative
22	Lime mudstone, laminated fine grainstone, minor lenses of flat-pebble conglomerate, thrombolites at [510]; medium to dark gray; argillaceous partings,; some beds burrowed, some burrows and trilobites in grainstone beds silicified, but otherwise chert is rare; unit is more thickly bedded than unit 21. Unit forms step ledges along a rise near the top of the mountain. [478–510]	32	242
21	Laminated fine grainstone, intraclast grainstone, flat-pebble conglomerate, and lime mudstone; gray to brown; very little chert except some silicified burrows in lime mudstones and some silicified trilobites; beds mostly 2–8 in (5–20 cm) thick. Unit forms low ledges along flat ridge crest. Nodular to tubular rare iron oxide pseudomorphs after pyrite occur along possible burrows [435]. Abundant black lingulid brachiopods [437]; brown trilobite grainstone [438] contains the trilobite *Jujuyaspis borealis.* Oncoids in one bed [460]. [435–478]	43	210
20	Intraclast to skeletal grainstone, laminated fine grainstone, and lime mudstone, base of unit is brown 2 in (5 cm) intraclast grainstone and flat-pebble conglomerate bed with abundant iron oxide pseudomorphs after pyrite along truncation surface; most of unit is light to medium gray; brown chert nodules; tan to pink argillaceous partings to wispy irregular layers; thin to medium beds. Top of unit is a grainstone bed with trilobites that forms a topographic break at top of interval of step ledges. [416.5–435]	18.5	167
19	Interbedded peloid to intraclast grainstone, laminated fine grainstone, and lime mudstone, a bed of intraclast conglomerate [409] with clasts up to 2.5 in (6 cm) across; light to medium gray; brown chert nodules and beds 1–2 in (2–5 cm) thick; tan to pink argillaceous partings; some beds locally have burrows filled with spar and orange silty dolomite; abundant oncoids [402–403]. Top of unit at planar truncation surface above lime mudstone bed. Unit forms step ledges. [400–416.5]	16.5	148.5
18	Stromatolitic boundstone, lime mudstone, and skeletal grainstone at base of unit and filling some areas between stromatolites; light to medium gray; 15 percent brown chert nodules and stringers; tan burrow mottling. Stromatolite heads are ca. 0.5–2.0 ft (15–60 cm) in diameter and may be locally irregular, stromatolites exposed in three intervals [380–381, 390–392, and 393–400]. Unit forms low step ledges. [375–400]	25	132
17	Lime mudstone and laminated fine grainstone; light to medium gray; argillaceous, with abundant argillaceous partings; 30 percent dark brown chert nodules and stringers; burrowed; gastropod coquina [365]. Unit forms step ledges to hilltop. [360–375]	15	107
16	Lime mudstone, skeletal grainstone, flat-pebble conglomerate with clasts mostly less than 1 in (2.5 cm) wide, and fine grainstone; 6 in (15 cm) of interbedded lime mudstone and silty dolomitic mudstone [335] comparable to ribbon limestone; medium to dark gray; 5–10 percent dark chert nodules. Unit forms step ledges below top of hill. [323–360]	37	92

NOTE: A small E-W fault breccia occurs in the lower part of unit 16 at about [331], but there is virtually no displacement of beds.

Unit	Description	Thickness (feet) Unit	Thickness (feet) Cumulative
15	Lime mudstone and fine grainstone; medium to dark gray; thin to medium beds; 20–30 percent dark brown laminated chert stringers and beds mostly 1–2 in (2.5–5 cm) thick, becoming more nodular at top of unit. Unit forms a cliff. [313.5–323]	9.5	55
14	Mostly lime mudstone, top 4 in (10 cm) is peloid to ooid grainstone; medium to dark gray; very few chert nodules. Unit is base of cliff formed by units 14 and 15. [311–313.5]	2.5	45.5
13	Fine grainstone interbedded with lime mudstone, minor flat-pebble conglomerate [302], some intraclast grainstone, top 1 ft (30 cm) thin bedded with abundant tan argillaceous partings; medium to dark gray; 15–30 percent chert as irregular nodules and semicontinuous 2–3 in (5–8 cm) beds, white chert	15	43

	that is common below extends as high as [302], another interval of white to brown chert [306–310]. Unit forms step ledges up to a break in slope at top of unit. [301–311]		

NOTE: Because of a numbering error, the interval between painted numbers at [300] and [310] is 15 ft instead of 10 ft, so the thickness of the unit has been adjusted to indicate true stratigraphic thickness.

12	Fine grainstone, some skeletal and intraclast grainstone; light to medium gray; abundant quartz sand; 50–60 percent white to brown chert in basal 1/3 of unit (30–40 percent in rest of unit) as 2–12 in (5–30 cm) beds and elongate nodules, with chert and limestone forming complex interbeds. Base of unit forms top of steep cliff; upper part forms step ledges. The interval [287–293] is poorly exposed in line of section but is better exposed to left (west) along a steep cliff. [280–301]	23	28

NOTE: A small fault cuts the section between [295 and 300] and results in a measured thickness that is too thin by 2 ft (0.6 m); the thickness is adjusted to indicate true stratigraphic thickness.

11	Lime mudstone to laminated fine grainstone, some beds silty; medium to dark gray; some trilobite skeletal fragments; 20 percent dark brown to black laminated chert beds up to 3 in (8 cm) thick, chert beds more continuous than in underlying unit; thin beds. Unit forms a ledge that weathers back from top of the underlying Notch Peak Formation. [275–280]	5	5

Contact conformable and placed at change from cliff-forming limestone with up to 10 percent discontinuous dark chert beds (assigned to Notch Peak Formation) to ledge-forming sandy limestone with 20 percent or more laminated chert that forms fairly continuous beds (assigned to House Limestone).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

NOTCH PEAK FORMATION [part]

Lava Dam Member [part; 79 ft (24.1 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
10	Lime mudstone to grainstone, lower half mostly grainstone to packstone, some intraclasts, upper half mostly wackestone to lime mudstone. Top 3 in (8 cm) bed of Notch Peak Formation is a coquina of the trilobite *Symphysurina* underlain by a prominent red argillaceous parting. Unit forms top of a large cliff that includes units 4–10; formation contact at a break in cliff. [271–275]	4	79
9	Skeletal grainstone to packstone, some beds with ooids, bioclasts, and intraclasts [263–264], interbedded with lime mudstone; medium to dark gray; 5–10 percent dark brown chert; red argillaceous partings; beds thick to massive. Unit forms part of a cliff. Planar truncation surface [259] separates lime mudstone below from grainstone above. [257–271]	14	75
8	Lime mudstone, minor lenses of coarse skeletal packstone to grainstone, mudstones probably are thrombolites; medium to dark gray; 5 percent dark chert stringers and nodules. Unit forms part of cliff. Planar truncation surface [257] separates lime mudstone below from packstone to grainstone above. [248–257]	9	61
7	Peloid and intraclast grainstone, intraclasts smaller than 1 mm, medium to dark gray; massive beds; grades laterally to dark gray lime mudstone, possibly thrombolitic, with orange silty burrows. Unit forms part of a cliff. Planar truncation surface [246] separates lime mudstone below from grainstone above. This surface probably is equivalent to the top of the microbial bioherm [278] in the lower segment of this section. [242–248]	6	52
6	Lime mudstone; dark gray; some burrow mottling; massive beds. Unit forms part of cliff. [233–242]	9	46
5	Peloid and fine intraclast grainstone; medium gray; some spar-filled burrows; irregular orange silty stylolites; massive beds. Unit forms part of cliff. [228–233]	5	37
4	Lime mudstone; dark gray; 5 percent brown chert; massive beds. Unit forms part of large cliff that includes units 4–10. Unit may be thrombolitic. Planar truncation surface at [228] at top of unit. [217–228]	11	32
3	Covered. [212–217]	5	21

RESET PAINTED NUMBERS TO 212 FT.

2	Lime mudstone; dark gray; 10 percent dark brown chert nodules and a few stringers; massive bedding. Unit forms a cliff that is not present to the east where equivalent stromatolitic strata form a slope. [4–16]	12	16
1	Covered. [0–4]	4	4

NOTE: The base of unit 1 is equivalent to the base of unit 33 in the lower segment of the section.

RESET PAINTED NUMBERS TO ZERO FEET AT BASE OF MIDDLE SEGMENT.

LOWER SEGMENT OF LAWSON COVE SECTION

NOTE: Immediately west of the top of this segment of the section is a fault breccia; the east side of the vertical fault is uplifted ca. 30 ft (ca. 10 m). The top bed of the Notch Peak Formation is the highest bed exposed east of this fault and within the lower segment of the Lawson Cove section.

NOTCH PEAK FORMATION [part]

Lava Dam Member [293 ft (89.3 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
40	Lime mudstone overlain by coarse trilobite grainstone; medium gray; two brown 1 in (2.5 cm) chert beds or stringers, some chert replaces burrows at top of unit; prominent, bright red, thick argillaceous parting within this unit; in some places along strike the top 3 in (8 cm) of this bed above the red parting is a coquina of the trilobite *Symphysurina*. Unit forms top of ledge and is top bed of Notch Peak Formation. [295–296]	1	293
39	Lime mudstone with skeletal wackestone to packstone in lower half of unit, which has red argillaceous partings; medium gray. Unit is one bed that forms a ledge. [293–295]	2	292

38	Mixed lithology; mostly grainstone to packstone, beds with much echinoderm debris [285 and 287]; trilobite and ooid grainstone [289]; some lime mudstone to wackestone. Strata are medium to dark gray; 15 percent dark brown chert nodules and stringers, chert replaces burrows [289]. Unit forms step ledges. [285–293]	8	290
37	Lime mudstone; light to medium gray; some dark burrow mottling; medium bedding. Unit forms top 1 ft (30 cm) of cliff and overlying slope. [282–285]	3	282
36	Lime mudstone, lenses of intraclast grainstone and flat-pebble conglomerate; medium gray; 10 percent dark brown chert nodules and stringers, some replacing small burrows near top of unit. Unit is one thick bed forming top of cliff with unit 35. [278–282]	4	279

NOTE: The base of unit 36 is equivalent to the truncation surface [246] in unit 7 in the middle segment of the section.

35	Stromatolitic and thrombolitic boundstone; some stromatolites up to 3 ft (1 m) across; medium gray; burrow mottled more than unit below; top of unit is a sharp planar truncation surface. Unit is massive, forming a cliff with unit 36. [250–278]	28	275

CROSS A FAULT marked by a 1 ft (30 cm) thick red-brown breccia within this unit between [260 and 265]; fault has almost no offset.

34	Thrombolitic boundstone; thrombolites have dark rims, most are less than 1 ft (30 cm) across; unit is light gray; abundant tan to pink burrow mottling in centers of thrombolites; some burrow material and interstitial material dolomitized. Unit is massive, forms smooth low ledge below unit 35. [227–250]	25	247

CROSS A FAULT within this unit between [240 and 245]; measured thickness is too thin by 2 ft (0.6 m); thickness of unit is adjusted to show correct stratigraphic thickness.

33	Thrombolitic boundstone; light gray. Unit poorly exposed in slope above unit 32. [212–227]	15	222

NOTE: The base of this unit is equivalent to the base of the middle segment of the Lawson Cove section.

32	Lime mudstone; medium to dark gray; lower 2/3 of unit with abundant brown dolomitized burrows and little chert, fewer burrows above [208], and upper 4 ft (1.2 m) has 15 percent chert as distinctive spheres and nodules; beds thick to massive. These strata grade laterally into stromatolitic boundstone. Unit forms a prominent ledge. [203–212]	9	207
31	Covered. [201–203]	2	198
30	Intraclast grainstone, lower 1 ft (0.3 m) is brown to gray flat-pebble conglomerate with grainstone matrix, clast supported, some very small clasts but some up to 4 in (10 cm) across, rests directly on stromatolites of unit 29; most of unit is intraclast grainstone which becomes finer grained upward; light to medium gray; abundant orthid brachiopod *Apheoorthis* in lower 6 in (15 cm) of unit. Large conglomerate clasts welded to undulating truncation surface at top of unit below. [196–201]	5	196

Lawson Cove Bed (Unit 29; Type Section)

29	Stromatolitic boundstone and intraclast grainstone, clasts very abundant but small, ranging 0.5–2 mm; light-medium gray; orange burrow mottling; most stromatolites in upper part of unit but may extend to base; up to 5 percent brown chert locally. Top of unit is an undulating truncation surface. [192–196]	4	191
28	Flat-pebble conglomerate with clasts up to 2 in (5 cm) across made of laminated fine grainstone and lime mudstone, conglomerate has fine grainstone matrix and locally is clast supported and edgewise, conglomerate grades laterally into in situ thin beds of material like the laminated grainstone clasts; gray to brown. Unit contains orthid brachiopod *Apheoorthis*. [191.5–192]	0.5	187
27	White to brown to black chert marker bed with some gray fine grainstone with planar lamination and low-angle cross-stratified sets; abundant quartz sand. [191–191.5]	0.5	186.5
26	Lime mudstone, lenses of skeletal wackestone; medium gray; 15 percent dark chert nodules, stringers, and silicified argillaceous partings, quartz sand; burrows. Unit forms part of a big ledge with unit 25, but differs from that unit in lacking grainstone. [185–191]	6	186
25	Interbedded lime mudstone, wackestone, intraclast and trilobite grainstone, one layer of ooid grainstone, 10 percent quartz sand at [182], abundant trilobite *Plethopeltis arbucklensis* at same level east of measured traverse; 15 percent brown chert at some levels, partly replacing argillaceous partings; beds 2–5 in (5–13 cm) thick between partings or stylolites; lithology similar to unit 23. Unit forms lower part of big ledge with unit 26. [179–185]	6	180
24	Covered. [178–179]	1	174
23	Complexly interbedded strata, mostly lime mudstone to wackestone with lenses of trilobite grainstone, some laminated fine grainstone, a 4-in (10-cm) thick ooid grainstone layer [168.5], some intraclasts in upper part of unit, an intraclast grainstone at top of unit; medium gray; 10–15 percent brown chert, partly as silicified argillaceous partings. Unit forms a single massive cliff with argillaceous partings and stylolites. [166–178]	12	173

Tank Canyon Bed (Type Section; Unit 22)

22	Ooid grainstone, large trilobite bioclasts, minor intraclasts on upper surface; dark gray, mottled light and dark gray but weathers rusty brown. [164.5–166]	1.5	161
21	Skeletal grainstone with ooids, peloids, and intraclasts up to 1 in (2.5 cm) long and mostly red in color, patches of lime mudstone; light to medium gray, mottled. Abundant small round hyoliths. Contact with underly-	0.5	159.5

Unit	Description	Unit	Cumulative
	ing lime mudstone at a red irregular argillaceous parting. [164–164.5]		
20	Lime mudstone with one bed of intraclast grainstone, brown clasts up to 1 cm long [162.75]; dark gray; beds mostly 2–3.5 in (5–9 cm) thick, thinner beds with abundant red argillaceous partings [162–162.25], partings are fewer than in unit 19. [161.5–164]	2.5	159
19	Lime mudstone, thin to very thin beds, interbedded with argillaceous lime mudstone as in unit below, a 1 in (2.5 cm) bed of intraclast grainstone [161.15] with brown to tan intraclasts up to 0.25 in (0.6 cm) long; dark gray on fresh surface; abundant red argillaceous partings. [159–161.5]	2.5	156.5
18	Very weathered lime mudstone and siltstone; light to medium gray; argillaceous; very thin bedded. [158.5–159]	0.5	154
17	Lime mudstone to wackestone, a single bed; dark gray; no chert; trilobite bioclasts in middle of bed. [157.5–158.5]	1	153.5
16	Trilobite wackestone with some intraclasts; medium gray, no chert; a single 6 in (15 cm) bed; 6 in (15 cm) covered intervals below and above this bed. [156–157.5]	1.5	152.5

NOTE: Units 16–20 usually form a covered slope but are exposed in a trench.

Unit	Description	Unit	Cumulative
15	Mostly lime mudstone and wackestone with trilobite bioclasts, a bed of intraclast grainstone with clasts up to 0.5 in (1 cm) wide [135], beds of intraclast and trilobite grainstone to packstone [140, 150, and 155]; medium to dark gray; top 6 ft (1.8 m) has brown chert. Unit forms ledges; exposed intervals include [134–140, 145–147, 148–151, 153.5–156]; intervening intervals are covered. [134–156]	22	151
14	Covered. [126–134]	8	129
13	Lime mudstone, trilobite bioclasts less common than unit 11 below; medium to dark gray; minor chert at top of unit; very strongly burrowed with pink to red mottling; pink argillaceous partings. Unit is similar to units 7–10 and forms a ledge. [122–126]	4	121
12	Mostly covered. Two 9 in (23 cm) beds of lime mudstone with pink argillaceous partings [119–120.5] west of measured traverse. [113–122]	9	117
11	Thin bed of brown to gray lime mudstone to wackestone, two beds of trilobite and intraclast grainstone to flat-pebble conglomerate; gray to pink; burrow mottled; negligible chert. Unit is mostly covered but includes conglomerate beds at [110 and 113] exposed left (west) of measured traverse. [109–113]	4	108
10	Lime mudstone and wackestone; medium to dark gray; burrows; 20 percent brown chert, mostly as stringers. Unit is one ledge with several beds. [103–109]	6	104
9	Lime mudstone and trilobite wackestone, more trilobite bioclasts than in lower units, bioclasts and intraclasts form thin caps on some ledges, intraclasts 1/8 in (3 mm) wide; light to medium gray; minor chert. Unit is similar to units 7 and 8, but ledges are thinner, mostly 1–2 ft (0.3–0.6 m) thick, with more covered intervals between ledges. Unit appears to consist of several meter-scale cycles of lime mudstone ledges separated by thin covered slopes; ledges exposed [75–77, 82–83, 86–87, 92–93.5, 98–100.5]; intervening intervals are covered. [72–103]	31	98
8	Lime mudstone, trilobite bioclasts and intraclasts form thin caps on some ledges; medium to dark gray; 1 percent chert; orange burrow mottling; some argillaceous partings; beds occur as 1–3 ft (0.3–0.9 m) ledges (thicker than below), with more exposed strata and less covered slope than in unit 7. Unit appears to consist of several meter-scale cycles of lime mudstone ledges separated by thin covered slopes; ledges exposed [36–42, 43–46, 50–53, 57–63, 67–72]; the intervening intervals are covered. [36–72]	36	67
7	Lime mudstone and rare trilobite wackestone, some lenses of trilobite and intraclast grainstone at [7 and 28] form caps on some ledges; medium to dark gray; up to 20 percent brown to black chert stringers in some ledges; pink argillaceous partings; orange burrow mottling; beds 0.5–1.5 ft (0.15–0.5 m) thick. Unit forms step ledges, much of interval is covered slopes between ledges. Unit appears to consist of several meter-scale cycles of lime mudstone ledges separated by thin covered slopes; ledges exposed [5–6, 8–10, 12–17, 25–27, 33–34]; intervening intervals are covered. [5–36]	31	31

CROSS A FAULT at the member contact; lower 5 ft (1.5 m) of unit 7 is repeated so that the base of the Lava Dam Member is at 5 ft. Contact conformable and placed above highest float of brown grainstone (assigned to Red Tops Member) and below lowest ledge of gray, cherty lime mudstone (assigned to Lava Dam Member).

RESET PAINTED NUMBERING SYSTEM TO ZERO.

Red Tops Member [52 ft (15.8 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
6	Mostly covered; exposures of flat-pebble conglomerate and intraclast, trilobite, and ooid grainstone to packstone, some thin layers of lime mudstone [16, 19, 23, 29, and 35]; rusty brown to gray-brown; grainstones may have minor brown chert; exposed beds are 3–6 in (8–15 cm) thick. Float includes 1 in (2.5 cm) beds of rusty brown parallel-laminated fine grainstone. Beds strongly burrowed near base of unit. Unit forms a mostly covered slope. [15–45]	30	52

NOTE: a fault slightly left (west) of the measured traverse crosses the traverse at the top of the Red Tops Member.

Unit	Description	Unit	Cumulative
5	Peloid, intraclast, and skeletal grainstone and stromatolitic boundstone. Grainstones fill between stromatolite heads, lateral distribution of the two lithologies is highly variable,	8	22

	intraclasts small, less than 1/4 in (0.5 cm) across; grainstones brown to medium gray. Stromatolite heads consist of irregular laminae and are irregularly shaped in top view, 10–20 in (25–50 cm) in diameter; medium gray, commonly with orange dolomitized areas between heads and filling burrows in cores of heads. Unit exposed on nearly level area. [7–15]		
4	Covered. [1.5–7]	5.5	14
3	Ooid and intraclast grainstone, intraclasts 1/4 in (0.5 cm) wide; medium gray. Unit is a single bed forming a small ledge together with unit 2. [1–1.5]	0.5	8.5
2	Ooid and intraclast grainstone with elongate but rounded clasts up to 5 in (13 cm) long made of rusty brown grainstone, some ooids preferentially dolomitized; red to brown; brown chert blebs. Units 2 and 3 form a small ledge. [0–1]	1	8
1	Mostly covered. Small exposures of yellow to red dolomitic ooid grainstone below and to east of measured traverse; similar gray dolomite 30 ft (10 m) west of measured traverse. [negative 7 to 0]	7	7

Hellnmaria Member

The Hellnmaria Member was not studied in detail. A complete section of the Hellnmaria was described by Hintze et al. (1988) from the area east of this measured traverse; they reported 1340 ft (408.4 m) for the thickness of the Hellnmaria Member. About 75 ft (25 m) of Hellnmaria strata are moderately well exposed on a gentle slope extending down to the bottom of the hill. Most Hellnmaria strata are stromatolitic dolomite overlain by ca. 10 ft (3 m) of light to medium gray dolomite. Contact with Red Tops Member is placed above the highest stromatolitic and crystalline dolomites (assigned to the Hellnmaria Member) and below the lowest ooid dolomite (assigned to the Red Tops Member). It is easy to drive an automobile to this contact at the base of the section. The uppermost strata of the Hellnmaria contain the conodont *Proconodontus muelleri*, and the yellow to red ooid dolomite at the base of the Red Tops Member contains the phosphatic fossil *Palaeobotryllus taylori*, which occurs only in the Red Tops in other sections in the Ibex area.

STEAMBOAT PASS SECTION
Southern House Range, Utah

This is the southernmost section of the Notch Peak Formation in the House Range, and it is one of the few sections that includes virtually the entire formation. All members of the formation were described by Hintze et al. (1988), but the description here includes only the uppermost part of the Hellnmaria Member, all of the Red Tops Member, and the lower half of the Lava Dam Member. This is the first section that L. F. Hintze and J. F. Miller measured in 1965 when they began studying the Notch Peak Formation. As a consequence of their original unfamiliarity with the details of the lithologic sequence, there were several false starts and restarts in delineating members and their boundaries, and the numbers painted on the rock reflect this situation. The section was measured in 5-ft (ca. 1.5-m) intervals, and the thickness was painted on the rock every 10 ft (ca. 3 m). The numbers in brackets within and after unit descriptions, such as [92–105] for the top unit of the Lava Dam Member, correspond to the numbering system painted on the rocks.

The Steamboat Pass area is shown on the Red Tops 7.5 minute topographic map and on a geologic quadrangle map by Hintze (1974a). The base of the lower map unit of the Hellnmaria Member is on the west side of the canyon north of Steamboat Pass at UTM zone 12 coordinates 295470 m E, 4297567 m N and trends westward. A partial measured section of the lower map unit is on the east side of the canyon at UTM coordinates 295531 m E, 4297371 m N; during measurement of this section a fault breccia was encountered that could not be offset across, so the section was abandoned. The base of the middle map unit of the Hellnmaria Member is at UTM coordinates 295586 m E, 4297781 m N, and the section trends up the ridge to the north and ends at UTM coordinates 295830 m E, 4298300 m N; a measured section of the upper map unit of the Hellnmaria Member is above the middle map unit. A partial measured section of the middle map unit begins in the middle of the unit at UTM coordinates 295474 m E, 4298012 m N and trends up the hill to the northwest, ending at the top of the hill. The measured traverse of the upper map unit of the Hellnmaria Member, the Red Tops Member, and the lower part of the Lava Dam Member reported by Hintze et al. (1988) begins at UTM coordinates 295454 m E, 4298295 m N, the base of the Red Tops Member is at UTM coordinates 295431 m E, 4298427 m N, and the base of the Lava Dam Member is at UTM coordinates 295419 m E, 4298523 m N. The top of the section is at UTM coordinates 295399 m E, 4298632 m N, somewhat above the middle of the Lava Dam Member. The measured traverse of the Red Tops and Lava Dam are along the E line, NE1/4 NW1/4 SW1/4 and into the E 1/2 SE 1/4 SW 1/4 NW 1/4 sec. 18, T. 23 S., R. 13 W. The upper part of the Lava Dam Member is incomplete due to faulting, but the upper beds of the Lava Dam Member are described at the nearby Lava Dam Five section.

Access to the section is via a dirt track that joins the Steamboat Pass Road at UTM coordinates 295538 m E, 4296252 m N; this track trends north and formerly ended at about the base of Steamboat Mountain. In 1993 someone staked a mineral claim at about the base of the measured traverse of the middle map unit of the Hellnmaria Member (location given above), and the dirt track now extends up the canyon to this claim. A measured section of the upper part of the Orr Formation, which underlies the Notch Peak Formation, is on the mountain west of Steamboat Mountain. The base of this section is at UTM coordinates 294822 m E, 4296807 m N, and the painted traverse trends north up the face of the mountain. The interval 0 to 167 ft (0 to 50.9 m) is a partial section of the Steamboat Pass Member of the Orr Formation, and the interval 167–320 ft (50.9–97.5 m) is a complete section of the Sneakover Member of the Orr Formation. Above this is a measured section of the lower map unit of the Hellnmaria Member of the Notch Peak Formation, but the section has not been utilized for study since it was measured by L. F. Hintze and J. F. Miller on June 24, 1965, and probably it is faulted.

These strata were restudied and redescribed by J. F. Miller in 1990, 1991, and 1994. As a result of this study, the contact between the Hellnmaria and Red Tops members has been moved up section by 44 ft (13.5 m). An interval of dominantly gray lime mudstone and wackestone was considered to be the lowest part of the Red Tops Member by Hintze et al. (1988, p. 25), but these strata are considered herein to be the uppermost part of the Hellnmaria Member, and the Red Tops Member is restricted to the overlying strata that consist of brown grainstone, stromatolitic boundstone, and flat-pebble conglomerate.

NOTCH PEAK FORMATION [part]

Lava Dam Member [lower part; 207 ft (63.1 m) described]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
58	Lime mudstone; medium to dark gray; pink burrow mottling; 10 percent dark brown chert nodules; massive beds. Unit forms ledges. Top of section is close to a small fault near [105]. Strata above fault not measured. [92–105]	13	207

57	Covered. [82–92]	10	194
56	Lime mudstone; dark gray; lower 3 ft (0.9 m) with abundant pink burrow mottling; lower 2 ft (0.6 m) with some spar-filled burrows, middle 1 ft (0.3 m) with few spar-filled burrows, upper 2 ft (0.6 m) with few spar-filled burrows and less burrow mottling; 2–5 percent dark chert nodules, mostly in upper half; massive bedding. Unit forms a ledge. [77–82]	5	184
55	Silty lime mudstone; light and dark gray bands; bedding disrupted by strong burrowing, horizontal burrows in silty light gray bands that overlie stromatolites of unit below; beds at base draped over relief on underlying stromatolites, but bedding is flat at top of unit; 5 percent brown chert nodules. [ca. 73–77, base is irregular]	4	179

Lawson Cove Bed (Unit 54)

54	Stromatolitic boundstone made of lime mud; dark gray; 3–4 in (8–10 cm) of relief on tops of stromatolites; *Epiphyton* is visible in some parts of stromatolites, which are best seen ca. 20 m west of the measured traverse. [71–ca. 73, top is irregular]	2	175
53	Limestone pebble conglomerate; pebbles flat in lower half, up to 4 in (10 cm) across, and made of dark gray lime mud (best exposed west of measured traverse); pebbles round, brown, and mostly less than 1 in (2.5 cm) across in upper half, also ooid and peloid; minor brown chert; orthoid brachiopods. [70–71]	1	173
52	Chert marker bed, white and brown; interbedded with gray to very light brown fine grainstone. Bed is at top of ledge formed mostly by unit below. [69.5–70]	0.5	172
51	Mixed lithology. Lower 4 in (10 cm) is lime mudstone, strongly burrowed, abundant tan argillaceous partings and burrow mottling; most of lower half of unit and some lenses in upper part are ooid, intraclast, and skeletal grainstone, weathers brown to red because of colored clasts, 1–3 in (2.5–7.5 cm) beds; most of upper part and some of lower part of unit are lime mudstone, some finely laminated; top 3 in (7.5 cm) is strongly burrowed silty wackestone; unit is mostly medium to dark gray; 20 percent dark chert, mostly in mudstone, some in grainstone. Unit forms a cliff. [60.5–69.5]	9	171.5
50	Intraclast and skeletal grainstone, clasts mostly lime mudstone mostly less than 0.5 in (1 cm) across, some 3 in (8 cm) across, some thin, long intraclasts are recurled through ca. 150 degrees (possibly formed by dessication); medium to light gray; spar-filled burrows. Unit consists of three beds that form a slope. [58–60.5]	2.5	162.5
49	Lime mudstone; medium to dark gray; orange argillaceous partings; strongly burrow mottled with gray to tan argillaceous material, some burrows spar filled; 10 percent dark chert, most is part of one semicontinuous bed. [56–58]	2	160
48	Ooid, skeletal, and intraclast grainstone; medium gray, interbedded with irregular lenses and beds of dark gray lime mudstone to wackestone with orange burrow mottling; vertical burrows with spar filling, horizontal burrows 1 cm wide, some partly spar filled. Unit forms a thick ledge. [51.5–56]	4.5	158

Tank Canyon Bed (Unit 47)

47	Mostly ooid grainstone, some skeletal and intraclast grainstone, lenses of lime mudstone; mottled medium and dark gray. Unit forms lower part of a ledge. [50.5–51.5]	1	153.5
46	Skeletal, peloid, and intraclast wackestone to packstone, argillaceous; medium gray; abundant red argillaceous partings; spar-filled burrows; beds ca. 1 in (2.5 cm) thick; contains trilobites. Unit is recessive. [49.5–50.5]	1	152.5
45	Covered. [This is not a painted interval on the outcrop]	6	151.5

CROSS A FAULT between [45 and 50]; fault cuts out ca. 6 ft (1.8 m) of section, which is a covered interval and is accounted for in unit 45.

44	Mostly lime mudstone, thin layers of fine intraclast grainstone, including at top of unit; medium gray; orange burrow mottling; dark chert stringers and nodules, increasing from none in lower 2 ft (0.6 m) to 20 percent at top of unit; medium to thick beds. Unit forms a prominent ledge. [38–49.5]	11.5	145.5
43	Covered. [34–38]	4	134
42	Lime mudstone, lenses of skeletal and intraclast grainstone to packstone; medium to dark gray; thin to medium beds. Unit is poorly exposed laterally. [32–34]	2	130
41	Covered. [27–32]	5	128
40	Lime mudstone, minor intraclast grainstone at [22, 23, and 27]; light to medium gray; abundant pink burrow mottling near top of unit; 5 percent black chert stringers; thin to medium beds. Unit is recessive and partly covered near top. [21–27]	6	123
39	Covered. [18–21]	3	117
38	Lime mudstone with intraclast conglomerate lens at top of unit; light to medium gray; orange burrow mottling, less than in unit 36; 10 percent black chert nodules in top 2 ft (0.6 m); beds 1–1.5 ft (0.3–0.45 m) thick. Unit forms thin ledges. [14–18]	4	114
37	Covered. [6–14]	8	110

CROSS A FAULT between [5 and 10 ft]; but by projecting numbers to the right across the fault and describing the strata to the right of the fault, its effects are avoided.

36	Lime mudstone; medium to dark gray; strong tan to orange burrow mottling; prominent chert bed at [5]. [0–6]	6	102

RESET PAINTED NUMBERING SYSTEM FROM 248 FT TO 0 FT]

35	Lime mudstone and trilobite wackestone, lenses of intraclast conglomerate at [240.5], slopes with gray to rusty fine grainstone as float, some burrowed; unit mostly medium	32	96

	gray; beds 2–3 ft (0.6–0.9 m) thick with 2–4 ft (0.6–1.2 m) covered slopes between beds; most ledges with one or more lenses of trilobite debris and most with brown to black chert stringers or replaced burrows; burrowed mudstone at [216.5]. [216–248]		
34	Lime mudstone; medium gray; float on covered areas is rusty brown fine grainstone and minor flat-pebble conglomerate, some burrowed; a few beds with 5–15 percent black chert nodules and beds, most beds without chert; beds 2–5 ft (0.6–1.5 m) thick with 3–6 ft (0.9–1.8 m) covered slopes between beds. Unit forms step ledges. [167–216]	49	64
33	Lime mudstone; medium gray; orange to tan burrow mottling; massive beds. Unit forms a ledge. [161–167]	6	15
32	Intraclast and skeletal grainstone; medium gray; burrow mottled; finely laminated at base. [160–161]	1	9
31	Lime mudstone; medium gray; argillaceous partings and tan burrow mottling. [159–160]	1	8
30	Covered. [155–159]	4	7
29	Lime mudstone; medium to dark gray; 1–2 percent black chert nodules; medium to thick beds. Unit forms step ledges. [152–155]	3	3

Conformable contact placed above highest flat-pebble conglomerate and ooid grainstone (assigned to the Red Tops Member) and below cherty lime mudstone (assigned to the Lava Dam Member).

RESET PAINTED NUMBERING SYSTEM TO 152 FT

Red Tops Member [87 ft (26.5 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
28	Flat-pebble conglomerate, lime mudstone, and ooid grainstone; medium gray; forms base of a ledge together with overlying basal unit of Lava Dam Member. [130–131]	1	87
27	Mostly covered. Small exposure near middle of covered slope and abundant float are both 1 in (2.5 cm) thick beds of gray fine grainstone with rusty argillaceous partings and a gray 4 in (10 cm) flat-pebble conglomerate bed with fine grainstone clasts. [126–130]	4	86

OFFSET MEASURED TRAVERSE ca. 75 ft (ca. 25 m) left (westward) across a small graben following the top of a bed at [121].

26	Lime mudstone; medium to dark gray; 5–10 percent brown to black chert nodules. Unit forms a ledge. [118–126]	8	82
25	Flat-pebble conglomerate, clasts brown, as large as 2 in (5 cm) across, some finely laminated; unit is medium gray to brown; float on slope and in situ beds have many silicified burrows and argillaceous partings; a few beds with brown chert. [101–118]	17	74
24	Ooid, skeletal, and intraclast grainstone, minor fine grainstone [101]; rusty brown to gray; strongly burrowed [99] with orange burrow fillings. Unit thickness variable over top of stromatolite mound of unit 23; laterally this unit merges with unit 22 where unit 23 is absent. [97–101]	4	57
23	Stromatolitic boundstone, a mound ca. 30 ft (10 m) wide; light to medium gray; *Epiphyton* visible in many stromatolite heads; laterally this mound is surrounded by rusty grainstone. [93–97]	4	53
22	Ooid, skeletal, and intraclast grainstone, at [89] a 6 in (15 cm) thick bed of flat-pebble conglomerate with pebbles up to 1.5 in (ca. 4 cm) across; rusty brown. Unit forms a thick ledge. [88–93]	5	49
21	Fine grainstone and intraclast grainstone, coarse trilobite, hyolith, and ooid grainstone [84 and 85.5]; gray to brown; siliceous argillaceous partings and horizontal burrows; thin to very thin beds. Unit forms low ledges on flat area. [80–88]	8	44
20	Lime mudstone; medium and dark gray; strong tan burrow mottling in lower 1 ft (0.3 m); thin to medium beds. [76.5–80]	3.5	36
19	Ooid grainstone, abundant silicified hyoliths and some intraclasts [69], higher strata have silicified argillaceous partings; medium gray to brown, mottled; silicified burrows and argillaceous partings [74]; medium beds. Unit forms step ledges. [65–76.5]	11.5	32.5
18	Lime mudstone, wackestone, minor fine grainstone, 4 in (10 cm) of ooid grainstone [61.5], 4 in (10 cm) of intraclast conglomerate [63.5]; no chert in lower 2 ft (0.6 m), 10–20 percent brown chert nodules and 1 in (2.5 cm) chert beds in upper 4 ft; thin beds. [59–65]	6	21
17	Ooid packstone and intraclast and trilobite grainstone, some lenses of fine trilobite packstone; medium gray to brown; 1–2 percent brown chert blebs; thin to medium beds. Unit forms top of a ledge that includes units 15 and 16 and part of a slope. [53.5–59]	5.5	15
16	Fine grainstone; light brown; abundant silicified argillaceous partings produce rough weathered surface; 10 percent brown chert stringers and nodules; laminated with cross-laminated sets. Unit is part of a cliff formed by units 13–16. [50.5–53.5]	3	9.5
15	Grainstone to packstone, trilobites, minor peloids, a few coated grains, rounded intraclasts up to 2.5 in (ca. 6.5 cm), ooid grainstone and minor intraclast conglomerate [48–50]; mostly rusty brown, some brownish gray; chert bed at [2.5]. Base of unit is a sharp truncation surface. [44–50.5]	6.5	6.5

Sharp and possibly unconformable contact placed above gray boundstone and burrowed mudstone (assigned to the Hellnmaria Member) and below brown grainstone and conglomerate (assigned to the Red Tops Member).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Hellnmaria Member [upper part]
Upper map unit [163 ft (49.7 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
14	Lime mudstone with lenses of intraclast	9	163

	packstone [35 and 40], clasts as large as 0.75 in (2 cm) across; medium gray; pink argillaceous partings, abundant pink burrow mottling; medium beds. Unit forms low ledges on a flat area. [35–44]		
13	Fine peloid, ooid, intraclast, and skeletal grainstone; light pinkish gray; medium beds. Unit forms low ledges. [29–35]	6	154
12	Peloid grainstone; medium gray; 10 percent brown chert nodules near top of unit. Unit is one thick ledge. [26–29]	3	148
11	Lime mudstone, some wackestone, intraclast grainstone at top of bed [20]; medium gray; strong pink and tan burrow mottling; top 2.5 ft (0.8 m) of unit with 10–15 percent brown chert nodules and stringers; thin to medium beds. [18.5–26]	7.5	145
10	Mostly lime mudstone to sparse wackestone with 1 in (2.5 cm) lenses of intraclast, peloid, and skeletal packstone; dark gray. Unit forms upper part of ledge that includes unit 9. [15–18.5]	3.5	137.5
9	Lime mudstone and wackestone; light to medium gray; strongly mottled by pink burrows; pink argillaceous partings; beds 4–8 in (10–20 cm) thick. Lower part is on a flat area; upper part forms a cliff with unit 10. [8–15]	7	134
8	Fine peloid and intraclast grainstone, a few skeletal grains; light to medium gray; brown chert nodules [7.5]; beds 6–10 in (15–25 cm) thick. Unit poorly exposed on flat area. [5–8]	3	127
7	Skeletal, peloid, and intraclast grainstone to wackestone; medium to dark gray; wackestone has pink burrow mottling; 1–2 percent brown chert blebs. Unit forms top of ledge that includes units 5 and 6. [2–5]	3	124
6	Wackestone, some 1 cm round lime mud intraclasts; light to medium gray. Unit forms a break in ledge formed by units 5–7. [1.5–2]	0.5	121
5	Wackestone; dark gray. Unit forms lower part of a ledge together with units 6 and 7. [0–1.5]	1.5	120.5

NOTE: Base of unit 5 is a sharp, somewhat irregular truncation surface which has karst relief several hundred meters up the canyon to the northeast.

RESET PAINTED NUMBERS TO ZERO at [119] at this horizon, which Hintze et al. (1988) considered to be the base of the Red Tops Member.

4	Fine peloid grainstone; light pinkish gray; strongly burrowed, burrows 3–4 in (7.5–10 cm) long, up to 1 in (2.5 cm) wide, filled with mostly white and some pink calcite spar; indistinct bedding. Unit forms a slope. [115–119]	4	119

[Description below adapted from Hintze et al. (1988, p. 25); these authors considered the top of unit 4 to be the top of the Hellnmaria Member. Herein units 5–14 are assigned to the upper map unit of the Hellnmaria Member.]

3	Stromatolitic boundstone, interstitial material is lime mudstone; light gray; most of unit consists of stromatolite heads 6–12 in (15–30 cm) in diameter. Unit forms rounded cliffs and smooth slopes. [44–115]	71	115
2	Dolomite; alternating light gray and dark gray beds; some relict stromatolite heads. Unit forms slopes. [9–44]	35	44
1	Stromatolitic dolomite; light gray. Unit forms low ledges. [0–9]	9	9

Conformable contact with middle map unit of the Hellnmaria Member; contact placed above mostly dark gray stromatolitic dolomite (referred to the middle map unit) and below mostly light gray stromatolitic dolomite (referred to the upper map unit of the Hellnmaria Member).

Middle map unit of Hellnmaria Member
Only part of this unit is exposed directly below the upper map unit, but a complete section of the middle and lower map units of the Hellnmaria Member is exposed farther south, as described by Hintze et al. (1988, p. 25–26).

LAVA DAM FIVE SECTION
Southern House Range, Utah

This section is located on the west side of the southern House Range, Millard County, Utah, slightly south of the volcanic rock feature called the Lava Dam. The area is shown on the Red Tops 7.5 minute topographic quadrangle and on a geologic quadrangle map by Hintze (1974a). The base of the measured traverse is in the lower part of the Red Tops Member of the Notch Peak Formation, and the traverse includes most of the Red Tops Member, a complete section of the Lava Dam Member, and the lower part of the Barn Canyon Member of the House Limestone. The base of the traverse is at UTM zone 12 grid coordinates 295977 m E, 4300996 m N, in NW1/4 SW1/4 SW1/4 SE1/4 sec. 6, T. 23 S, R. 13 W. The top of the section is at UTM grid coordinates 295900 m E, 4300649 m N, near the SE corner NE1/4 NE1/4 NW1/4 sec. 7, T. 23 S, R. 13 W. Access to the section is via a good dirt track leading east from the Tule Valley Road at UTM coordinates 294800 m E, 4301422 m N, ca. 15 m south of a small gully; the east end of the track is at UTM coordinates 295870 m E, 4301030 m N. It is easy to drive an ordinary automobile to the end of this dirt track, which is about 100 m west of the base of the section, located in the bottom of a gully.

The lower part of the section was measured by J. F. Miller and J. R. Howell III on August 26, 1972 in order to study the Red Tops and lower Lava Dam members. Their measurement ended at a fault in the upper part of the Lava Dam Member. The measured traverse was marked with yellow paint every 5 ft (ca. 1.5 m), and the measured footage was marked every 10 ft (ca. 3 m). On July 13, 1973 Miller and L. F. Hintze offset across this fault, extended the measured traverse to the top of the hill, and made a general description of the upper strata. They placed no paint marks on this upper portion of the section. M. E. Taylor remeasured the portion of the section above the fault on July 4, 1976, and he made red paint marks in 5 ft (ca. 1.5 m) increments, beginning with "0" ft at the base of the white chert marker bed (unit 57 of the description below). Subsequently the system of yellow numbers begun by Miller and Howell was extended to the top of the hill by offsetting across the fault and using Taylor's measurements.

Two faults occur in the measured traverse of this section; both high-angle faults offset beds within the Lava Dam Member, and both are noted in the description below. The lower fault has an offset of 3 ft (0.9 m), with the east side up. This fault was not noted during measurement of the section, so the offset within unit 32 is not accounted for in the measurement. In this description the thickness of duplicated strata is subtracted for all stratigraphic data above the fault, so reported thicknesses are correct stratigraphic thickness. The upper fault crosses the section near the base of unit 66. This fault was noted during the original measurement in 1972, and the traverse ended at 175 ft without crossing the fault. Subsequent measurement of strata above this level involved an offset of the measured traverse across the fault at the base of unit 66, so thicknesses of units are not affected by this fault. The fault strikes about northeast and has an offset of ca. 40 ft (12.2 m), with the southeast side down. To facilitate field identification of stratigraphic units described below, the numbers in brackets within and after unit descriptions, such as [332–340] for the top unit of the House Limestone, correspond to the numbering system painted on the rocks.

A description of part of the Lava Dam Five section was published by Hintze et al. (1988, p. 23–24). Only the descriptions of the House Limestone and Lava Dam Member are from the Lava Dam Five section, and the published description of the Red Tops Member is from the nearby Steamboat Pass section. That published description was a composite of descriptions made by Miller and Taylor. The description here was made by Miller in 1990–93.

This section is the stratotype for the base of the Ibexian Series, which is defined at a point in rock that is 131 ft (39.93 m) in the measured traverse of the Lava Dam Member. Because the small fault in the lower portion of the Lava Dam Member duplicates 3 ft (0.9 m) of strata, the designated point at 131 ft in the measured traverse is actually 128 ft (39.01 m) in true stratigraphic thickness above the base of the Lava Dam Member. This point in rock was chosen so as to coincide with the base of the *Cordylodus proavus* Zone (lowest occurrence of *Cordylodus andresi*) and to coincide essentially with the base of the *Eurekia apopsis* Zone.

HOUSE LIMESTONE [lower part]
Barn Canyon Member [lower 86 ft (26.2 m) described]

Unit	Description	*Thickness (feet)* Unit	Cumulative
74	Lime mudstone and fine grainstone; light to medium gray; some beds with orange burrow mottling; both spar-filled and silicified burrows; 30 percent irregular brown chert beds, nodules, and stringers; thin to medium beds. Unit forms small ledges to top of hill. [332–340]	8	86
73	Skeletal and intraclast grainstone and lime mudstone; medium gray; some beds with orange burrow mottling; both spar-filled and silicified burrows; 5–10 percent brown to black chert nodules and beds; beds 6–12 in (15–30 cm) thick. Unit forms step ledges. [315–332]	17	78
72	Mostly lime mudstone, some fine grainstone, some beds of intraclast and skeletal grainstone and lenses of such grainstone at tops of some beds, as at [297] and [303]; light to medium gray; some beds with orange burrow mottling; abundant horizontal burrows, both spar-filled and silicified; 20 percent brown to black chert beds and nodules; thin to medium beds, thinner and more uniformly bedded than unit below. Unit forms step ledges. [280–315]	35	61
	OFFSET MEASURED TRAVERSE about 30 ft (10 m) to left (east) at [295].		
71	Lime mudstone, fine grainstone, with minor skeletal grainstone and flat-pebble conglomerate, as at [259]; light to medium gray; 30–40 percent bedded, nodular, and lenticular white, brown, and black chert; abundant quartz sand; medium bedding. Unit forms prominent ledges. [254–280]	26	26

OFFSET MEASURED TRAVERSE about 30 ft (10 m) to left (east) at [260].

Conformable contact placed at prominent break in slope above *Symphysurina* coquina and other cliff-forming strata that are mostly lime mudstone with 5–10 percent dark nodular chert (referred to the Lava Dam Member) and below ledge-forming lime mudstone and grainstone with 30 percent brown to white bedded chert and terrigenous sand (referred to the House Limestone).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

NOTCH PEAK FORMATION [upper part]
Lava Dam Member [251 ft (76.5 m) measured]

Unit	Description	*Thickness (feet)* Unit	Cumulative
70	Lime mudstone; medium gray; orange burrow mottling; argillaceous partings, mostly in lower part. Unit is one massive bed that forms a ledge with unit 69. Top of unit is a coquina of the trilobite *Symphysurina.* [251.5–254]	2.5	251
69	Fine grainstone and lime mudstone; light to medium gray; silty, with abundant pink argillaceous partings; minor white and black chert with relict lamination and cross-laminated sets. Unit weathers back from underlying strata and forms a ledge with unit 70. [249.5–251.5]	2	248.5
68	Very fine trilobite grainstone to packstone and lime mudstone; dark gray; orange to pink burrow mottling; 5–10 percent brown to black chert nodules and stringers; massive beds. Unit forms top of a massive cliff with units 66 and 67; top of unit forms a flat bench. [237–249.5]	12.5	246.5
67	Lime mudstone, a lens of intraclast and skeletal grainstone at [219]; medium gray; orange burrow mottling and pink argillaceous partings; 15–20 percent dark brown to black chert nodules and stringers; large linguloid brachiopods [220]; massive beds. Unit forms part of massive cliff with units 66 and 68. [204–237]	33	234
66	Lime mudstone; medium to dark gray; pink to lavender burrow mottling, some burrows silicified; argillaceous partings; 5–10 percent brown to black chert nodules and stringers in lower part of unit, less chert in upper part; massive beds. Unit forms lower part of a massive cliff at top of Lava Dam Member. [161–204]	43	201
	OFFSET MEASURED TRAVERSE ca. 50 ft (ca. 15 m) to left (east) along base of unit 66 so as to cross a vertical fault; strata on right (west) side of fault are uplifted ca. 40 ft (12 m).		
65	Covered. [156–161]	5	158
64	Lime mudstone; medium gray; pink to brown burrow mottling, mottling especially strong in lower 3 in (8 cm); bed is nonresistant. Unit is at top of a ledge formed by units 63 and 64. [154.75–156]	1.25	153
63	Grainstone and packstone; medium gray; lower 1 ft (0.3 m) is intraclast and peloid grainstone, upper part is oncoid, ooid, and	2.75	151.75

	peloid packstone. Unit forms lower part of a ledge with unit 64. [152–154.75]		
62	Covered. [151–152]	1	149
61	Grainstone; lower part with abundant brown round intraclasts and a few flat pebbles of lime mudstone, upper part is finer grained with small intraclasts, peloids, trilobites, and articulate brachiopods; light to medium gray, weathers brown to gray; fauna includes trilobite *Missisquoia typicalis* and brachiopods *Glyptotrophia imbricata, Nanorthis hamburgensis,* and *Syntrophina campbelli.* Unit is a resistant bed at top of a ledge. [150–151]	1	148
60	Lime mudstone, fine grainstone, and chert; chert is 20–40 percent of rock, forms beds and irregular stringers; thin to very thin beds; thickness is laterally variable due to unit draping over stromatolites of unit 59. [149.5–150]	0.5	147

Lawson Cove Bed (Unit 59)

59	Stromatolitic boundstone; fine grained; light to medium gray; dark brown chert bodies fill some interstices, other irregular chert bodies are within unit. Unit forms a ledge. The thickness of this unit is laterally variable, and it is absent in some places. [148.2–149.5]	1.3	146.5
58	Flat-pebble and edgewise conglomerate, clasts mostly fine grainstone, up to 3 in (8 cm) across, some with vertical orientation; conglomerate grades laterally into light gray fine grainstone. [147.5–148.2]	0.7	145.2
57	Chert marker bed, chert grades laterally into grainstone; chert is white to brown; laterally variable in thickness because lower part intertongues with underlying unit. [147.1–147.5]	0.4	144.5
56	Fine grainstone, lime mudstone, and very fine wackestone with fine quartz sand, one lens of peloid and intraclast grainstone; gray to brown; lower part burrowed, upper part lacks burrows and is finely laminated; minor black chert in middle. [145.75–147.1]	1.3	144.1
55	Mostly lime mudstone, a few 3–6 in (8–15 cm) beds of peloid to intraclast packstone, as at [143]; medium to dark gray; red argillaceous partings; some tan burrow mottling, some spar-filled burrows; lower part of unit poorly exposed, above [143] ca. 20 percent brown to black chert beds and nodules. Unit forms a ledge. [142–145.75]	3.75	142.75
54	Peloid to fine intraclast grainstone; light to medium gray. Unit weathers back from top of cliff formed by underlying units. [141.5–142]	0.5	139
53	Mixed lithology. Lime mudstone, wackestone, and packstone alternating in 1–3 in (2.5–8 cm) beds, skeletal and peloid, with intraclasts in some beds; medium to dark gray; pink burrow mottling. Unit extends to top of a cliff formed by units 46–53. [138.25–141.5]	3.25	138.5
52	Peloid, ooid, and skeletal packstone and grainstone; light to medium gray. Unit is a resistant bed that forms part of a cliff. [137.4–138.25]	0.85	135.25
51	Lime mudstone; dark gray; burrowed and mottled pinkish brown. [137–137.4]	0.4	134.4
50	Grainstone; mostly ooid, some skeletal grains, most ooids are white, some are black; medium to dark gray; burrowed. [136.1–137]	0.9	134
49	Lime mudstone; dark gray; abundant red argillaceous partings; beds 0.5–1 in (1.25–2.5 cm) thick. Unit forms part of cliff. [135–136.1]	1.1	133.1

OFFSET MEASURED TRAVERSE northward ca. 50 ft (ca. 15 m) along top of unit 28 to the main measured traverse, where younger strata are exposed.

Tank Canyon Bed (Units 47–48)

48	Mixed lithology. Wackestone, packstone, and fine grainstone with skeletal grains and sparce ooids; matrix is part mud, part spar; medium gray, mottled tan; red argillaceous partings; burrows; thin beds. Unit forms part of a cliff but is not resistant. [134.25–135]	0.75	132
47	Grainstone, ooid, intraclastic, clasts are lime mudstone up to (1 in/2.5 cm) long, but most are smaller; dark gray; orange burrow mottling. Unit is one resistant bed that forms part of a cliff. [133.7–134.25]	0.55	131.25
46	Mostly lime mudstone and wackestone, one lens of skeletal and intraclast packstone; medium gray; argillaceous partings, tan horizontal burrows abundant in upper half. Contact with overlying ooid grainstone is mostly irregular but flat in places. Unit forms base of a cliff that includes units 46–53; base of cliff overhangs unit below. [133.2–133.7]	0.5	130.7
45	Lime mudstone; medium gray; abundant pink argillaceous partings; beds 0.25–0.75 in (0.6–1.9 cm). Unit weathers back from overlying cliff. [132.4–133.15]	0.75	130.15
44	Lime mudstone; medium gray; tan to pink argillaceous partings; 2 mm horizontal spar-filled burrows and larger tan burrows. Unit is at top of 2.15 ft (0.66 m) interval of strata exposed by digging at a location ca. 50 ft (ca. 15 m) southeast of main part of measured traverse; this interval is covered laterally. [131.9–132.4]	0.5	129.4
43	Grainstone and wackestone, very fine skeletal grains, intraclasts, some beds with spar cement; medium gray; abundant pink argillaceous partings; strongly burrowed. Unit is resistant. A metal sign attached to the base of this unit is engraved "Base of Ibexian Series J. F. Miller 1992." This point is the defined base of the Ibexian Series. [131.33–131.9]	0.6	128.9
42	Lime mudstone and fine grainstone; medium to dark gray; abundant argillaceous partings and burrows; beds 0.5–1 in (1.25–2.5 cm) thick. Unit is nonresistant and forms a slope. [131.08–131.33]	0.08	128.08

41	Wackestone, intraclasts in lower half, ooids in upper half; pinkish gray. Unit is one thin bed that is part of a covered slope laterally but is more resistant than unit 42. [131–131.08]	0.08	128.08
40	Wackestone to packstone, fine peloids, some trilobite fragments, lenses of fine intraclasts; medium to dark gray; minor chert at [130.5]; argillaceous partings; horizontal burrows and pink to tan burrow mottling; beds 1–2 in (2.5–5 cm) thick. Unit forms lowest part of covered slope that was exposed by digging. [130.25–131]	0.75	128

OFFSET MEASURED TRAVERSE southward ca. 50 ft (ca. 15 m) along a chert bed exactly at the [130] painted field number so as to gain better exposure of overlying units. The overlying ca. 4.75 ft (1.45 m) of strata are described from this southern location, where some of the strata were exposed by digging.

39	Mostly lime mudstone, some very fine peloid and sparse skeletal packstone lenses and thin beds; medium to dark gray; 10 percent black chert beds and stringers, mostly 1–3 in (2.5–8 cm) thick, painted field number [130] is at highest chert bed; tan and pink argillaceous partings and burrow mottling; medium to thick beds. Unit is resistant and forms top of resistant beds below thin-bedded, slope-forming units above. [125–130.25]	5.25	127.25
38	Mostly lime mudstone, lenses of trilobite debris and intraclasts on some bedding surfaces; medium to dark gray; some beds with orange burrow mottling; 5–10 percent black chert nodules and stringers; mostly thin beds that form slopes, one thick bed forms a ledge [115–117]. [112–125]	13	122
37	Lime mudstone; light to medium gray; tan argillaceous partings and burrow mottling; spar-filled and silicified horizontal burrows on bedding surfaces; top 2 ft (0.6 m) has 5–10 percent black chert nodules and stringers; thin to medium beds. Unit forms two ledges. Fault breccia occurs left of the measured traverse, but there is no offset of strata. [102–112]	10	109
36	Lime mudstone with one bed of intraclast and flat-pebble conglomerate; light gray; abundant very light tan argillaceous partings and abundant horizontal burrows; very thin, flaggy bedding. Unit forms a slope and is similar to unit 33. [101–102]	1	99
35	Lime mudstone, very dense; medium to dark gray; long spar-filled burrows on bedding surfaces; contains partly silicified trilobites, including *Eurekia* and *Euptychaspis*. Unit forms part of a flat bench with unit 34. [100.5–101]	0.5	98
34	Lime mudstone; medium to dark gray; abundant orange burrow mottling; 15 percent black chert stringers in upper 6 in (15 cm); medium to thick beds. Unit forms a prominent ledge with a flat bench at top. [95–100.5]	5.5	97.5
33	Intraclast conglomerate, lime mudstone, and very fine packstone; light to medium gray, with abundant tan argillaceous partings and abundant burrow mottling; beds 1–3 in (2.5–8 cm) thick, flaggy; small covered slope below this unit probably underlain by similar material. [93–95]	2	92
32	Lime mudstone, lens with trilobite debris at [60]; medium gray, some weathers brown; some beds with silicified horizontal burrows; 5–15 percent brown to black chert stringers and nodules; beds 1–3 ft (0.3–0.9 m) thick, thinner than in units below. Unit forms ledges with covered slopes between beds. [46–93]	44	90

CROSS A FAULT between [65 and 70] and repeat 3 ft (0.9 m) of section. The reported thickness of unit 32 is reduced by this amount.

31	Covered. [40–46]	6	46
30	Lime mudstone; medium gray; some burrows; 10 percent black chert nodules and stringers. Unit forms a ledge. [35–40]	5	40
29	Covered. [29–35]	6	35
28	Lime mudstone; medium to light gray; argillaceous partings; burrows on bedding surfaces; a few small black chert nodules in upper part of unit, which forms a ledge. [26–29]	3	29
27	Covered. [22–26]	4	26
26	Mostly lime mudstone, lenses with skeletal debris; medium gray; lower 7 ft (2.1 m) with abundant orange burrow mottling; one black chert band near [20]. Unit forms a massive ledge. [9–22]	13	22
25	Covered. [7–9]	2	9
24	Lower part is intraclast, trilobite, and echinoderm grainstone overlain by fine grainstone, upper part is coarse intraclast to flat-pebble conglomerate; medium gray to brown. Unit is at top of ledge formed by units 21 to 24. [6–7]	1	7
23	Lime mudstone with lenses of skeletal and intraclast grainstone; medium gray; 5 percent black chert nodules; a massive bed. Unit is part of one ledge formed by units 21–24. [3–6]	3	6
22	Trilobite wackestone and packstone; medium gray; abundant orange burrow mottling; trilobite collection from this bed. Unit is part of one ledge formed by units 21–24. [2–3]	1	3
21	Fine grainstone and lime mudstone; medium gray; abundant argillaceous partings in lower half. Unit is part of basal ledge of the Lava Dam Member formed by units 21–24. [0–2]	2	2

Conformable contact placed above strata consisting dominantly of brown, coarse grainstone and flat-pebble conglomerate (referred to the Red Tops Member) and below strata consisting dominantly of gray lime mudstone (referred to the Lava Dam Member). The contact is at the highest major unit of lithology typical of the Red Tops Member.

RESET PAINTED NUMBERING SYSTEM TO ZERO AT CONTACT.

Red Tops Member [upper 66 ft (20.1 m) described]

Unit	Description	Thickness (feet) Unit	Cumulative
20	Flat-pebble conglomerate, matrix is skeletal grainstone; pinkish gray to rusty brown; silicified burrows. [65.25–66]	0.75	66
19	Fine grainstone, laminated and with cross-laminated sets, and lime mudstone, some intraclast and flat-pebble conglomerate lenses; medium gray with brown laminations; lower part has thin flaggy beds with tan argillaceous partings similar to unit 16. [64.25–65.25]	1	65.25
18	Covered. [62.5–64.25]	1.75	64.25
17	Mostly lime mudstone and wackestone with 1 in (2.5 cm) of laminated fine grainstone overlain by a lens of trilobite and intraclast grainstone at top of lower bed [61]; medium gray; argillaceous partings, especially in upper bed; lower bed has a few black chert nodules. Unit consists of two beds that are poorly exposed laterally. [60–62.5]	2.5	62.5
16	Mostly covered, but top 6 in (15 cm) has very thin flaggy beds of silty and intraclast-bearing lime mudstone to fine grainstone with tan argillaceous partings; similar lithology occurs as float on the covered slope. [58–60]	2	60
15	Lime mudstone with thin lenses of intraclast and skeletal grainstone near base and top; medium gray; pink argillaceous partings; 5 percent brown to black chert nodules. Lithology is similar to overlying Lava Dam Member. [55–58]	3	58
14	Flat-pebble conglomerate. Unit grades upward into lime mudstone of unit 15. [54.5–55]	0.5	55
13	Grainstone, intraclast, peloid, skeletal, with a few coated grains; gray to redish brown. Unit is one bed that is poorly exposed laterally. [53.75–54.5]	0.75	54.5
12	Flat-pebble conglomerate and laminated fine grainstone, clasts made of similar fine grainstone; gray to brown; thin to medium beds. Unit is poorly exposed laterally. [53–53.75]	0.75	53.75
11	Covered. [50–53]	3	53
10	Flat-pebble conglomerate with a few thin intervals of laminated fine grainstone, many clasts made of similar fine grainstone; gray to rusty brown. Unit consists of three beds. [47–50]	3	50
9	Covered. [41.5–47]	5.5	47
8	Flat-pebble conglomerate with clasts up to 5 in (13 cm) long, many clasts with fine lamination; and intraclast, skeletal, and peloid grainstone with cross-laminated sets, and minor fine grainstone with fine lamination and cross-laminated sets; medium gray to brown. Unit caps the ledge formed by unit 7. [40–41.5]	1.5	41.5
7	Wackestone and packstone, skeletal, peloid; medium gray; abundant argillaceous partings and burrows; lower part finely laminated; thin to medium beds. Unit forms a ledge. [33.5–40]	6.5	40
6	Flat-pebble conglomerate with clasts up to 2 in (5 cm) long, some clasts finely laminated, unit consists of three beds, some parts of beds with fine lamination and cross-laminated sets; matrix of conglomerates is skeletal, peloid, and ooid grainstone; rusty brown to gray. Unit forms a ledge. [32 to 33.5]	1.5	33.5
5	Skeletal and ooid grainstone; gray to reddish brown; some beds with red burrow mottling, some burrows silicified; abundant argillaceous partings, especially at base and top of unit; some beds with fine lamination and cross-laminated sets at top; medium to thick beds. Unit forms a prominent ledge capped by unit 6. [25–32]	7	32
4	Covered. [19–25]	6	25
3	Grainstone and wackestone, very coarse trilobite skeletal grainstone at [15], ooid grainstone [19]; brown to medium gray; cherty in lower ledge [7–10]; medium to thick beds. Unit forms low ledges. [6–19]	13	19
2	Interbedded grainstone and shale, lime grainstone is skeletal, intraclastic, peloid, and glauconitic, mostly in beds 0.5–2 in (1.25–5 cm) thick, shale beds 0.25–0.5 in (0.06–0.25 cm) thick; halite and gypsum present, mostly concentrated on bedding surfaces and in joints. Unit is eroded so as to form fresh exposures on south side of dry gully beneath overhanging ledge of unit 3. Gypsum and halite may be of secondary origin. [1–6]	5	6
1	Ooid, skeletal, and intraclast grainstone; reddish brown; two beds exposed; top of unit is ripple-marked. Unit forms lowest exposures in bottom of dry gully. [0–1]	1	1

Underlying strata are concealed by alluvium and colluvium. More of unit 1 is exposed ca. 30 m farther up the dry stream valley and across a small fault.

LAVA DAM NORTH SECTION

Southern House Range, Utah

This section is located in the southern House Range, north of the Lava Dam Five section and north of the topographic feature named the Lava Dam. The lower part was measured and described July 1, 1965 by L. F. Hintze and J. F. Miller in order to study strata exposed above the top of the Lava Dam South section. The section originally ended at 157 ft (47.9 m) (Miller, 1969). L. F. Hintze later extended the measurement to include the entire House Limestone, and a description of the section was published by Hintze (1973). Further study by Hintze and Miller on July 13, 1973 resulted in the discovery of several faults in the lower part of the section. The description here was made by J. F. Miller in 1990, 1991, and 1994. The boundary between the Notch Peak and the House formations utilized in this description differs from that of Miller (1969) and Hintze (1973). Later study of these units in the southern House Range (Hintze et al., 1988) indicated that a lower horizon should be utilized for the formation boundary in order to be consistent throughout the Ibex area. This is the type section for the Red Canyon Member of the House Limestone and was chosen instead of the type section of the

House Limestone, Section A of Hintze (1952, 1973), because of easier access.

The base of the section is in the SE1/4 NW1/4 NE1/4 sec. 6, T. 23 S, R. 13 W, at UTM zone 12 grid coordinates 296254 m E, 4302084 m N. The section trends up the hill to the southeast, but at the top of unit 43 the traverse turns to the northeast at UTM coordinates 296522 m E, 4301989 m N. The measured traverse continues northeast to the base of the Fillmore Formation and ends at UTM coordinates 296750 m E, 4302560 m N. Access to the base of the section is by a dirt track that proceeds eastward from the Tule Valley Road, at a slight hillcrest at UTM coordinates 294889 m E, 4301824 m N; this hillcrest is approximately 0.5 mile north of the junction of the Tule Valley Road with a road leading west to Snake Pass. The east end of this dirt track is at UTM coordinates 296120 m E, 4301960 m N. The middle of the section can be accessed by driving north from Steamboat Pass toward Red Canyon and turning west at UTM coordinates 296670 m E, 4301324 m N toward the north end of the Lava Dam. After driving west ca. 100 m, turn north, follow a dry stream valley, and park at the ridge crest at UTM coordinates 296570 m E, 4301860 m N. Walk northwest to the hilltop at 296580 m E, 4302080 m N, at 480 ft in the measured traverse.

The section is located on the Red Tops 7.5 minute topographic quadrangle and on a geologic quadrangle map by Hintze (1974a). The section was measured beginning at the lowest exposures above alluvium in a dry stream bed; intervals of 5 ft (approximately 1.5 m) are marked in yellow paint. Numbers are footages above the base of the section and are continuous from the Notch Peak Formation into the base of the Fillmore Formation.

In June, 2001 someone used yellow spray paint to mark a second set of numbers on this section using metric increments. These numbers begin at an apparently arbitrary stratigraphic horizon in the middle of the Barn Canyon Member and continue to the top of the section. The zero mark is in a deep gully south of the original painted traverse. The system of metric numbers initially follows the gully eastward, but then they trend northward. The metric numbers intersect the original painted traverse and then follow it, so that both sets of numbers are found together through most of the type section of the Red Canyon Member. Confusion caused by the presence of two sets of mumbers can be avoided by paying close attention to the original system of painted numbers, which are painted every 10 ft.

The lower part of this section is characterized by several faults that trend north-south, paralleling the boundary fault of the range to the west. The true sequence and thickness of some units in the lower part of the section are questionable, although the sequence of conodont faunas indicates no biostratigraphic units are missing or out of order. These faults were not noted during measurement of the section, so the displacement causes discrepancies between measured numbers and stratigraphic thickness. The numbers in brackets within and after unit descriptions correspond to the numbering system painted on the rocks in the field, such as [592–602] for the top unit of the House Limestone.

The contact relationships with the overlying Fillmore Formation are only moderately well preserved at the Lava Dam North section. All of the uppermost ledge of the House is present at the top of the formation at [602], but the top of the section is at [607]. Thus only the lowest 5 ft (1.5 m) of the Fillmore is preserved, and typical lithology of the Fillmore is not present. The section crosses a fault at [607] in the measured traverse. The measured traverse described herein is west of this fault and is faulted down ca. 100 ft (ca. 30 m) relative to the block east of the fault. Thus the upper part of the Red Canyon Member is repeated and was measured by L.F. Hintze east of this fault up to the repeated top of the House Limestone; these duplicated strata have never been described. The contact with the Fillmore can be studied a few miles north at the base of the 1965C section of Hintze (1973).

FILLMORE FORMATION [lower 5 ft (1.5 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
57	Lime mudstone, dark gray, medium beds. Base of unit is at a bedding plane that forms a topographic break above the cliff at the top of the House Limestone. Unit forms ledges above the underlying cliff. Large trilobites of *Leiostegium-Kainella* Zone and large lingulids at [606]. [602–607]	5	5

Conformable contact placed above massive cliff-forming, dark lime mudstone (referred to House Limestone) and below ledge-forming dark lime mudstone (referred to Fillmore Formation). Contact coincides with white caliche layer ca. 6 in (15 cm) thick that can be traced along strike.

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

HOUSE LIMESTONE [541 ft (164.9 m) measured]
Red Canyon Member [Type Section; 229 ft (69.8 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
56	Mostly lime mudstone with some fine grainstone, 8 in (20 cm) of coarse round-pebble conglomerate at base grading upward into 12 in (30 cm) of skeletal grainstone; mostly dark gray, grainstone is brownish gray; laminated; mostly thin to medium beds. Unit forms a 10 ft (3 m) prominent and persistent dark ledge at top of House Limestone. Large rock cairn near top of ledge at ca. [599]. [592–602]	10	229
55	Mostly covered; light gray argillaceous lime mudstone at top of unit. [590–592]	2	219
54	Flat-pebble conglomerate grading upward into trilobite-brachiopod grainstone; light to medium gray. Unit is a poorly exposed ledge. [588–590]	2	217
53	Covered. [286–288]	2	215
52	Dense lime mudstone and fine grainstone, some finely laminated and dolomitic; light gray to tan, weathers brown and forms a persistent brown band; 15–20 percent black chert nodules and vertical chert bodies. [585–586]	1	213
51	Fine grainstone and intraclast and skeletal grainstone, flat-pebble conglomerate near top of unit; fine grainstone is laminated, some grades laterally into laminated brown chert; medium gray to tan; 20 percent dark brown to black chert nodules and beds. Unit forms top of a ledge. [583–585]	2	212
50	Lime mudstone and wackestone, beds and lenses of skeletal grainstone and flat-pebble conglomerate, minor fine grainstone beds in upper half of unit; dark gray; some beds with horizontal burrows, some silicified; silicified trilobites on some bed surfaces; ripple marks [537] with silicified brown to black skeletal debris in ripple troughs; some beds with 5 percent black to brown chert beds and nodules, persistent 12 in (2.5–5 cm) chert bed at base of unit. Unit forms low ledges and slopes. [518–583]	65	210

49	Lime mudstone, lenses of skeletal grainstone and intraclast and flat-pebble conglomerate; medium gray; burrow mottling, tan to orange burrows and silicified trilobites on bed surfaces; less than 1 percent brown chert blebs and nodules; medium beds. Unit forms ledges and slopes. [503–518]	15	145
48	Lime mudstone, skeletal wackestone to grainstone with some silicified trilobites, some intraclast conglomerate; light to medium gray; thin to very thin beds. Unit is poorly exposed in recess below cliff formed by unit 46. [500–503]	3	130
47	Covered. [496–500]	4	127
46	Lime mudstone and fine grainstone, some beds and lenses of flat-pebble conglomerate; dark gray; 5–10 percent dark brown to black chert nodules, silicified trilobites on some bed surfaces; thin to medium beds. [488–496]	8	123
45	Lime mudstone, some fine grainstone, minor flat-pebble conglomerate; medium gray; some beds with horizontal burrows; 10 percent dark brown to black chert beds, stringers, and nodules, some chert beds internally laminated and follow laminae in adjacent limestone; silicified trilobites on some bed surfaces. Unit is poorly exposed in a low saddle; dip of beds indicates a small syncline in this saddle. [486–488]	2	115
44	Lime mudstone, argillaceous and fine grainstone; medium to light gray, weathers with slight tan color; very thin to medium bedded, some beds laminated; 1–2 percent brown chert blebs and laminated beds, some burrows replaced by chert. Unit forms ledges. [481–486]	5	113
43	Lime mudstone, minor fine grainstone and flat-pebble conglomerate; 4 in (10 cm) clasts in conglomerate [415]; light to medium gray (blue gray); 10–20 percent black chert nodules and stringers, some chert forms vertical bodies, some parts of unit have little chert, silicified trilobites on some bed surfaces; some beds are finely laminated; horizontal burrows on some bed surfaces in upper part of unit, some burrows silicified; thin to medium beds. Unit forms step ledges to top of ridge. [380–481]	101	108
42	Covered. [373–380]	7	7

Conformable contact placed above cliff-forming, brown-weathering limestone (mostly fine grainstone and flat-pebble conglomerate) with up to 60 percent white to black chert (referred to Burnout Canyon Member) and below ledge-forming gray limestone (mostly lime mudstone) with 10–20 percent chert (referred to Red Canyon Member).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Burnout Canyon Member [64 ft (19.5 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
41	Fine grainstone and lime mudstone, silty, laminated and with cross-laminated sets; light gray, some weathers brown; 20–30 percent black, brown, and white chert, a 4–6 in (10–15 cm) black chert bed at base of unit, some irregular chert bodies, upper part of unit is mostly limestone with black chert nodules. Unit forms a ledge at top of Burnout Canyon Member. [371–373]	2	64
40	Covered. [368–371]	3	62
39	Lithology similar to unit 37. Unit forms a ledge. [365–368]	3	59
38	Covered. [362–365]	3	56
37	Fine and coarse grainstone, flat pebble conglomerate, and 40–60 percent white to brown to black chert; limestones light gray, tan, and rusty brown; limestones silty, some finely laminated and with cross-laminated sets; some chert beds likewise laminated and cross-laminayed on freshly broken surfaces, chert occurs as beds, irregular vertical bodies, and as surface silicification on joint surfaces. Unit forms a prominent cliff. [350–362]	12	53
36	Fine and coarse grainstone and flat-pebble conglomerate, abundant quartz silt and some quartz sand; light gray near base, medium gray in upper part; grainstone finely laminated and with cross-laminated sets; 15 percent black and white laminated chert in beds up to 2 in (5 cm) thick, chert less abundant and black near base; beds mostly thin to very thin. Unit forms base of cliff that weathers brown. [346–350]	4	41
35	Covered. [340–346]	6	37
34	Flat-pebble conglomerate, peloid grainstone, and 30–40 percent white to brown to black chert; some chert is surface silicification on joint surfaces and outlining pebbles in conglomerates, some chert beds are laminated, white chert is only near base of unit but is a bed up to 1 ft (0.3 m) thick. Unit weathers to a brown ledge and forms base of brown-weathering interval when viewed from a long distance (base of "brown marker bed" of Hintze, 1973, p. 16). [335–340]	5	31
33	Interbedded brown laminated fine grainstone, brown flat-pebble conglomerate, and light gray lime mudstone; 10–15 percent brown to black chert, some burrows in mudstone and laminae in grainstone are silicified; very thin to medium beds. Unit variably forms slope or cliff along strike. [309–335]	26	26

Conformable contact placed above ledge-and slope-forming limestones with little chert (referred to Barn Canyon Member) and below limestones with considerable brown to black bedded chert (referred to Burnout Canyon Member).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Barn Canyon Member [248 ft (75.6 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
32	Interbedded lime mudstone and flat-pebble conglomerate; light gray; some silicified burrows; some beds with fine lamination. Unit forms ledges and slopes. [295–309]	14	248

31	Fine grainstone; gray to brown; finely laminated and with cross-laminated sets. Unit forms a ledge. [293–295]	2	234
30	Mostly flat-pebble conglomerate with a few very thin (1 in/2.5 cm) beds of lime mudstone and fine grainstone, pebbles up to 1.5 by 6 in (4 by 15 cm); gray-brown; conglomerate beds mostly 0.5–1.5 ft (15–45 cm) thick and form ledges; covered slopes between ledges apparently are lime mudstone and fine grainstone. [268–293]	25	232
29	Mostly silty lime mudstone; medium gray; pink burrow mottling; argillaceous partings; a 5 in (13 cm) pebble conglomerate bed overlies planar eroded top of lime mudstone bed with truncated vertical and U-shaped burrows [253]; thin to very thin beds. Unit is poorly exposed but is better exposed to right (south) of painted traverse. [245–268]	23	207
28	Covered. [230–245]	15	184
27	Interbedded fine grainstone, skeletal and intraclast grainstone, flat-pebble conglomerate, lime mudstone, and minor shale; brown to medium gray; minor chert replaces some vertical burrows in a 2 in (5 cm) lime mudstone bed [203] that has a prominent planar truncation surface (firmground), vertical and U-shaped burrows filled with clasts from skeletal and intraclast grainstone above; 3 in (8 cm) of yellowish-brown fissile shale [207] overlain by intraclast grainstone, to the north this shale contains the planktic graptolite *Anisograptus matanensis*, shale underlain by sequence of 1–3 in (2.5–8 cm) grainstone and lime mudstone; 3 in (8 cm) of flat-pebble conglomerate [229] with pebbles 1.5 in (4-cm) wide is overlain by 3 in (8 cm) of fine grainstone; this and some other fine grainstone beds are finely laminated; entire unit mostly made of beds 1–3 in (2.5–8 cm) thick. Unit is poorly exposed but is better exposed right (south) of painted traverse. [203–230]	27	169

CROSS A FAULT [200]; right side of fault uplifted about 4 ft (1.2 m), and strata from about [199–203] are repeated.

26	Fine grainstone; gray to brown; finely laminated, with small-scale cut-and-fill channeling. [198–199]	1	142
25	Trilobite grainstone with some intraclasts, grades laterally into fine grainstone; medium gray to brown. Brown grainstone [196–197] contains the trilobite *Jujuyaspis borealis*. Unit forms a ledge that includes units 23–25. [196–198]	2	141
24	Interbedded lime mudstone, fine grainstone, and lenses of peloid to fine intraclast grainstone; 10 percent brown chert nodules and stringers. Unit forms part of a ledge. [191–196]	5	139
23	Intraclast and peloid packstone; light brown; red burrow mottling. Forms base of ledge that includes units 23–25. [190–191]	1	134
22	Lime mudstone with lenses of intraclast, skeletal, and fine grainstone; brown to pink; thin to very thin beds; some very thin beds finely laminated. [185–190]	5	133
21	Intraclast and peloid grainstone interbedded with lime mudstone and flat-pebble conglomerate [163 and170], pebbles edgewise and up to 6 in (15 cm) across [164–165] but thickness variable laterally, a 6-in (15-cm) thick brown bed [170] with 0.5 by 3 in (1.3 by 8 cm) pebbles, pebbles imbricate in some other conglomerate beds, some grainstone beds capped by lime mudstone; unit is medium gray to brown; lime mudstones in lower part of unit burrowed, especially abundant at [163], some spar-filled at tops, some burrows replaced by brown chert; grainstone beds 1–8 in (2.5–20 cm) thick. [161–185]	24	128
20	Lime mudstone; medium to dark gray; pink burrow mottling; 2 percent brown chert nodules. [155–161]	6	104

The Notch Peak Formation-House Limestone contact as described by Hintze (1973) is at [157].

19	Intraclast, peloid, ooid, and skeletal grainstone; light gray to brown; weathers back from top of cliff formed by units 16–18. [154–155]	1	98
18	Strata similar to unit 16 (below). Unit forms top of cliff that includes units 16–18. [148.5–154]	5.5	97
17	Stromatolite boundstone; medium gray; 1–2 percent brown chert; stromatolites not distinct but visible on some weathered surfaces. Unit forms part of a cliff. [145–148.5]	3.5	91.5
16	Mostly lime mudstone, some lenses of skeletal and intraclast grainstone, a lens of ooid grainstone [141]; medium gray; some silicified horizontal burrows; 20–40 percent brown chert beds and nodules; massive beds. Unit is base of cliff that includes units 16–18. [135–145]	10	88
15	Lime mudstone, argillaceous; medium gray; burrowed pink argillaceous partings; 20–30 percent brown chert beds; poorly exposed below and at base of cliff formed by units above; thin to medium bedded. [125–135]	10	78
14	Covered. [105–125]	20	68

CROSS PROBABLE FAULT within the covered interval of unit 14; beds below the covered interval dip slightly to the south, whereas higher exposures dip slightly to the north.

13	Lime mudstone with lenses of intraclast and skeletal grainstone with a few dark oncoids; medium to dark gray; some pink horizontal burrows; 10 percent dark chert stringers; gastropods present. [95–105]	10	48
12	Mostly peloid and ooid grainstone with some oncoids made of coated intraclasts, some lime mudstone with 1–2 in (2.5–5 cm) diameter spar-filled burrows, some silicified; light to medium gray. [86–95; also 79–84 below fault]	9	38

CROSS A FAULT at [84]; this fault has about 7 ft (2.1 m) displacement so that some beds are repeated in the section, as noted in description.

11	Lime mudstone; dark gray; horizontal burrows up to 1 in (2.5 cm) across, some partly spar filled; 10 percent dark brown chert; medium to thick beds. [70–79; also 84–86 above fault]	9	29

CROSS A FAULT BRECCIA at [70]; there is no obvious displacement.

10	Mostly fine grainstone, lime mudstone, and chert, some lenses of skeletal and intraclast grainstone, one flat-pebble conglomerate bed [53]; limestones are medium gray, chert is brown and white in beds 1–6 in (2.5–15 cm) thick; 20–30 percent chert, chert and fine grainstone less abundant in upper part; silicified argillaceous partings; thin to medium beds. Unit is nonresistant and forms low ledges above the Notch Peak Formation. [50–70]	20	20

Conformable contact placed above lime mudstone with minor brown chert (referred to the Lava Dam Member) and below limestones with 20–30 percent brown to white chert (referred to the House Limestone). PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

NOTCH PEAK FORMATION [part]
Lava Dam Member [upper 50 ft (15.2 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
9	Mostly lime mudstone, some lenses of skeletal and intraclast grainstone; medium gray; 10 percent brown chert stringers. Lower 3 ft (0.9 m) of unit forms a ledge with top of unit 8; top 2 ft (0.6 m) of unit is covered. [46–50]	4	50
8	Lower part is intraclast, skeletal, ooid, and oncoid grainstone, upper part is skeletal, intraclast, and peloid grainstone; silicified burrows; 10 percent brown chert stringers; some covered interval [43–45]. Lower part of unit forms a cliff with unit 7; upper part is a ledge formed with unit 9. [34–46]	12	46
7	Lime mudstone; medium gray; 10 percent dark brown chert nodules and stringers; massive beds. Unit forms lower part of a cliff with lower part of unit 8. [29–34]	5	34
6	Grainstone, lower half ooid, oncoid, and skeletal, upper half mostly skeletal with a few ooids and oncoids; medium gray. Unit forms top of a ledge. [27–29]	2	29
5	Mostly lime mudstone, lower 2 ft (0.6 m) with some intraclast packstone and possible stromatolitic boundstone; 5 percent dark chert nodules; massive beds. Unit forms ledges. [22–27]	5	27

PROBABLE FAULT in covered interval indicated by change in dip at [22].

4	Covered. [13–22]	9	22
3	Lime mudstone and intraclast and peloid packstone; medium gray; 10 percent brown chert nodules and stringers. [12–13]	1	13
2	Covered. [6.5–12]	5.5	12
1	Lime mudstone; dark gray; pink burrow mottling; 1–2 percent brown chert blebs and nodules; massive bedding. Unit forms a ledge. [0–6.5]	6.5	6.5

Lower strata concealed beneath alluvium in a dry stream bed.

DRUM MOUNTAINS SECTION
Northwest Drum Mountains, Utah

This section is located in the Wildcat Hills, near the northwestern end of the Drum Mountains, Juab County, Utah. The area is shown on the Topaz Mountain West 7.5 minute topographic quadrangle and on a geologic map by Dommer (1980). Strata measured in this section include the upper part of the Notch Peak Formation and the lower part of the overlying House Limestone; these strata were measured in several segments separated by offsets made to avoid numerous small east-west faults. The base of the section is at UTM zone 12 grid coordinates 316177 m E, 4390539 m N, near the NE corner, NW 1/4 NW 1/4 SE 1/4 sec. 36, T. 13 S, R. 12 W. The lower segment of the measured traverse trends northwestward to near the crest of the hill, at UTM coordinates 316009 m E, 4390642 m N. From there it is offset downhill and to the north, to UTM coordinates 316002 m E, 4390794 m N. The section continues northwest up to the crest of the hill, at UTM coordinates 315975 m E, 4390770 m N. Here the section is again offset to the north, to UTM coordinates 315935 m E, 4390877 m N. These and additional smaller offsets are noted in the description. The section ends at the top of a dip-slope cliff above a shoreline gravel from Lake Bonneville, at UTM coordinates 315840 m E, 4390920 m N, in the NW 1/4 NE 1/4 SE 1/4 NW 1/4 sec. 36, T. 13 S, R. 12 W.

Access to the section is by driving along the Sand Pass Road to a junction with a dirt track leading south along the east edge of the Wildcat Hills, in the south-central part of sec. 25, T. 13 S, R. 12 W. The base of the section is ca. 0.7 mile (ca. 1 km) south of the Sand Pass Road. The section was studied in reconnaissance fashion by J. F. Miller and Stanley Fagerlin on May 30, 1981 and was measured in part in mid June with the assistance of Judith Wright, F. W. Woodard, and Donzil Worthington. The upper part of the section was measured in June, 1983 by Miller and Chen Qin-bao. The descriptions are by Miller. The measured traverse is marked in yellow paint every 5 ft (ca. 1.5 m), and the footage is marked every 10 ft (ca. 3 m). The numbers shown in brackets within and after unit descriptions, such as [530–585] for the top unit of the House Limestone, correspond to numbers painted on the rocks.

HOUSE LIMESTONE [lower 198.5 ft (60.5 m) measured]
Red Canyon Member [lower 50 ft (15.2 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
23	Lime mudstone, some peloid grainstone; medium gray (blue-gray); minor brown chert nodules and stringers; minor burrowing; beds 1–3 ft (0.3–0.9 m) thick, thicker than in unit below. Unit forms low ledges on flat-topped ridge. Measured traverse ends at highest exposures on top of a dip-slope cliff above a Lake Bonneville shoreline. [535–585]	50	50

Conformable contact placed above very cherty fine grainstone, flat-pebble conglomerate, and lime mudstone (referred to Burnout Canyon Member) and below very slightly cherty lime mudstone (referred to Red Canyon Member).
PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Burnout Canyon Member [48 ft (14.6 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
22	Fine grainstone, flat-pebble conglomerate, and lime mudstone, grainstone is sandy,	28	48

	laminated, and laminae are often silicified; rusty brown and brownish gray; mudstone has silicified burrows; 30–40 percent white to brown to black chert in beds and irregular nodules up to 8 in (20 cm) thick and in irregular vertical bodies; bedding is irregular; top of unit is a white chert bed. Unit is poorly exposed along ridge. [507–535]		
21	Fine grainstone and flat-pebble conglomerate, grainstone is sandy, laminated, and many laminae are silicified; rusty brown and brownish gray. [487–507]	20	20

Conformable contact placed above slightly cherty lime mudstone (referred to Barn Canyon Member) and below very cherty fine grainstone, flat-pebble conglomerate and lime mudstone (referred to Burnout Canyon Member).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Barn Canyon Member [100.5 ft (30.6 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
20	Lime mudstone; brownish gray; 5 percent dark brown chert nodules and stringers; 3 ft (0.9 m) exposed at base of unit, rest of unit is poorly exposed. [464–487]	23	100.5
19	Lime mudstone and flat-pebble conglomerate; rusty brown to medium gray; conglomerate beds [457 and 464], upper bed is 15 in (38 cm) thick. Unit is poorly exposed on slope. [452–464]	12	77.5
18	Grainstone; light gray to rusty brown; upper surface made by megaripples; ripple wavelengths are 2–3 ft (0.6–0.9 m) and wave heights are 3 in (8 cm); the measured traverse is offset downhill to the southwest ca. 20 m along this bed. [451–452]	1	65.5
17	Lime mudstone, medium gray with minor brown silicified burrows, most weathers reddish brown, and skeletal grainstone and flat-pebble conglomerate, brown to gray-brown. Beds are 3–15 in (8–38 cm) thick. Brown trilobite grainstone at base of unit [408] contains *Jujuyaspis borealis,* as described by Stitt and Miller (1987). [408–451]	43	64.5
16	Lime mudstone and dolomite; dark gray; slightly cherty; beds 8–15 in (20–38 cm) thick. Unit forms prominent thin ledges. Basal bed is irregularly dolomitized along strike. [398–408]	10	21.5

OFFSET MEASURED TRAVERSE about 100 m to northwest along ridge crest and down slope to cross several small faults; top of unit 15 is used to make offset.

15	Dolomite; gray and white, striped zebra-rock fabric, apparently dolomitized planar stromatolites; lower 1 ft (0.3 m) of unit has a stromatolite head. Unit is exposed slightly west of hill crest and forms a prominent marker bed. [387.5–398]	10.5	11.5
14	Chert-cobble conglomerate; brown to white. Unit is only locally present along strike. [386.5–387.5]	1	1

Unconformable contact placed above dolomitic and stromatolitic boundstone (referred to Lava Dam Member of Notch Peak Formation) and below chert-cobble conglomerate, zebra-rock dolomite, and lime mudstone (referred to Barn Canyon Member of House Limestone).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

NOTCH PEAK FORMATION [part; upper 386.5 ft (117.8 m) measured]
Lava Dam Member [184.5 ft (56.2 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
13	Dolomite; fine to medium crystalline, weathered surfaces show ghosts of coarse texture; dark gray on fresh surface, weathers brownish gray. Domal stromatolites [317–330] and [373–386]. Paint mark [375] is near erosional base of dolomitized grainstone forming a tidal channel that cuts out the upper stromatolite unit; this channel is ca. 30 ft (10 m) wide. Unit forms crest of hill. [317–386.5]	69.5	184.5
12	Covered. Digging reveals stromatolitic boundstone with grainstone in interstices [311]; light to medium gray; yellow argillaceous partings. [301–317]	16	115
11	Grainstone; medium gray. [300–301]	1	99
10	Lime mudstone; dark gray. [299–300]	1	98
9	Dolomite; fine to medium crystalline; dark gray on fresh surface, weathers light gray; minor chert in middle of unit; fine zebra-rock fabric (white crystalline dolomite bands in gray dolomite) in much of unit is apparently related to former planar stromatolite horizons; domal stromatolites in most of lower 20 ft (6.1 m) of unit, some stromatolites have convex-upward zebra-rock fabric. [230–299]	69	97
8	Lime mudstone; dark gray; pink burrow mottling in lower part; some beds cherty; medium to thick beds. [202–230]	28	28

OFFSET MEASURED TRAVERSE about 200 m to right (north) and down hill, following top of lime mudstone unit below. Conformable contact placed above lime mudstone and grainstone (assigned to Red Tops Member) and below lime mudstone and crystalline dolomite (assigned to Lava Dam Member).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Red Tops Member [27 ft (8.2 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
7	Lime mudstone with pink burrow mottling, interbedded with skeletal and ooid grainstone; medium to dark gray; slightly cherty; beds 6–12 in (15–30 cm). [186–202]	16	27
6	Mostly covered. Digging reveals lime mudstone, grainstone, and flat-pebble conglomerate; medium gray; mostly thin beds. [175–186]	11	11

Conformable contact placed above stromatolitic dolomite (assigned to Hellnmaria Member) and below limestone (assigned to Red Tops Member).

PAINTED NUMBERING SYSTEM CONTINUES FROM BELOW.

Hellnmaria Member [part; upper 175 ft (53.3 m) measured]

		Thickness (feet)	
Unit	*Description*	*Unit*	*Cumulative*
5	Stromatolitic dolomite; medium gray, mottled light gray. [170.5–175]	4.5	175

4	Dolomite; medium crystalline; interbedded light brown to tan and dark gray intervals, latter poorly exposed; beds 3–4 ft (0.9–1.2 m) thick. Lower light-colored interval [132–139] has possible fenestral fabric; other light-colored intervals [144–151] and [161–170.5], upper interval appears to be dolomitized ooid grainstone. Dark-colored intervals [142–144] and [151–161]; upper dark interval has domal stromatolites with interstitial oncoids. [132–170.5]	38.5	170.5
3	Dolomite; fine crystalline; dark gray, mottled light gray; medium beds. [104–132]	28	132
2	Dolomite; fine to medium crystalline, on weathered surfaces some beds show ghosts of original coarse-grained texture, some beds appear to have had fine texture prior to dolomitization, a cherty, silty unit with cross bedding at [48–51], prominent 3 in (8 cm) oncoid band [96], a 4 in (10 cm) oncoid band is left of measured traverse [100], zebra-rock fabric from dolomitized planar stromatolites [101–104], and this interval has some thrombolites surrounded by dolomitized mudstone and grainstone; medium to dark gray; up to 5 percent dark chert in some beds as stringers and nodules and replaced argillaceous partings; beds 1–3 ft (.03–0.9 m) thick. [38–104]	66	104
1	Dolomite; medium crystalline, on weathered surfaces are ghosts of original fine to coarse textures, unit has much zebra-rock fabric; light to medium gray; 5–10 percent dark chert as stringers and small irregular bodies that may be silicified burrows; medium beds. [0–38]	38	38

Underlying strata are covered by colluvium and alluvium but are exposed to the south along the same ridge.

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New Occurrence of *Aulocopella winnipegensis* Rauff, 1895, in Western Montana

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INTRODUCTION

A new specimen of the rare Ordovician sponge *Aulocopella winnipegensis* Rauff, 1895, was recently collected from road gravel in western Montana, near the community of Darby. The species has been reported previously only from the Lake Winnipeg area of Manitoba. The genus and species were first described by Rauff (1895) from material collected from the Cat Head Member of the Ordovician Red River Formation, at Cat Head, along the west central shore of Lake Winnipeg, in southern Manitoba.

Rauff (1895) designated *Aulocopella* as a subgenus of *Aulocopium,* based on the position of the point from which the skeletal structure radiates, from the base of the sponge in *Aulocopium,* but from within the lower sponge body in *Aulocopella.* Whiteaves (1897) separated the forms into two genera, a classification followed by Bassler (1915), De Laubenfels (1955), and most recently by Rigby (1971) and Rigby and Leith (1989).

The Montana specimen of the sponge was collected by Ernest Johnson from road gravel along a driveway that leads off of Gorus Lane, which connects the old Darby Road to U.S. Highway 93, 3 1/2 miles north of Darby, Montana (Fig. 1). The driveway where the sponge was found is located in the north-central part of Section 35, T. 4 N, R. 21 W. on the Darby, Montana 7 1/2-minute quadrangle. Darby is 64 miles south of Missoula in the west-central part of the state.

This is only the third specimen of the species known, and it is a more nearly complete sponge than the original type material. The Montana sponge is preserved as chalcedony, much like the type material, and appears to be a water-worn rounded clast. Because it was recovered from road gravel, the formation of its origin is unknown, although it probably came from Ordovician rocks exposed in the Bitterroot Range, to the west of the Bitterroot Valley where the sponge was found.

Class DEMOSPONGEA Sollas, 1875
Order LITHISTIDA Schmidt, 1870
Suborder ORCHOCLADINA Rauff, 1895
Family ANTHASPIDELLIDAE Miller, 1889
Genus *AULOCOPELLA* Rauff, 1895
AULOCOPELLA WINNIPEGENSIS RAUFF, 1895
Plate 1, figs. 1–3, Text-figs. 2,3

Description.—The new specimen is a rounded clast approximately 65 mm high and 95 mm in diameter that contains a gear-shaped, silicified, sponge. Its seven vertical outer blades or fins radiate from a central, moderately thin-walled, obconical spongocoel, which is now largely filled with matrix. The straight to gently curved fins are more or less uniformly spaced, as seen from above. From below, there are only six such skeletal fins developed below the spongocoel margin in the slightly uparched base, which is also partially covered by matrix. The spongocoel is 33 x 39 mm in diameter at the summit of the sponge, and is approximately 40 mm deep, with a smooth unfolded spongocoel margin and a rounded base. It is surrounded by a wall 13 to 20 mm thick in the rounded grooves between the radiating skeletal fins.

Individual fins are up to 35 mm long, as preserved, but originally probably extended an additional 10–15 mm before they were partially eroded. They are 10–12 mm wide where they are initially differentiated from the wall around the spongocoel, in the upper part of the sponge. They thicken more or less uniformly vertically and radially, to where they are up to 29 mm thick or wide at their outer preserved edges. One of the six proximal fins in the base is subdivided into two fins near the outer margin of the sponge so that seven fins show on the edge and summit of the specimen. Outer preserved edges of the fins are separated by wedge-shaped matrix fillings up to 26 mm wide. Matrix filling between blades of the subdivided fin is only to 9 mm wide, where widest at the circumference of the sponge.

Coarse excurrent canals are exposed as tubular openings in sections in weathered surfaces of the fins, and in vertical sections of the sponge interior where the sponge has been broken and the interior structure is exposed. These canals arch upward from an initial outer subvertical orientation, in lower and oldest, first-formed canals, to

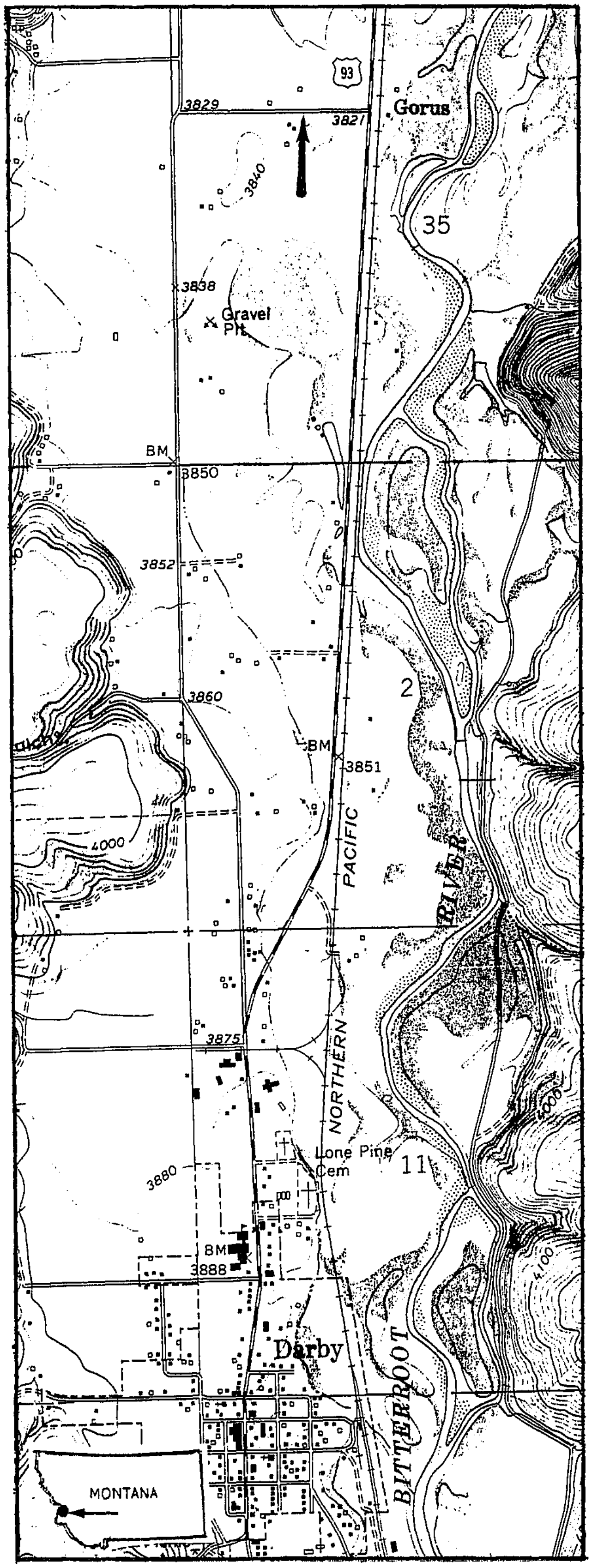


Figure 1. Index map to the locality (arrows) where the loose specimen of Aulocopella winnipegensis *RAUFF, was collected from road gravel near Gorus, north of Darby, Montana (base map, Darby 7 1/2-minute quadrangle, Montana).*

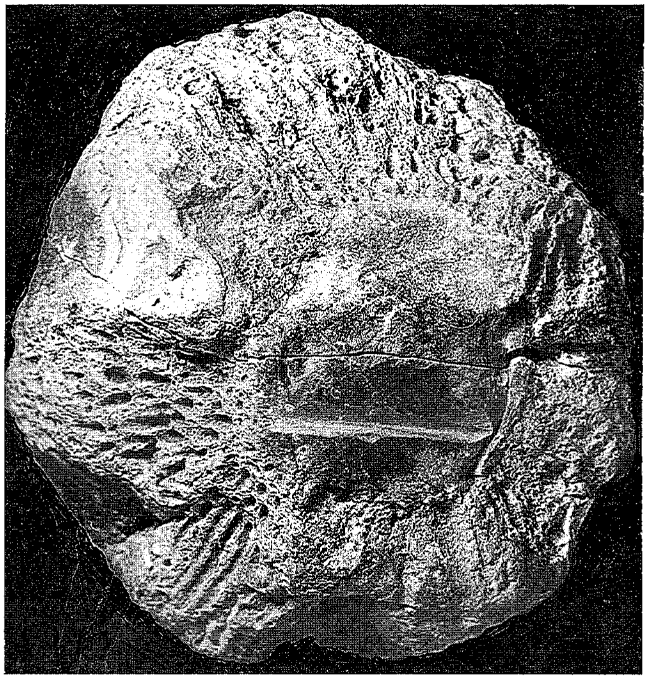
become essentially horizontal where they empty into the spongocoel. These canals are also commonly on or near the axial plane of the radiating fins, where they are vertically stacked 3–4 canals per cm, in concentric-appearing series. Similar excurrent canals occur lateral to these and gently converge upward and inward where they commonly merge with the axial series. These lateral canals are also uparched, even in upper parts of the fin, where inner ones may empty directly into the spongocoel. These excurrent canals are the coarsest in the silicified skeleton and range from 1.4 mm to 2.1 mm in diameter.

Similar canals empty vertically to subvertically into the base of the spongocoel. These 12–14 canals have their origins near the skeletal radiante, the point in the lower part of the skeleton from which the skeletal structure radiates. Canals radially from these converge toward the spongocoel at decreasing angles until those from the lower to upper parts of the spongocoel pierce the gastral wall more or less horizontally.

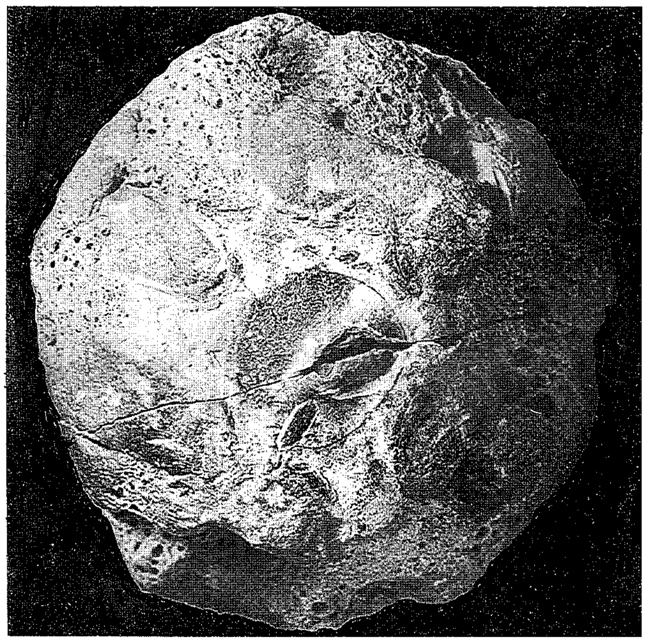
Smaller diameter incurrent canals pierce the somewhat more densely spiculed outer or dermal part of the sponge and converge toward the exhalant system. These incurrent canals range from approximately 0.9 mm to 1.1 mm in diameter. They are usually only a few mm long.

Skeletal pores within the anthaspidellid structure range up to 0.6–0.8 mm in diameter and locally interconnect openings in both the incurrent and excurrent canal systems where those canals are closely spaced.

The skeletal net is typically anthaspidellid, with prominent rodlike trabs that are cross-connected by small dendroclones in the ladder-like structures of the skeleton. Trabs radiate from a radiante that is centrally located and 8–9 mm below the base of the spongocoel and above the invaginated base of the sponge. Trabs are arranged in upward and outward curving pinnate fashion in each of the radiating fins. As in the type specimen, there are two surfaces seen in vertical sections from which the trabs diverge, one in the medial part of the spongocoel wall, and the other a more or less horizontal plate out from the radiante. Trabs in the spongocoel wall arch toward both margins and meet gastral and dermal surfaces at high angles in areas between radiating fins. Below the lower plane, trabs arch downward to meet the base of the sponge at moderately high angles. Above it they arch upward and outward to meet the outer surface of the sponge at high angles. Trabs also are arranged in pinnate fashion when viewed in horizontal sections of the radial blades. They



A



B

Figure 2. Aulocopella winnipegensis *RAUFF, 1895, USNM 480604. A. View from above shows coarsely canalled radial fins diverging from thin wall around circular spongocoel, which is filled with dark matrix, natural size. B. View from below shows lower part of radial fins diverging from circular matrix filling of invaginated base, natural size.*

arch laterally from the medial planes to meet sides of blades at high angles too.

Trabs are 0.1–0.2 mm in diameter and are spaced approximately 0.3–0.4 mm apart throughout the sponge skeleton. I-shaped dendroclones are occasionally preserved in the chalcedonic replacement. They are spaced approximately 0.1 mm apart in the ladder-like structure. Details of their ray terminations that united to produce the trabs are largely lost in the siliceous preservation.

Discussion.—Provenance of the Montana sponge is in question because it is a transported clast recovered from road gravel, and because the species has been reported previously only from the Lake Winnipeg area. It is highly unlikely, however, that it was transported as an erratic into westernmost intermontane Montana by Pleistocene continental ice. Bedrock around the Darby region and in headwaters of the Bitterroot River is dominated by igneous rocks of the Idaho Batholith and Precambrian units. There is no obvious Ordovician bedrock source. It is possible that the sponge was brought into the area by a collector and subsequently discarded.

Depository.—U. S. National Museum 480604.

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Geology of the Mc Rae Springs Quadrangle, McCone County, Northeastern Montana

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ABSTRACT

Nearly flat-lying Late Cretaceous to early Paleocene rocks, including the upper part of the Bearpaw Shale, the Fox Hills Sandstone and Hell Creek Formation, and lowermost beds of the Tullock Formation, are exposed in the Mc Rae Springs Quadrangle in McCone County, in eastern Montana. Structure in the region is simple, with beds dipping 15–30 feet per mile toward the southeast, off Bowdoin Dome, generally toward the southern Williston Basin.

The upper Bearpaw Shale is largely dark gray to gray-brown marine shales that contain common calcareous concretions with assemblages that range from the *Baculites eliasi* Zone up to the *Baculites grandis* Zone, indicating that these exposed beds are of Lower Maastrichtian age. An upper, light gray-weathering, silty, transition zone separates the darker Bearpaw beds from the overlying Fox Hills Sandstone. Only approximately 100 meters of the upper Bearpaw Shale are exposed in the quadrangle.

The Bearpaw-Fox Hills contact and the Fox Hills-Hell Creek contact were mapped at laterally persistent concretionary sandstone beds at the top and the bottom of the crossbedded, fine-grained, yellowish-gray to dusky yellow Fox Hills Sandstone. Isolated log-like to egg-shaped concretions of limonite-cemented sandstone occur throughout the formation and characterize the formation where it is widely exposed east and west of Montana State Highway 24, which crosses diagonally through the southwestern part of the quadrangle. The Fox Hills Sandstone accumulated in marginal marine to tidal environments. It is of middle Maastrichtian age, and is approximately 40 meters thick in this part of Montana.

The Late Maastrichtian Hell Creek Formation is widely exposed in the southern part of the quadrangle and consists of interbedded, thin, sheet-like sandstones, less extensive lenticular sandstones, and greenish-gray siltstones and mudstones, thin carbonaceous shales, and thin coals. This dinosaur-bearing formation is approximately 62 meters thick where complete sections are exposed in the southeastern part of the quadrangle.

Youngest bedrock units preserved in the quadrangle are basal beds of the lower Paleocene Tullock Formation. They are exposed in isolated outliers in the southeastern corner of the quadrangle and include approximately 20 meters of beds from the formational boundary Z-Coal up to the X-Coal, in units of interbedded shales, claystones, and sandstones, with thin bituminous coals. They are all in the lower part of the Nelson Ranch Member of the Tullock Formation.

Uplands throughout the region are commonly blanketed by a thin veneer of Pleistocene terrace gravels that may locally include glacial erratics over 1 meter in diameter. The terrace gravels characteristically include red and green quartzite, chert, and quartz fragments, and pebbles and cobbles of metamorphic and igneous rocks. Erratics are characteristically coarse-grained igneous and high-rank metamorphic rocks, like

those exposed in the Canadian Shield. The terrace gravels are of lithologies like those exposed in the Belt Mountains to the west, but also may have had a Canadian Shield source.

Flat valley bottoms are blanketed by Quaternary alluvium, locally showing terraces and entrenchment of the streams in the valleys, adjusted to elevations of the Missouri River to the north and west.

INTRODUCTION

LOCATION

The Mc Rae Springs Quadrangle is located in northeastern Montana, southeast of Fort Peck, and east of the Fort Peck Reservoir in western McCone County (Figure 1). The central part of the quadrangle lies approximately 20 miles (30 kilometers) southeast of Fort Peck, and 100 miles (165 kilometers) north of Miles City, Montana. The community of Fort Peck is approximately 14 miles (22 kilometers) southeast of Glasgow, the major shopping center for the region and the closest major source for supplies.'

The quadrangle (Figure 1) lies between 47° 52′ 30″ and 48° 00′ North Latitude and 106° 07′ 30″ to 115° 15′ West Longitude. Montana State Highway 24 crosses diagonally through the southwestern part of the quadrangle. It connects southward to Montana State Highway 200, one of the major east-west highways through the central part of the state, and northward to U.S. Highway 87, which is a major east-west highway across the northern part of the state.

The quadrangle has only moderately low relief (Plate 1), with somewhat step-like topography where "risers" are produced by the relatively resistant Upper Cretaceous Fox Hills Sandstone and somewhat laterally persistent, resistant, sandstones within the Hell Creek Formation (Table 1). Highest relief in the area is in the southeastern part of the quadrangle, where major badland bluffs generally formed on the northern sides of ridges, which rise boldly through upper Hell Creek rocks to small outliers of Tertiary Tullock Formation (Figure 2). The broader steps or slopes between are carved, in large part, on the nonresistant Bearpaw Shale, the oldest rocks exposed in the region, and the more easily eroded mudstones and siltstones of the Hell Creek Formation.

Much of the southwestern half of the region is drained by Bear Creek (Figure 3), which empties westward into Bear Creek Bay, one of the bays along the east shore of Fort Peck Reservoir. The northeastern part drains northeastward from a divide, approximately at Montana Highway 24, into the West Fork of Hungry Creek, Cheer Creek and upper tributaries of Lost Creek, which drains northeastward into Hungry Creek, and ultimately northward into the Missouri River below the Fort Peck Dam.

Elevation in the region ranges from approximately 2100 feet near the Missouri River valley in the northeastern part of the quadrangle, to slightly over 2700 feet in high knobs in the southeastern part. Much of the quadrangle is at an elevation of approximately 2500 feet. Major drainages, like Bear Creek, Hungry Creek, and Lost Creek have flat alluvial plains into which the creeks may be locally steeply entrenched. These flats were locally tilled for grain and forage crops by the local ranchers.

Numerous springs occur in the region, generally associated with thicker sandstone beds that overly impervious clays in the lower part of the Hell Creek Formation or where the Fox Hills Sandstone rests on the Bearpaw Shale (Figure 4). Most of these springs are of small production, but are important elements in the agricultural economy of the grassy prairies.

ACCESS

A moderately intricate net of rustic ranch roads interconnect to somewhat more well defined and traveled county roads, which show on the topographic map of the quadrangle as solid double-lined roads. The ranch roads, developed for local use, provide moderate ready access to the back country of the quadrangle. A few original homesteader log cabins, and second generation cabins, occur throughout the area. However, there are no full time residents within the quadrangle, but rusting remnants of farm machinery are found near many of the springs where isolated ranch homes were early established as homestead bases in the grassy prairies.

FIELDWORK

Field work, mapping, and stratigraphic studies were done during July of 1997, August, 1999, and in June, 2000 as part of continuing investigations of Cretaceous-Tertiary rocks and faunas by Earthwatch and subsequent University of Notre Dame-sponsored research programs, directed by J. K. Rigby Jr. Geologic contacts and other key units were plotted on the 1:24000 topographic maps of the Mc Rae Springs Quadrangle. Final compilation of geologic contacts on a green-line mylar photocopy of the topographic base was completed by tracing from paper copies of the map. Formation contacts and key beds were traced in the field, often using distinctive topographic expressions of the contrasting shale and sandstone sequences or of the coal and bentonitic mudstone sequences throughout the area. A few contacts are locally shown as dashed lines where they were inferred to cross grassland prairies devoid of exposures, or in a few small areas not personally observed

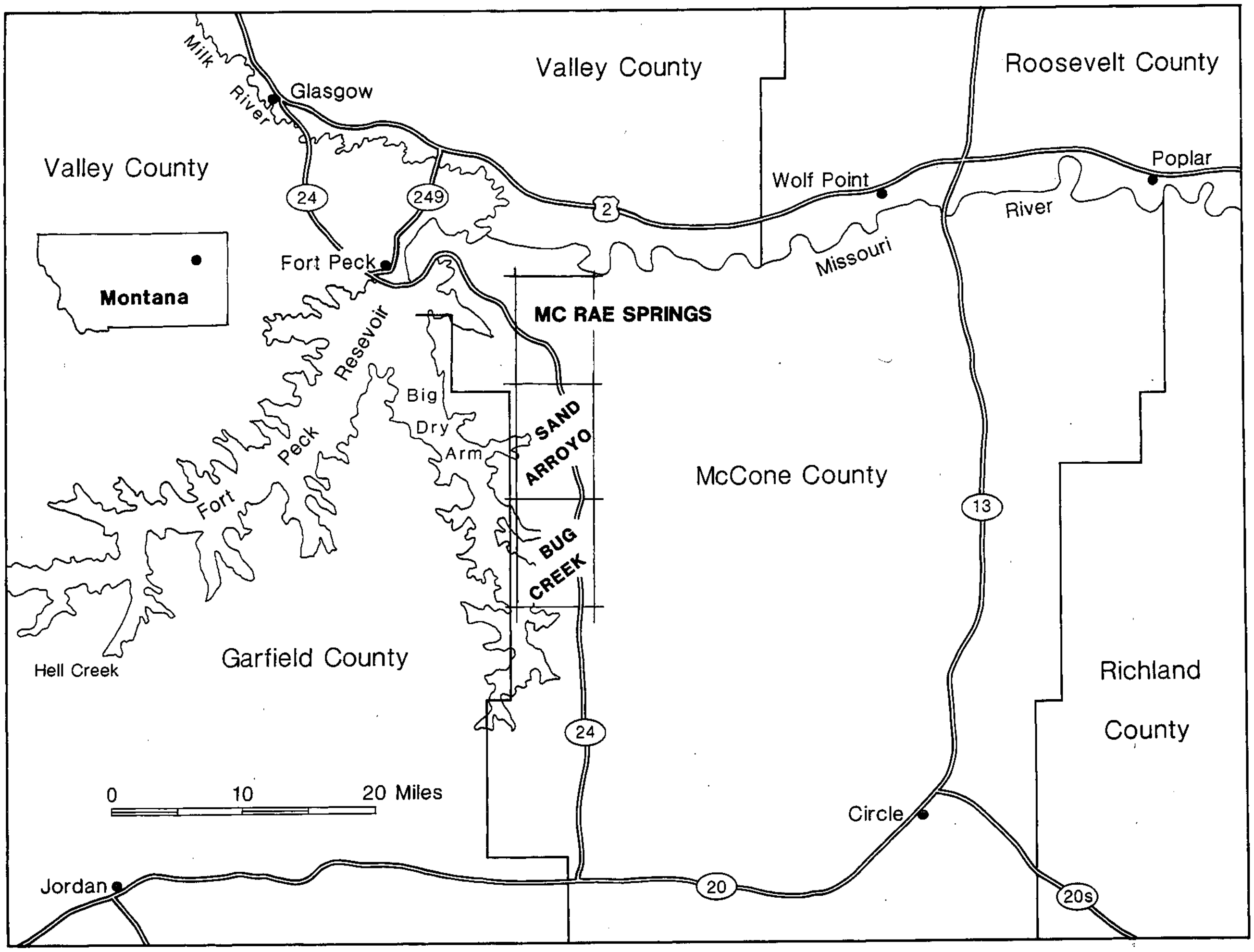


Figure 1. Index map to the Mc Rae Springs Quadrangle, in northwestern McCone County, in northeastern Montana.

in the field by one of us. Stratigraphic sections were measured with the Jacob staff, generally to 0.1 meter accuracy. Xerox copies of aerial photographs of the quadrangle were made available by the regional office of the Agriculture Department Conservation Service in Circle, Montana. Aerial photographs, however, proved less valuable for mapping in the essentially flat-lying beds than the topographic map.

STRATIGRAPHY

Cretaceous System

Montana Group

Bearpaw Shale

Introduction.—Oldest rocks exposed in the Mc Rae Springs Quadrangle (Table 1) are included in the Cretaceous Bearpaw Shale. The dark gray to brownish-gray Bearpaw Shale is part of a widespread Upper Cretaceous clastic sequence that marked the final regression of the Western Interior sea from the Alberta-Saskatchewan-Montana region, and the next to the last major marine transgression from the interior of North America and the Rocky Mountain region (Sloan, 1987). The formation is extensively exposed in the Fort Peck area, in bluffs along the south side of the Missouri River, and in drainages leading into the northeastern part of the Mc Rae Springs Quadrangle (Figure 5). Lower beds and base of the formation are not exposed in the Mc Rae Springs Quadrangle, but the dark shale does crop out beneath the concretionary Fox Hills Sandstone across much of the quadrangle.

The Bearpaw Shale was originally defined by Hatcher and Stanton (1903, p. 211–212) as the concretion-bearing, dark clay shale of marine origin that conformably overlies the Judith River beds and underlies the Fox Hills Sandstone and equivalent units in northern and eastern Montana. The formation has its type locality in the Bearpaw Mountains

Table 1. Stratigraphic sequence of rock units exposed in the Mc Rae Springs Quadrangle, McCone County, northeastern Montana.

AGE			ROCK UNITS	
Quaternary			Recent alluvium and terrace deposits Pleistocene glacial outwash and debris	
Tertiary	Paleocene		Tullock Formation	X-coal Z-Coal
Cretaceous	Maestrichtian	Late Medial	Hell Creek Formation	upper Barbeque sandstone middle Gunsight sandstone lower Null coal lower
		Early	Fox Hills Sandstone	
			Bearpaw Shale	base not exposed

of central Montana, but has been recognized extensively in northern, eastern, and southern Montana and in the Elk Basin region of southern Alberta and northern Montana.

Collier and Knecktel (1939, p. 9) observed that the upper contact with the Fox Hills Sandstone is gradational and marked by a general increase in sand upward within the transition zone. They noted that the Bearpaw Shale is approximately 300 meters thick in eastern Montana. Later, Jensen and Varnes (1964, p. F5) observed that in the Fort Peck area the Bearpaw Shale area is 348 meters thick. In the Mc Rae Springs Quadrangle only the upper approximately 100 meters of the formation is exposed in the northeastern part of the quadrangle and even less than that in southwestern areas.

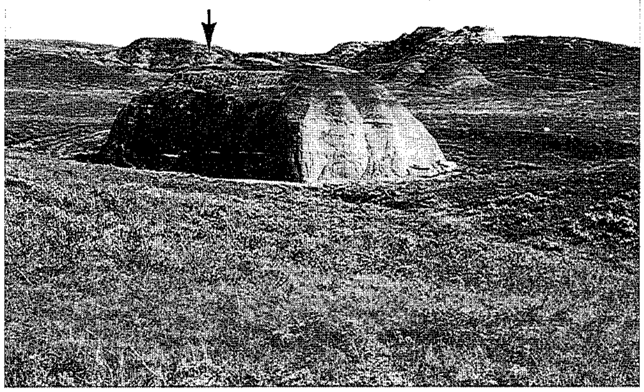


Figure 2. View southeastward to darkly shadowed Combine Butte, in the central part of Sec. 22, T. 25 N., R. 43 E., which is held up by lower massive sandstones and carbonaceous bentonitic mudstones of the lower Hell Creek beds. High points in the background are capped by lower beds of the Tullock Formation and extend up from the Z-Coal indicated by the arrow in the left center. Those outcrops are in the northern part of Section 26, on the divide between Widow Coulee, in the foreground, and Bear Creek to the south of the ridge.

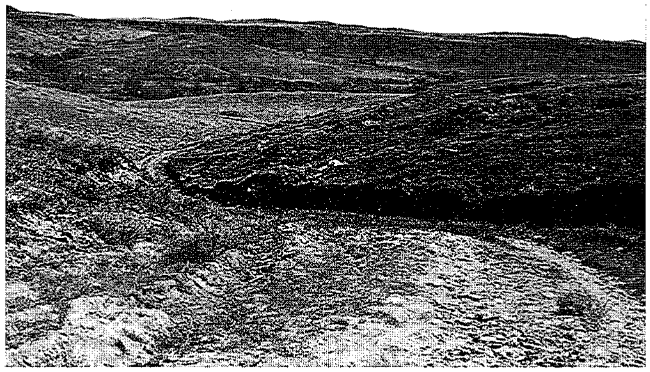


Figure 3. View northward along the ranch road across Bear Creek, from the center of Sec. 24, T. 25 N., R. 42 E. Bear Creek is marked by the line of trees in the valley floor. Costello Coulee is the tree-lined tributary to Bear Creek on the left. Concretionary Fox Hills Sandstone is exposed in the road and in rough exposures on either side of the road in the foreground and capping the hills beyond Bear Creek. High hills on the skyline are near Montana State Highway 24 and are held up by lower beds of the Hell Creek Formation. Coal Hill is the high point on the skyline near the left margin.

Lovering and others (1932, p. 702–703) also observed that the contact between the Bearpaw Shale and overlying Fox Hills Sandstone is somewhat gradational. They defined the top of the Bearpaw Shale at the base of the dominant buff and brown sandstones and at the top of the gray marine clay shale and sandy shales. We have generally utilized that same boundary and have mapped the contact at the base of the lowest ledge-forming, concretionary yellow-gray sandstones of the Fox Hills Sandstone throughout the quadrangle.

In the eastern part of the quadrangle there is a transitional unit that appears very light yellow gray beneath the concretionary Fox Hill beds and above the darker marine clay shales that are more characteristic of the lower part of the formation (Figure 6). That transitional sequence is approximately 12 meters thick, at its thickest, where extensively exposed in section 3, T. 25 N., R. 43 E., beneath outliers of the basal Fox Hills Sandstone in hills between the junction of Cheer Creek and the West Fork of Hungry Creek. It is Unit 4 of the Poplar Anticline section of Reiskind (1975), and may be a facies equivalent to the Colgate Member of the Fox Hills Formation as exposed at Glendive, Montana (R. Sloan, personal communication, 2001)

The light yellow-gray transitional unit is also exposed in promontories to the west, in headwaters of the West Fork of Hungry Creek, but it is thinner there. The light gray transition is not exposed in the limited northwesternmost or southwesternmost, commonly grass-covered, outcrops in the quadrangle.

Outcrop Area and Topographic Expression.—Throughout the area underlain by the Bearpaw Shale, the formation has been carved into intricate badlands and irregular grassy prairies. No well exposed complete section of the beds occurs in the quadrangle, but the dark shale crops out in numerous low escarpments, meander bends, and barren hills throughout the area. The formation is the principal outcrop unit in the northeastern part of the quadrangle, but is also moderately well exposed in the southwestern part of the quadrangle along Bear Creek, east of Bear Creek Bay in the Fort Peck Reservoir area. Because of the ease of erosion of the shale, it tends to form smooth hills and low grass-covered slopes, except where exposed in limited badlands, particularly in the northeastern part of the quadrangle. Only the upper 20–25 meters of the formation is exposed in lower Bear Creek bluffs beneath the concretionary Fox Hills Sandstone in the southwestern part of the quadrangle. Those exposures extend up drainages to small springs or seeps that form at the top of the impervious Bearpaw Shale and base of the porous Fox Hills Sandstone in many of the tributaries. Similar springs are developed in headwaters of many of the small gullies that drain the northeastern part of the

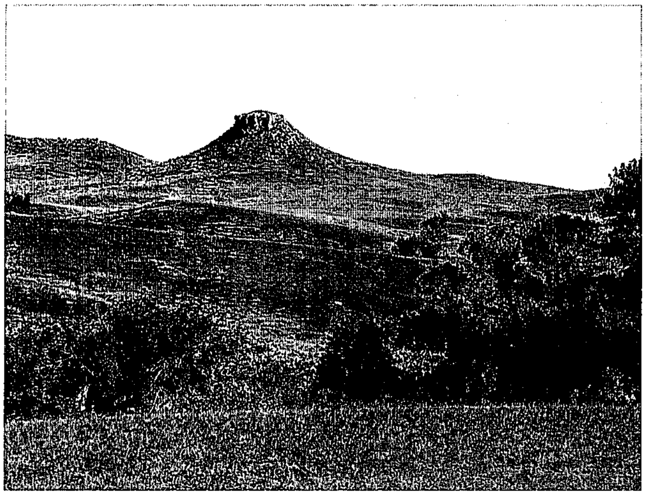


Figure 4. View northward to Caprock Butte, in the north-central part of Sec. 6, T. 25 N., R. 43 E., looking across the spring-watered, tree-lined, headwaters of Bridge Coulee in the central part of Sec. 26. Caprock Butte is held up by the basal Hell Creek Sandstones above the more slope-forming Fox Hills Sandstone. Springs in the foreground are characteristic contact springs formed at the base of the porous sandstones of the Fox Hills Sandstone and the top of the impervious Bearpaw Shale.

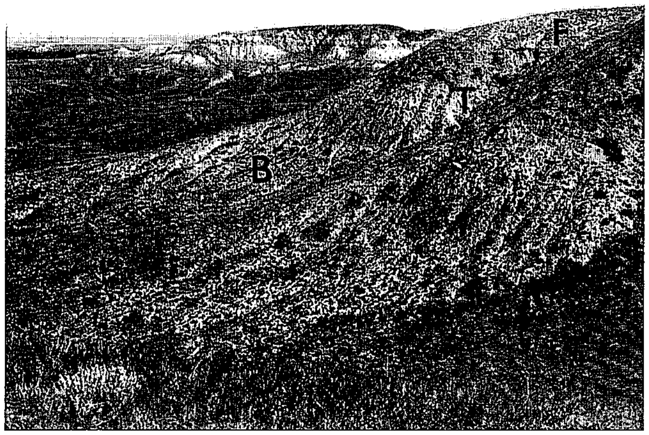


Figure 5. View northward from the east-central part of Sec. 21, T. 26 N., R. 43 E., showing the upper part of the dark Bearpaw Shale in the low outcrops on the left (B), overlain by the light shaly transition zone (T) prominently exposed in the central part of the photograph. These light slope-forming beds are overlain by the Fox Hills Sandstone (F) that produces the concretionary low ledgy zone in the foreground and caps the promontory and ridge in the near distance. The dark tree-covered valley of the Missouri River, in the background, is beyond the northern edge of the quadrangle.

quadrangle, as well. Mc Rae Springs, for example, is a contact spring near the top of the Bearpaw Shale and base of the Fox Hills Sandstone. These springs are important economic resources in the grassland-prairie ranching economy of the region.

Best exposures of the Bearpaw Shale are perhaps those in tributaries to Hungry Creek (Figure 7) and Lost Creek in the north-central part of the quadrangle, generally beneath the Fox Hills outlier south and west of Bone Bluff, in the northeastern part of Section 21 T. 26 N., R. 43 E. (Figure 5). This is also the thickest sequence of Bearpaw Shale exposed in the quadrangle.

Lithology.—The Bearpaw Shale is a moderately uniform, dark gray to medium gray, clay shale throughout the quadrangle. Several horizons of moderately large, fossiliferous, calcareous concretions occur in isolated exposures throughout the outcrop band, but are particularly prominent in outcrops east of the reservoir along Cheer Creek, in the western part of Section 2, T. 25 N., R. 43 E., and along the access road to Bone Bluff triangulation station in the north-central part of Section 22, T. 26 N., R. 43 E. The concretions are commonly dark gray, micritic-appearing, limestone. Most are septarian and weather into angular fragments on the slopes. Concretions range up to approximately 1 meter in diameter as flattened obloids, but more common concretions are only 0.1–0.2 meters in diameter or smaller. Many of these concretions contain abundant ammonites and bivalves, but the fossils are commonly difficult to collect because the concretions shatter in such irregular fashion. Reiskind (1975, Figure 2) reported that these concretion layers range upward from the *Hopoloparia* lobster concretionary layer, through the *Baculites eliasi* concretionary layer, the *Baculites baculus* concretionary layer, the *Protocardia* concretionary layer, and the *Baculites grandis* concretionary layer in the Poplar Anticline area, which would include part of the McRae Springs quadrangle. Slopes are locally littered with angular fragments of the concretions and are locally associated with obvious residual pebbles from overlying terrace gravels of Quaternary age.

Scattered small selenite gypsum crystals occur throughout the sequence, but are most common in upper clay shales beneath the silty transition beds near the top of the formation.

The upper few meters of the Bearpaw Shale in the transition beds are consistently lighter gray to medium gray-brown and weather very light-gray to light yellowish-gray. The transition unit forms a prominent distinct light band visible even from a distance in northeastern parts of the quadrangle. Yellowish-gray silty sandstone occurs interbedded with clay shales of lighter gray tones in the upper part in the gradational sequence. These upper beds lack concretions and commonly form light slopes in the contact zone.

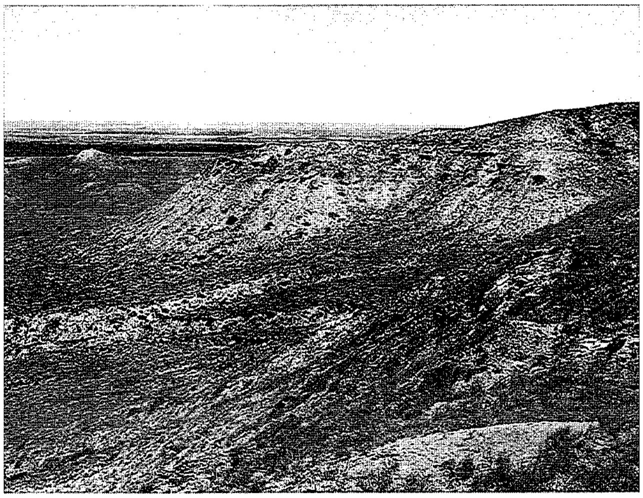


Figure 6. View northward from the south-central part of Sec. 21, T. 26 N., R. 43 E., showing the light slope formed on the transition beds at the top of the Bearpaw Shale largely obscured by debris, in the intermediate distance, but forming prominent light slope zones below the darker, overlying, ledgy Fox Hills Sandstone that erodes to form the rough exposures on the right and caps the outlier in the distance. The Missouri River valley in the background is indicated by the dark trees on the left.

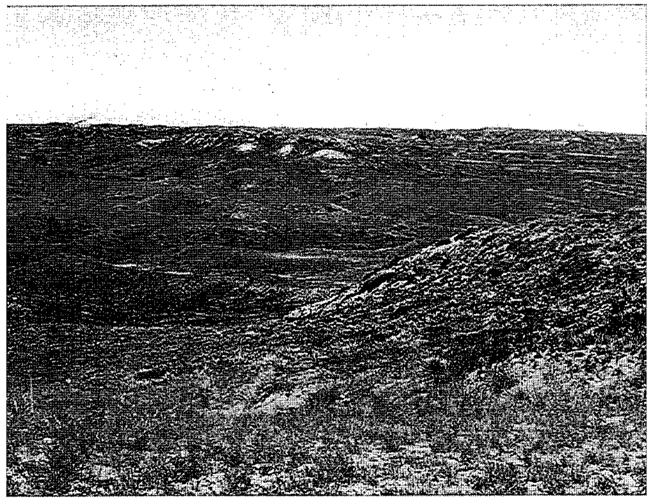


Figure 7. View toward the northwest over Hungry Creek Pass, carved in poor exposures of the upper Bearpaw Shale, to an outlier of dark lower Fox Hills Sandstone above the light transition beds in the distance, in the west-central part of Sec. 29, T. 26 N., R. 43 E., as seen from the southeastern part of Sec. 29. Concretionary beds in the foreground are of the lower part of the Fox Hills Sandstone, above beds of the transition zone.

Fossils and Age.—Marine fossils are moderately common throughout the exposed Bearpaw sequence, but all of the fossils observed by us occurred in concretions, where on many of the ammonites and on some of the *Inoceramus* oysters the original mother-of-pearl nacreous layer is still intact. All of the ammonites recovered by us are *Baculites grandis* from the upper part of the formation. These beds are of lower Maastrichtian age. Reiskind (1975) reported the occurrence of fossils characteristic of the older *Baculites eliasi* and *Baculites baculus* Zones in lower Bearpaw Shale beds in the Poplar Anticline area, which includes the northeastern part of the Mc Rae Springs quadrangle. Obradovich and Cobban (1975, p. 36) put the base of the Maastrichtian two ammonite zones below the *Baculites eliasi* Zone. Thus the Bearpaw Shale beds exposed in the Mc Rae Springs quadrangle are all of lower Maastrichtian age. They are laterally continuous and part of the major fine-grained terrigenous clastic sequence equal to the upper Pierre Shale of the Dakotas (Cobban and Reeside, 1952).

Thickness.—Full thickness of the Bearpaw Shale is not exposed in the Mc Rae Springs Quadrangle. Thickest exposed sections there are approximately 100 meters (300 feet) thick, and are exposed above the alluvial fill of the valleys and below the overlying Fox Hills Sandstone in Sections 21, 22, 27, and 28 of T. 26 N., R. 43 E., in the vicinity of Bone Bluff triangulation station, and to the west and southeast.

Fox Hills Sandstone (Montana Group)

Introduction.—Meek and Hayden (1862, p. 419, 427) named the Upper Cretaceous Fox Hills Sandstone for yellowish gray and gray sandstone and sandy clays that occur above the dark gray shales, which are now known as the Pierre Shale in the Dakotas and the Bearpaw Shale in eastern and north-central Montana, and below the gray non-marine clays and yellowish sandstones of the "Fort Union Formation," the lower part of which is now included in the Hell Creek Formation. They named the formation for exposures on Fox Ridge in northwestern South Dakota, 550 miles (884 kilometers) southeast of Fort Peck. The name, however, has been widely used throughout the northern Rocky Mountains and the northern plains for a regressive, marginal marine, sandstone at the western margin of the Cretaceous Interior Seaway.

Lovering and others (1932, p. 702–703) defined the base of the formation as a transition from the gray marine clays and clay shales of the Pierre Formation, below the base of the dominant yellowish-gray concretionary sandstones of the Fox Hills Sandstone. They placed the top of the Fox Hill Sandstone where that lithologic unit grades upward into predominantly fresh or brackish water, lighter gray-brown, sandstones and bentonitic claystones that are occasionally accompanied by coal or lignitic shale of the Hell Creek Formation. Thom and Dobbin (1924, p. 490) assigned the upper very light-gray sandstone to the Colgate Sandstone, a member of the Fox Hills Formation.

Collier and Knechtel (1939, p. 9–10) followed that usage, as did Brown (1914), who recognized the Colgate member of the Fox Hills Sandstone and an underlying marine Fox Hills Sandstone as an unnamed member. Stevenson (1947) concluded that the formation in the McIntosh quadrangle in South Dakota consists in ascending order of the Trail City, Timber Lake, Bullhead, and Colgate Members. Waage (1961) studied the Fox Hills Formation in the type area and continued the subdivision of the formation into several members.

Collier and Knechtel (1939, p. 10), in their study of the coal resources of McCone County, made no attempt to separate members of the Fox Hills Sandstone, although they did suggest that the Colgate Member is present in McCone County. Jensen and Varnes (1964, p. F11–F16) later described the geology of the Fort Peck area and concluded that the light gray sandstone of the Colgate Member is not distinguishable in northern McCone County, northeast of Hell Creek, which is approximately 40 miles southwest of the Mc Rae Springs area. Bell (1965) in his regional study concluded that the Bullhead Member of Waage is the upper fine-grained sandstone and interbedded gray sandy shale that he could recognize through much of McCone County. Bell (1965) reported that the member may be as much as 10 meters thick in the Sand Arroyo Quadrangle, just south of the Mc Rae Springs area.

We have not differentiated members within the Fox Hills Formation in the McRae Springs area, but have mapped the formation as a single unit.

Outcrop Area and Topographic Expression.—The Fox Hills Sandstone is broadly exposed in upper tributaries and in the drainage divide region between Bear Creek in the southwestern, and Hungry Creek and Lost Creek in the northeastern parts of the quadrangle (Figures 6, 7). Fox Hills beds cap the ridges extending out from the drainage divide. The formation is the most areal extensively exposed unit in the quadrangle. Exposures extend from the high outlier of the formation at Bone Bluff, southeastward along the divide between Lost Creek and the West Fork of Hungry Creek, to the extensive outcrops in parallel bands northeast and southwest of the drainage divide through the central part of the quadrangle.

Although outcrop areas are extensive and the formation is widespread in the quadrangle, no complete sections of the formation are exposed. Rather, laterally continuous ledges of sandstone concretions form lower and upper outcrops (Figures 5–7) and are separated by a broad slope zone of poor exposures. Sandstone units crop out discontinuously throughout the region where blowouts, slumps, or steeply undercut banks of drainages locally expose the soft, nearly unconsolidated sedimentary units typical of the formation. Excellent exposures of the upper part of the unit, however, occur in road cuts along Montana State Highway 24, in the northern part of Section 12, T. 23 N., R. 42 E., in the western part of the quadrangle, and in road cuts along the highway northwestward beyond the quadrangle. There characteristic limonite-cemented calcareous concretions, which as so common in both the upper and lower ledgy parts of the formation, occur in the soft, yellow-gray to orange-gray-weathering, cross-bedded sandstones. Elsewhere, similar exposures occur as isolated barren lands or as slumped-appearing, sprawling conifer-covered, outcrops on northern slopes in some of the steeper topography. Lower cross-bedded concretionary sandstones are also well exposed in road cuts along Montana State Highway 24, immediately northwest of the quadrangle.

Contacts.—Basal and upper contacts of the Fox Hills Sandstone have been drawn at the base of the lowermost and at the top of the uppermost, cross-bedded, concretionary, ledge-forming sandstones of the formation.

Lithology.—The Fox Hills Sandstone in the Mc Rae Springs area consists of upper and lower ledge-forming sandstone units, 10 m or more thick, separated by a middle more slope-forming unit of less well-cemented sandstone and minor interbedded gray mudstone. Sandstones of the formation are commonly only moderately cemented, but consistently crossbedded, very fine-grained to fine-grained, and medium to well sorted. They are generally yellowish-gray to dusky yellow and weather yellowish-gray in irregularly, poorly cemented units. In more resistant concretionary units, the sandstone may be dusky yellow to grayish-orange, or dark yellowish-orange. Most ledgy exposures of the upper and lower units appear massive, without shaly partings, although all are irregularly crossbedded, moderately to well-sorted sandstone. Small lenses of rip-up clasts of lighter gray siltstones or claystones occur between crossbed sets or as platy elements in layers on cross-bed surfaces throughout the formation, and show particularly well in highway cuts in the western part of the quadrangle where details of sedimentary structure are best displayed.

Large egg-shaped to log-like concretions occur throughout the area and may occur in distinct layers, as well shown in road cuts of the upper sandstone in Section 12, T. 25 N., R. 42 E., Montana Highway 24. The concretionary resistant units (Figure 6) were noted by Jensen and Varnes (1964, p. 16), who observed that they "form the intricately eroded rimrock that is a conspicuous feature of the Fox Hills Sandstone in this area." These concretions are commonly 2 or 3 meters long and a meter or less thick, or in diameter, although some 10–15 m long are well exposed in highway road cuts. They have dense limonite-cemented cores, but less cemented spheroidal layered weathering in the outer yellowish-gray rinds, which are also calcareous. Elongate concretions are commonly parallel to crossbed directions in the direction of paleoflow, although those in the upper part of the formation exposed in the north-central part of Section 12, are locally essentially at right angles to crossbed directions.

Crossbed sets or troughs within sandstones of the formation are commonly one meter or less high, and generally indicate sediment transport toward the south and east. However, in excellent road cut exposures in both the upper and lower sandstones along Montana Highway 24, opposed northeast and southwest transport directions in trough cross-bed sets indicate deposition under tidal conditions.

Channel fills or trough cross-bed sets in the upper sandstone are commonly only 2 m or less wide and to 0.5 m deep. Most of the more planar cross-bed sets are in units 30–40 cm thick in the same area. Stratification is often clearly defined by aligned flat pebbles or carbonate- or limonite-cemented concretions.

Details of the internal structure of the lower sandstone are evident in road cut exposures at approximately mile 46.3 on Montana Highway 24, a short distance beyond the quadrangle boundary to the northwest. The lower part of that exposure is of poorly cemented sandstone with low-angle cross-stratification indicating current flow toward the east in nearly every set. These sets range from 10 cm up to 30 cm thick and are composed of only moderately sorted sand in which ferromagnesian minerals and black and green chert are common. Up section, cross-bed sets are thicker and also indicate dominant flow toward the east or northeast. A few trough deposits are preserved and also show currents flowed to the northeast. This relatively uniform section is cut by a major channel approximately 3 m deep. That channel is filled with numerous small cross-bed sets, each only a few cm thick and each showing direction of transport of the more quartzose sand toward the northeast.

A small silicified and limonite-stained log, approximately 20 cm in diameter and one-half meter long, was found in the channel fill. It was lying parallel to stratification on one of the thicker cross-bed sets. Other silicified fragments, limonite concretions, and limonite-replaced rip-up clasts also occur in the same section.

Some sandstones, where well exposed, show trains of crossbed sets, like those described by Rigby and Rigby (1990) from the Annabelle Beach region in the Bug Creek Quadrangle to the south. Some show remarkable uniformity in rhythmically bedded crossbed where laminae are 1 to 2 centimeters thick in the steeply sloping, laterally stacked, barchanoid linear structures. There are no major exposures of bedding type outcrops in the Mc Rae Springs quadrangle that would allow studies like those done in the Annabelle Beach region along the shore of Fort Peck Reservoir (Rigby and Rigby, 1990).

The middle part of the formation is poorly exposed over much of the quadrangle, probably because it is composed of virtually uncemented light gray to yellow-gray sandstone and interlensing dark to medium gray bentonitic mudstone.

Age.—Gill and Cobban (1973) concluded that the Fox Hills Sandstone in central Montana is probably of lower Maastrichtian age. It is probably of middle Maastrichtian age (*Baculites grandis* Zone or younger) in this part of Montana (Sloan and others, 1986). We collected no fossils from the Fox Hills Sandstone in the Mc Rae Springs area, other than fragments of a silicified log, so we cannot add additional information on the age of the unit.

Thickness.—The Fox Hills Sandstone, as mapped, is 35–40 meters thick in the Bear Creek area in the southwestern part of the quadrangle. It is approximately 40 meters thick in the Mc Rae Springs area in the northwestern part of the quadrangle and in the Alexander Springs area in the east-central part of the quadrangle. It appears to be relatively uniform in thickness across the quadrangle, as mapped. If the additional 10–12 meters of transition beds included in the upper Bearpaw Shale, in the northeastern part of the quadrangle, were added the formation would thicken in that direction.

Post-Montana Group Formations

Hell Creek Formation

Introduction.—Brown (1907, p. 829–835) differentiated the Hell Creek beds as fossiliferous freshwater deposits that occur above the Fox Hills Sandstone in the western part of then Dawson County, now in part Garfield County, Montana. Hell Creek, in Garfield County, is the type locality for the formation where it is extensively exposed, there and on nearby tributaries of the Missouri River.

Later, Collier and Knechtel (1939, p.10–11) in their McCone County report discussed the Hell Creek Member of the Lance Formation where it is exposed along Dry Creek. They included the Lance Formation in the Eocene (?) series, but observed in a foot note, that after the report was written, the Hell Creek and Tullock Members, as they recognized them, were raised to formation rank, and the U.S. Geological Survey put the Hell Creek beds in the Cretaceous and the overlying Tullock Formation in the Cretaceous or Eocene. Frye (1969, p. 3–16) summarized development of stratigraphic nomenclature of the Hell Creek beds.

Brown (1938) placed the Cretaceous-Tertiary boundary between the Hell Creek and Fort Union Tullock beds at the approximate stratigraphic position where it is placed today, based on his work with the fossil plants. Discussion of the exact stratigraphic position of the boundary continued through the 1960's to the 1980's, with renewed emphasis following the debate on a possible catastrophic extinction of the dinosaurs related to a meteorite impact. The iridium anomaly layer, presumably from that supposed impact, has been mapped near the traditional Cretaceous-Tertiary boundary, in areas to the south. It is a thin carbonaceous sandstone and clay that shows marked enrichment in iridium (Nichols and others, 1986; Orth and others, 1981; Orth *in* Sloan and others, 1986; Smit and others, 1987; Tschudy and others, 1984; and Rigby and Rigby, 1990). Those boundary rocks are exposed on isolated outliers in the southeastern part of the quadrangle, a few meters below the formational Z-Coal, that we have mapped as the base of the Tullock Formation and top of the Hell Creek Formation, which is the Z-Coal of Collier and Knechtel (1939).

Contacts.—The base of the Hell Creek Formation has been mapped at the base of the generally muddy or clay-rich beds of the formation, or below a non-resistant light green-gray sandstone that overlies the ledge-forming, yellow-gray, concretionary sandstones of the Fox Hills Formation (Figure 2). The formational contact at the top of the Hell Creek Formation and base of the Tullock Formation has been mapped at the formational Z-Coal (Figure 2), as utilized by Rigby and Rigby (1990) in the Bug Creek and Sand Arroyo quadrangles to the south. It is the lowest prominent coal zone in the contact zone, although two or three additional carbonaceous shales, or very thin coals, appear in the same general unit. We have selected the most prominent and thickest, most continuous, one as the boundary Z-Coal. This may result in a few meters of Tertiary beds actually being included within the Hell Creek Formation as we have mapped it, following along the pattern of Rigby and Rigby (1990). The lower carbonaceous shale and thin streaky bituminous shale of the lower Z-Coal associated with the iridium event has been recognized in good exposures. A shift of the contact to this less certainly identifiable and less evident topographic break would result in only minor differences from that shown on the accompanying geologic map (Plate 1).

The Hell Creek Formation has been subdivided into informal members, with lower and middle members separated by the moderately persistent Gunsight Butte sandstone, and middle and upper members separated by the similarly moderately persistent Barbeque sandstone (Plate 1).

Outcrop Area.—The Hell Creek Formation is broadly exposed in the south half of the quadrangle (Plate 1). It generally forms uplands along the divide between Bear Creek, in the southwestern part of the quadrangle, and the major drainages of Lost Creek and Hungry Creek in the northeastern part of the quadrangle. The formation is also exposed locally in badland exposures in the southern part of the map (Figure 8), generally on the divide between Bear Creek and headwaters of streams draining southward into Sand Arroyo. Most extensive exposures of the formation are in the bold badland bluffs beneath outliers of the Tullock Formation in the northern part of Sections 26 and 27 of T. 25 N., R. 43 E., in hills north of the headwaters of Bear Creek and east of Montana Highway 24 (Figures 2, 9). Dinosaur-bearing sandstones (Roberts, 1998) and underlying mudstone and claystone beds are also well exposed in the west-central part of Section 22, T. 25 N., R. 43 E. (Figure 10).

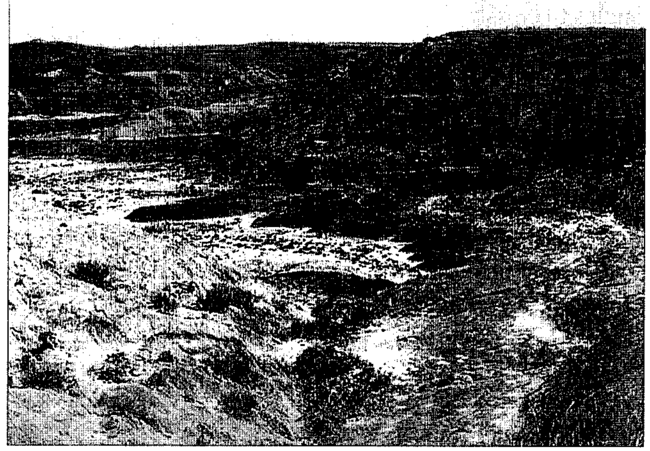


Figure 8. Badland exposures of the lower Hell Creek Formation Nelson Ranch Member, as seen eastward from the southeast corner of Sec. 30, T. 25 N., R. 43 E. The Gunsight Butte sandstone, or the Number 3 Sandstone as that term was utilized in the San Arroyo Quadrangle to the south (Rigby and Rigby, 1990), caps the near exposures. Bentonitic claystones and mudstones form the light outcrops in the foreground.

The Hell Creek Formation commonly forms flat-topped uplands or holds up small buttes, such as Gunsight Butte, in the southeast part of Section 7, T. 25 N., R. 43 E. Sandstones in the formation form broad, easily mapped shoulders in the badlands and provide key stratigraphic units for mapping.

Small, steep, intricately-carved badland exposures are developed on interbedded bentonitic mudstones and claystones where the protecting remnants of sandstone have been removed by erosion. Such mammillary-shaped outliers are well developed in Sections 22 and 27, in the drainage divide area in the southeastern part of the quadrangle.

Lithology.—The Hell Creek Formation in the Mc Rae Springs Quadrangle consists of interbedded mudstones, claystones, and carbonaceous shales, separated into major units by laterally persistent sandstones (Figure 11, Plate 1). The Hell Creek beds were commonly referred to as the "somber beds" in the early literature, because of their generally gray appearance, in contrast to that of the underlying yellowish-gray and buff Fox Hills Sandstones

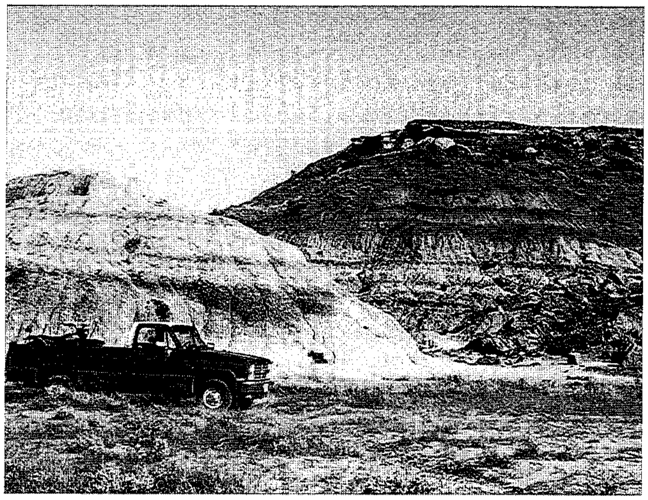


Figure 9. Lower Hell Creek beds in badland exposures in the southeastern part of Sec. 22, T. 25 N., R. 43 E. The Gunsight Butte sandstone caps the ridge on the right, above the carbonaceous shale triplet of the Null-Coal zone in the lower part of the Hell Creek Formation. Bentonitic claystones and carbonaceous shales alternate in the badlands and domal outlier of the lower beds.

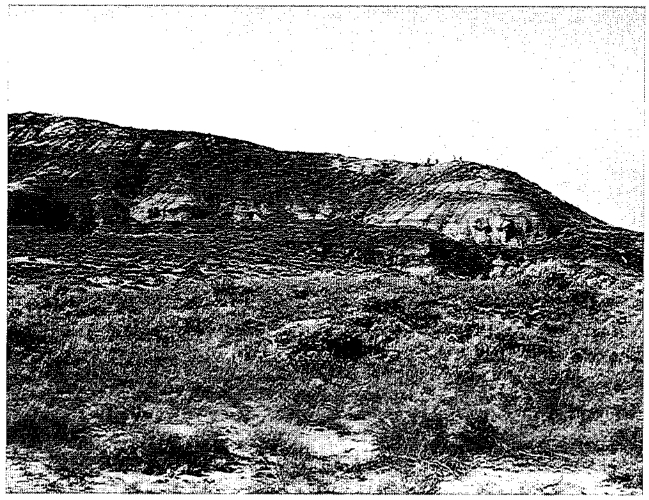


Figure 10. View northward to the prominent ridge and the Barbeque Quarry dinosaur locality, indicated by figures on the skyline. The Gunsight Butte sandstone forms the ragged ledges near the base of the escarpment and the Barbeque Quarry sandstone forms the light band in exposures left of the quarry, which is in the west-central part of Sec. 22, T. 25 N., R. 43 E.

and the overlying more yellowish-gray banded Tullock Formation. Sandstones of the Hell Creek Formation occur in relatively laterally continuous thin sheets or in elongate channel-fill lenses. These sheet sandstones are characteristically fine-grained to medium-grained, and are commonly crossbedded and ripple marked. They appear like salt-and-pepper sandstones, because they contain moderate quantities of fragments of dark, ferromagnesian minerals and dark chert intermixed with the dominant coarse quartz sand. Two of these sandstones have been mapped as informal subdivisions of the formation (Plate 1) in southern and southwestern parts of the quadrangle.. The lower of these (Figure 11) is termed the Gunsight Butte sandstone, for exposures on that distinctive outlier west of the highway, in the southwestern part of Section 1, T. 25 N., R. 42 E., in the western-central part of the quadrangle. What we have mapped as the Gunsight Butte sandstone in the southwestern part of the quadrangle is considered to be equivalent to the Number 3 sandstone of the Hell Creek Formation as mapped by Rigby and Rigby (1990) in the Sand Arroyo quadrangle, adjacent on the south. The upper laterally persistent sandstone in the Mc Rae Springs quadrangle is termed the Barbeque sandstone because it is well exposed in and near the Barbeque dinosaur quarry, in the west-central part of Section 22, T. 25 N., R. 43 E., in the southeastern part of the quadrangle. This sandstone, as we have mapped it in the southwestern part of the quadrangle, is considered to be equivalent to the Number 4 sandstone of the Hell Creek Formation of the Sand Arroyo quadrangle, to the south, as mapped by Rigby and Rigby (1990).

Bell (1965, p. 82–88) studied heavy mineral compositions of 10 samples from the Hell Creek Sandstone and noted the most common grains are magnetite, ilmenite, and limonite followed by biotite, chlorite, muscovite, zircon, apatite, epidote, and tourmaline. He concluded the sands were apparently derived from volcanic terrains to the west or northwest.

Most sandstone lenses within the formation range from light olive-drab to light yellow-gray. Most have high clay content, generally with little cement except where concretionary units are cemented by limonite or calcite. There the rocks range from medium yellow-gray to dark yellow-brown, depending upon the concentration of limonite in the cement.

Because the concretionary units are the most firmly cemented, they commonly form cap rocks or basal units to the more easily eroded sandstones (Figure 9). Less-well cemented sandstones commonly form rounded hills or gentle slopes, except where protected in steep areas by the overlying concretionary units. There they commonly form almost vertical walls beneath the protecting lithified layers. Where the protecting layers have been removed, the sandstones weather and erode away moderately quickly.

Lenticular sandstones commonly contain clay-pebble units. These have been associated with fossil small-vertebrate localities (Rigby, 1987) and the clasts generally are of rip-up origin and of local derivation.

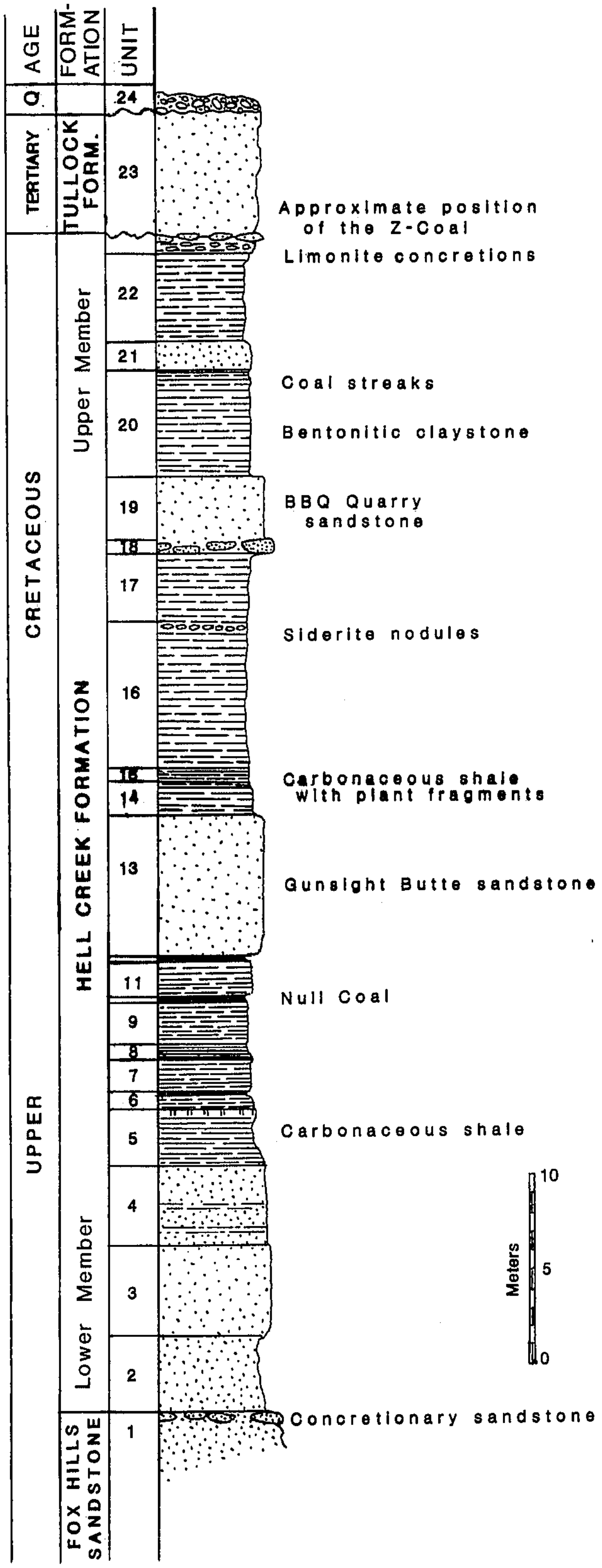


Figure 11. Stratigraphic section through the Hell Creek Formation exposed north of the Barbeque Quarry, in the south part of the northwest quarter of Sec. 22, T. 25 N., R. 43 E., beginning in the headwaters of Widow Coulee, near the center of Sec. 22 and continuing westward to the high point with a spot height of 2690 feet.

Moderately massive sandstones mapped as the basal unit of the formation in southern and southeastern parts of the quadrangle appear relatively uncemented and have much the same mineral composition as the underlying Fox Hills Sandstone. Where well exposed, for example in the small hill immediately west of the center of Section 22, T. 25 N., R. 43 E. in the headwaters of Widow Coulee (Figure 2), the relatively uncemented sandstone forms vertical walls protected in part by thin concretionary sandstones or by the cap of gray sandy mudstone. They rest on the uppermost concretionary sandstone layer of the Fox Hills Sandstone, which is commonly yellowish-gray to dusty yellow or grayish-orange to dark yellowish-orange in weathered exposures. Above those basal units, the sandstones are light olive-drab to light yellow-gray and appear much like sandstones from the middle part of the Hell Creek Formation, such as those exposed in vertical bluffs to the west and southwest in the west-central part of Section 22 and into the east-central part of Section 21 of T. 25 N., R 43 W. Most of these sandstones contain isolated carbonaceous fragments and are of non-marine origin.

It is because of the contrast in color and structure, and similarity with sandstones higher in the formation, that this lower transition unit has been placed in the Hell Creek Sandstone. In addition, the underlying yellowish concretionary bands form a more consistent mappable horizon than the poorly and rarely exposed basal claystones of the Hell Creek beds across the rounded grass covered prairies.

Much of the Hell Creek Formation is composed of siltstones and mudstones that weather to form rounded "popcorn" surfaces where they are bentonitic (Figure 9). Most of the fine clastic units appear pale olive-gray or light olive-gray to olive gray-green and weather light gray. Some units are light to medium yellow-gray, particularly those associated and laterally equivalent to some of the lenticular sandstones. They form massive-appearing beds that are routinely fine grained and commonly darken upward into carbonaceous shales that contain fragments of fossil leaves or "coffee grounds" of plant debris. Some of the massive units appear virtually unbedded, but others with silty partings are well bedded and weather to flakes and irregular debris.

Some of the claystones contain dark brown to reddish-brown siderite nodules and form somewhat purplish-appearing units. Carbonaceous shales in the formation range from light gray-brown to dark gray and coally, with shiny bituminous-appearing partings in the more organic-rich units, like that associated in the sequence with the Null-Coal in the lower part of the formation (Figure 9). Where plant debris is abundant, these units weather to dark gray or dull black powdery slopes, and where less abundant to reddish brown or purplish zones.

The Null-Coal is part of the triplet of carbonaceous shale and coal (Figure 9) that occurs approximately 22 meters above the base of the formation, as we have mapped it in the west-central part of the quadrangle in Coal Hill and surrounding areas. That coal is approximately 0.3 meters thick and consists of approximately half brown and dark gray carbonaceous shale and shiny vitrinite bituminous-appearing coal. It is a laterally persistent unit in the lower part of the formation in the western part of the quadrangle, and was mapped across much of the Sand Arroyo and Bug Creek Quadrangles to the south (Rigby and Rigby, 1990).

Some weathered slopes of mudstones and claystones are littered with small crystals of selenite, apparently related to break down of sulfides during the weathering process.

Gray metallic marcasite concretions are common throughout the Lower Hell Creek Formation, but are particularly evident in the unconsolidated sandstones that may make up the lower units of the formation in sections east of the Barbeque Quarry dinosaur locality and in southernmost exposures in the south-central part of the quadrangle.

An environmental interpretation of the sequence in the quadrangle is like that described for equivalent beds in the Sand Arroyo and Bug Creek Quadrangles to the south (Rigby and Rigby, 1990, p. 101). "The organic shale, coal, and siltstone-mudstone of the formation represent flood plain deposits, in contrast to the sandstones that appear to be deposits of meandering and braided channels and splay systems." These rocks accumulated onshore from the margin of the regressive Late Cretaceous seaway.

Fossils and Age.—The Hell Creek Formation, as mapped in the quadrangle, includes youngest Cretaceous and basalmost Paleocene rocks. The Hell Creek Formation is of Late Maastrichtian age (Sloan and others 1986), but also include a few meters of basal Paleocene rocks above the iridium layer and below the formational or upper Z-Coal. The formation is the principal dinosaur-bearing unit in eastern Montana.

Thickness.—Within the Mc Rae Springs Quadrangle, the formation is approximately 62 meters thick. The dinosaur bone bed at Barbeque Quarry (Figures 10 and 11) (Roberts, 1998) occurs approximately 40 meters above the base and 20 meters below the top of the formation.

Tertiary System
Paleocene Series
Tullock Formation

Introduction.—Only the basal part of the Tullock Formation is preserved in the quadrangle as high caps of butte-like outliers in southeastern sections of the quadrangle (Figure 2). Thickest preserved exposures are in the central and southeastern part of Section 35 T. 25 N., R. 43 E., in the southeastern corner of the mapped area, where approximately 15 meters of the lower Tullock Nelson Ranch Member (Rigby and Rigby, 1990) is exposed. Three small outliers occur north of the headwaters of Beaver Creek, in Sections 26 and 27 of T. 25 N., R. 43 E., and include from only a few meters, in the small outlier, to perhaps 15 meters in the larger isolated erosional remnants.

The Tullock Formation overlies the Hell Creek Formation in the quadrangle and areas to the south, where it is more extensively exposed in the Bug Creek and Sand Arroyo Quadrangles. The Tullock Formation is the basal Tertiary unit of that sequence and was named by Rogers and Lee (1923, p. 29) for the interbedded yellowish sandstones and shales, with minor lenticular coal beds, that occur in what was then termed the upper part of the Lance Formation in the Tullock Creek coal field, in Treasure County, Montana. The beds have a complex history of stratigraphic nomenclature, summarized by Frye (1969) and Rigby and Rigby (1990.)

Collier and Knechtel (1939, p. 11) discussed the Tullock beds as a member of the Lance Formation and noted the questionable Eocene age for the rocks, but in a footnote they reported that the underlying Hell Creek beds had been reassigned to the Cretaceous and the Tullock beds to the Cretaceous or Eocene by the U. S. Geological Survey. Brown (1938) placed the Cretaceous-Tertiary boundary where it is currently mapped, between the Hell Creek and Fort Union or Tullock beds, for the first time and discussed reasons for placing the boundary there. As late as 1959, however, confusion still persisted because Denson and others (1959) concluded there were no distinct lithologic reasons for differentiating what had been called upper and lower Hell Creek beds, in spite of Brown (1952) pointing out that the top of the lower Hell Creek beds marked the uppermost limit of common *Triceratops*. Stanton (1909, p. 286) correctly concluded that earlier collected floras were mixed and that the dinosaur-bearing beds ought to be separated from the overlying Tullock rocks. Dorf (1942, p. 95–97) correctly concluded that rocks now commonly included in the Tullock Formation, in northern Wyoming, contain plants of typical Paleocene floras and are not of uppermost Cretaceous age.

Rigby and Rigby (1990) mapped the boundary between the Tertiary Tullock formation and underlying Hell Creek formation at the base of the upper or formational Z-Coal, although as reported by others, the pollen break and the carbonaceous clay of the iridium anomaly at the precise Cretaceous-Tertiary boundary occur one to six meters (commonly two to three meters) below that coal. The carbonaceous shale, however, that marks the iridium layer is less easily mapped and the formational contact on the geologic map in the Bug Creek and Sand Arroyo quadrangles was drawn at the base of the upper Z-Coal, as we have done here in the limited outcrops of the Tullock Formation in the southeastern part of the Mc Rae Springs Quadrangle.

Rigby and Rigby (1990) erected the Nelson Ranch Member for the lower part of the formation and the Collins Ranch Member for the upper part of the formation. Only rocks included in the Nelson Ranch Member are preserved in the Mc Rae Springs Quadrangle. Rigby and Rigby (1990, p. 104) concluded that the Tullock Formation apparently rests unconformably across the Hell Creek Formation in the Bug Creek and Sand Arroyo quadrangles, as was earlier observed by Rigby and others (1986). That unconformity is marked by development of numerous Paleocene stream channels cut down into the Cretaceous beds, and by variations in thickness of the Hell Creek Formation below. One such channel is well preserved in the central part of Section 35, T. 25 N., R. 43 E., where a channel of a north-flowing stream has been filled by light yellow-gray sandstone that cuts into the lowermost Tullock and uppermost Hell Creek beds. So little is preserved of the Tullock Formation and the contact zone in the quadrangle that little new information can be contributed to conclusions reached by earlier workers. In the southeastern part of the quadrangle, the thickest sequences preserved range from the contact zone up through the Z-Coal sequence to near the X-Coal in the middle and lower parts of the Nelson Ranch Member.

Lithology.—Interbedded, commonly cyclic-appearing, tan to light gray sandstones alternate with light yellow-gray to gray shales or mudstones, with locally interbedded siderite or ironstone concretions, and carbonaceous shale or minor coal, and characterize exposures in the southeastern part of the quadrangle.

Rigby and Rigby (1990, p. 106) described characteristic cycles within the lower Tullock Formations as ranging upward from moderately laterally persistent, though commonly channeled sandstone, through sideritic shales, to banded light gray or light yellow-gray siltstones. These grade upward into bentonitic claystones or mudstones, with only minor ironstones, although they may contain thin concretionary lenses of sandstone in the dominantly marshy or lacustrine section. These are capped by thin carbonaceous shales or low-rank bituminous coals and carbonaceous shale. Several such cycles are visible in bold badland exposures in the mapped outliers in divide areas on both sides of Bear Creek, but are probably best and most extensively exposed on north slopes in Section 26, T. 25 N., R. 43 E.

Fossils and Age.—Age of the lower Tullock Formation has been conclusively shown to be lower Paleocene, based on vertebrate and plant fossils from nearby areas (Shoemaker, 1966; Norton and Hall, 1969; Van Valen, 1978; Sloan, 1987; Rigby, 1985, 1987; Rigby and others, 1987; and Sloan and Rigby, 1986).

Cenozoic Deposits

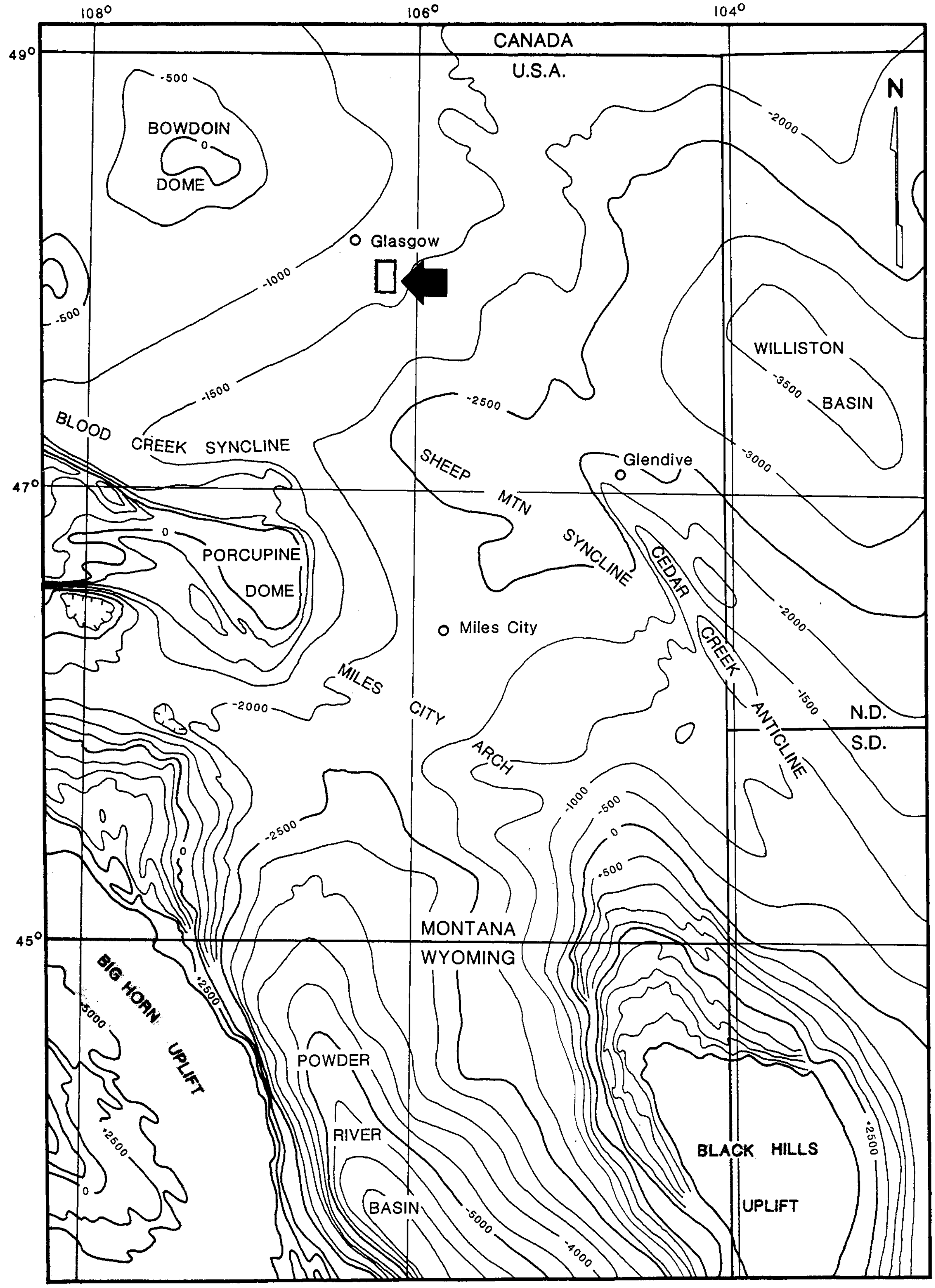
Although we were principally concerned with the Cretaceous and Tertiary bedrock exposures, we have differentiated broad areas of Quaternary alluvial fill in the flat valley bottoms of Bear Creek, in the south, and tributaries of Hungry Creek and Lost Creek, in the northeastern part of the quadrangle. Some moderate terrace development shows as abandoned benches, particularly along Cheer Creek and the West Fork of Hungry Creek in the east-central part of the quadrangle. Throughout the area, present drainages are uniformly entrenched into the fill of the flat valley bottoms.

Collier and Knechtel (1939, Plate 8) showed Iowan (?) or Illinoisan (?) ground moraine covering all of the quadrangle, and extending for several miles to the south in McCone County and Garfield County. They mapped the southern limits of Wisconsin ground moraine in Valley County and Roosevelt County about thirty miles north of the Missouri River and the Mc Rae Springs Quadrangle.

Uplands in the quadrangle are commonly veneered by unconsolidated pebble and cobble gravels that contain a mixture of red and green quartzite, black chert, and fragments of igneous and metamorphic rocks. Associated with these are large blocks and cobbles of exotic igneous and metamorphic rocks. These are commonly only a few centimeters in diameter, but fragments 50 cm to 1 m in diameter are moderately common and appear as light exotic elements across the landscape. Locally large blocks, a meter or more in diameter, also occur as light gray, isolated exotic elements scattered over the hills.

Many of the small pebbles are reminiscent of lithologies common in the Belt Terrain in mountains to the west. Whether all of the upland gravels are associated with a ground moraine source, or represent terrace gravels abandoned by the down-cutting Missouri River, remains a project for analysis. We have not attempted to differentiate these Pleistocene deposits throughout the quadrangle.

Figure 12. Regional structure contour map showing the Mc Rae Springs quadrangle (arrow) situated on the southeast homoclinal flank of Bowdoin Dome and the western part of the Williston Basin (modified from Rigby and Rigby, 1990).


108°
106°
104°
49°
47°
45°
CANADA
U.S.A.
N
BOWDOIN
DOME
Glasgow
WILLISTON
BASIN
BLOOD CREEK SYNCLINE
SHEEP MTN SYNCLINE
Glendive
PORCUPINE
DOME
Miles City
CEDAR CREEK ANTICLINE
MILES CITY ARCH
N.D.
S.D.
MONTANA
WYOMING
BIG HORN UPLIFT
POWDER
RIVER
BASIN
BLACK HILLS
UPLIFT
-500
0
-1000
-1500
-2000
-2500
-3000
-3500
+500
+2500
+5000
-4000
-5000

STRUCTURE

Bedrock units in the quadrangle are essentially flat lying, with a simple homoclinal dip towards the southeast, as evidenced by the contact of the Fox Hills Sandstone and overlying Hell Creek Formation occurring at an elevation of approximately 2610 feet in the west-central part of the quadrangle, near Coal Hill, and the same contact occurring at an elevation of approximately 2430 along the lower part of Widow Coulee, in the southeastern part of the quadrangle. This amounts to a drop of approximately 180 feet in 6 miles, or at a rate of 30 feet per mile, which amounts to a general regional dip of approximately 0.5 degrees.

A somewhat lesser dip of approximately 17 feet per mile is suggested by the contact of the Fox Hills Sandstone on the Bearpaw Shale, which is at an elevation of 2490 feet in the northwestern part of the quadrangle, but slopes down southeastward to an elevation of approximately 2370 feet, in exposures east of Cheer Creek in the east-central part of the map.

No major faults or even marked regional folds are evident in the virtually homoclinal formational sheets in the quadrangle. The quadrangle is located on the southeast flank of Bowdoin Dome, in the simple homoclinal structure shown there on the generalized structural contour map of the United States (Figure 12, modified from Rigby and Rigby 1990).

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An Unusual Specimen of *Allosaurus* from Southeastern Utah

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ABSTRACT

An adult specimen of *Allosaurus fragilis* (BYU 2028) was recovered in the 1970's by James Jensen and Kenneth Stadtman, both of Brigham Young University, from southeastern Utah. It was described by Lisak (1980), who's description is summarized here in light of later research on the allosaurid skull by Witmer (1997) and Currie and Zhao (1993). BYU 2028 represents an *Allosaurus* with some unusual characters. It possesses an expanded nasal crest and increased paranasal pneumaticity that are unusual for the genus. Therefore, this partial skull is used to more fully document the range of variation of these characters in *Allosaurus*.

INTRODUCTION

A moderate-sized partial skull of *Allosaurus* (BYU 2028) was discovered by Gene Day of the U. S. Bureau of Land Management in the mid-1970's in the of Salt Valley of the Paradox Basin (Moab-10 Quadrangle, T24S, R20E), near Moab, Utah (Figure 1) (Stadtman, pers. com., 2001). The specimen was found in a conglomeratic boulder that had rolled from a ridge on the west side of Mill Canyon Wash in the region of Mill Creek Dinosaur Trail (Lisak, 1980). It was collected by James Jensen and Kenneth Stadtman, who determined that it was derived from the upper part of the Brushy Basin Member of the Morrison Formation (Stadtman, pers. com., 2001).

Lisak (1980) referred this specimen to *Allosaurus* cf. *fragilis*. It consists of both sides of a partial skull (Figures 2–4) and both mandibles (Figures 5–6). In general, the left side of the skull is better preserved than the right. The premaxillae, maxillae, nasals, vomer, and fragmentary lacrimals are present in this specimen. The preserved part of the mandibles consists of the dentary, surangular, prearticular, splenial, coronoid, and intercoronoid (=supradentary). Unlike the skull, the right mandible is better preserved than the left. The skull was distorted so that the left premaxilla was displaced anteriorly and medially around the anterior end of the right premaxilla.

Most of the bones are very typical of *Allosaurus fragilis* (Madsen, 1976). There are, however, some unusual characters in BYU 2028 that increase the range of morphological variation for the species. This paper documents the novel cranial variation observed in this single taxon.

Abbreviations.—BYU, Brigham Young University, Provo, Utah; DNM, Dinosaur National Monument, Vernal, Utah; MOR, Museum of the Rockies, Bozeman, Montana; OH, Ohio University, Athens, Ohio; UUVP University of Utah Vertebrate Paleontology, Salt Lake City, Utah; UVSC, Utah Valley State College, Orem, Utah.

Systematic Paleontology
Dinosauria Owen, 1842
Theropoda Marsh 1881
Carnosauria von Huene 1920
Allosauridae Marsh, 1877
Allosaurus Marsh, 1877
Allosaurus fragilis Marsh 1877

Description.—Some of the information presented here repeats or elaborates upon previous descriptions of this taxon (Lisak, 1980; Madsen, 1976). All descriptions are based on the better preserved left side of the skull. Comparison with bones from Dry Mesa, Cleveland-Lloyd, and Dinosaur National Monument Quarries indicate that most of the Moab *Allosaurus* are typical for *A. fragilis* (Madsen, 1976; Currie and Zhao, 1993). However, a highly ornamented crest is present that is reminiscent of, though

*Current address unknown

less exaggerated than that in *Alioramus* (Kurzanov, 1976). Another feature is the increased convexity of the ventral margin of the maxilla and premaxilla. Pneumatization of the maxillary ascending process and paranasal region is more pronounced than would be expected for this species. Pneumatic terminology follows Witmer (1997).

Premaxilla.—The left premaxilla (Figure 2) was displaced anteriorly and medially to cover the original joint with the right premaxilla (Lisak, 1980). Unlike many specimens of *Allosaurus fragilis,* the body of this bone is higher than long (Currie and Zhao, 1993). Otherwise, it is typical for *Allosaurus* (Madsen, 1976). The lateral side is smooth, with small, random fenestrae as is the case in most other theropods. Presumably, they serve the same function as proposed for *Sinraptor,* accommodating the subnarial artery and branches of the medial ethmoidal nerve (Currie and Zhao, 1993). There is a vertical anterior margin, so the supranarial process (= ascending nasal process of Madsen, 1976) is inflected at the base. A lateral groove receives the supranarial process of the nasal. Unlike *Sinraptor,* the subnarial process (=maxillary process of Madsen, 1976) does not contact the nasal, so the maxilla is not excluded from the narial opening. Hence, the wall of the vestibular bulla is visible in lateral view, separating the premaxilla from the nasal (Witmer, 1997). The subnarial foramen is typical in size and location for *Allosaurus fragilis* (Madsen, 1976). The contact with the maxilla is vertical below the subnarial foramen, then it slopes back to form the ventral boundary of the subnarial process.

The interdental plates are fused and all about the same height. There are 5 premaxillary teeth or alveoli present. Teeth 3 and 4 are preserved in the right premaxilla. On this side, 1 and 5 are broken at the base. Tooth 4 is significantly shorter than the rest. Tooth 2 is the only one preserved in the left premaxilla. The rest are broken at or near the base. Premaxillary teeth 1 and 2 are somewhat D-shaped in cross-section, becoming increasing oval proceeding from 3 to 4 to 5. The dental carinae are on the lingual side in the first two teeth, then move to the posterior margins of the subsequent teeth.

Maxilla.—In most respects, the maxilla (Figure 2) is typical for *Allosaurus* (Madsen, 1976). The lateral surface is rugose anteriorly and immediately above the toothrow as in *Sinraptor* (Currie and Zhao, 1993). Small labial foramina are present above the teeth, accommodating the branches of the superior alveolar nerve and maxillary artery (Currie and Zhao, 1993). There is a well-developed excavation with a smooth surface around the antorbital fenestra. Unlike most specimens of *Allosaurus,* the ventral border is convex. The maxillary fenestra is larger and higher in the ascending process than in *Sinraptor* (Currie and Zhao, 1993), or many other specimens of *Allosaurus* (Madsen, 1976). The lateral surface of the ascending process has a pronounced pneumatic excavation (Witmer, 1997) that is subdivided by a ridge from the posterodorsal corner to the anteroventral corner. The resulting anterior excavation is continuous with a deep groove between the nasal and maxilla that may be equivalent to foramen 4 in *Sinraptor* (Currie and Zhao, 1993). Another pneumatic opening, anterior to the maxillary fenestra, is identified as the promaxillary fenestra (Figure 4) (Witmer, 1997). The premaxilla and nasal exclude most of the maxilla from the margin of the external nares. The end of the ascending process bifurcates at its junction with the lacrimal. The two resulting processes are about the same length.

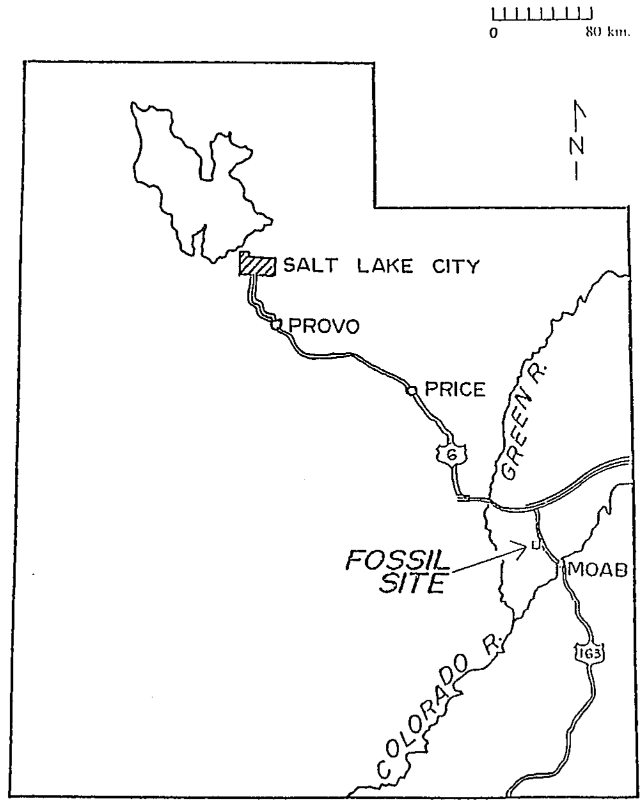

Figure 1. Locality of BYU 2028 (after Lisak, 1980). Statewide scale equals about 80 km.

Under the external nares, there is a well-preserved vestibular bulla (Figure 3) (Witmer, 1997). Part of the wall of this bulla can be seen in lateral view separating the subnarial processes of the premaxilla and maxilla. Within the naris, the bulla forms an excavated base of the narial chamber. The bone making up this base is very thin and typically not preserved, although there is a partial base in BYU 5126. Going posteriorly, the bone splits into two horizontal processes medial to the maxillary fenestra. This

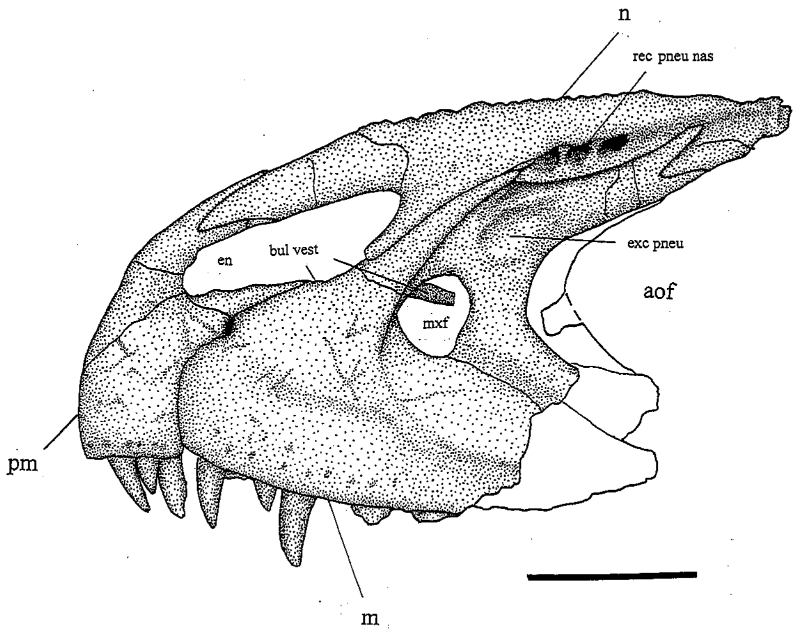

Figure 2. Allosaurus fragilis *snout (BYU 2028) in left lateral view. Abbreviations: aof, antorbital fenestra; bul vest, vestibular bulla (bulla vestibularis); en, external nares; exc pneu, pneumatic excavation (excavatio pneumatica); m, maxilla; mxf, maxillary fenestra; n, nasal; pm, premaxilla; rec pneu nas, nasal pneumatic recess (recessus pneumaticus nasalis). Scale bar equals 10 cm.*

process is apparently related to the promaxillary diverticulum between the vestibular bulla and maxillary fenestra (Witmer, 1997).

There are no teeth preserved in the right maxilla, although there is a replacement tooth in the fifth alveolus. In the left maxilla, teeth 1–5 are preserved. The fourth tooth is significantly shorter than the rest.

Nasal.—The nasal (Figure 2) is long with a narrow dorsal surface that is distinct from that part contributing to the antorbital fenestra. It is dorsally concave as a result of the presence of an ornamented ridge from the lacrimal to the anterior part of the nasal. This ridge is similar to, but less pronounced, than the one in *Alioramus* (Kurzanov, 1976). The nasal pneumatic recess is expanded so that it has invaded the wall of the nasal and is visible externally. There are three pneumatic openings that interconnect internally in the left nasal and two on the right within the antorbital excavation (Witmer, 1997). The chamber extends anteriorly into the nasal. This development is similar to that seen for *Sinraptor* (Currie and Zhao, 1993). Like other specimens of *Allosaurus,* the nasal splits in the anterior and posterior ends. The posterior end overlays the maxilla and is covered itself by the lacrimal.

Vomer.—The vomer can be seen in ventral view. BYU 2028 is only the third specimen, after UUVP 6000 (Madsen, 1976) and MOR 693 (Madsen, pers. com., 2001), where the vomer is preserved in place. Unlike *Sinraptor* where it splits anteriorly (Currie and Zhao, 1983), this element is fused along almost its entire length, except for the posterior end, in BYU 2028 and other specimens of *Allosaurus* (Madsen, 1976). It is long, thin, and anteriorly spatulate as in UUVP 6000 (Madsen, 1976). Posteriorly, this bone is partially concealed in BYU 2028, but forms a vertical plate. The bone was distorted and has been displaced dorsally against the ridge at the base of the promaxillary fenestra.

The frontal and lacrimal are fragmentary, so no new information regarding these bones is available from this specimen.

Dentary.—The dentary (Figures 4–5) is similar to that in other specimens of *Allosaurus,* except that the lower margin is more concave, so the thinnest part is in the middle of the bone. As in *Allosaurus* described previously (Madsen, 1976), mental foramina are present on the lateral surface. Other small foramina can be found on the anteroventral end. Like *Allosaurus,* the interdentary symphysis is poorly defined. Posteriorly, the dentary increases in depth. Most of the interdental plates are not visible, as they are covered by a straplike supradentary (=intercoronoid). The dentary is concave at Meckel's groove. On the posterior end of the groove are two foramina, as in *Sinraptor* (Currie and Zhao, 1993). Currie and Zhao (1993) indicate that the upper one accommodates the inferior alveolar nerve and internal mandibular artery. They did not ascribe a function to the lower one.

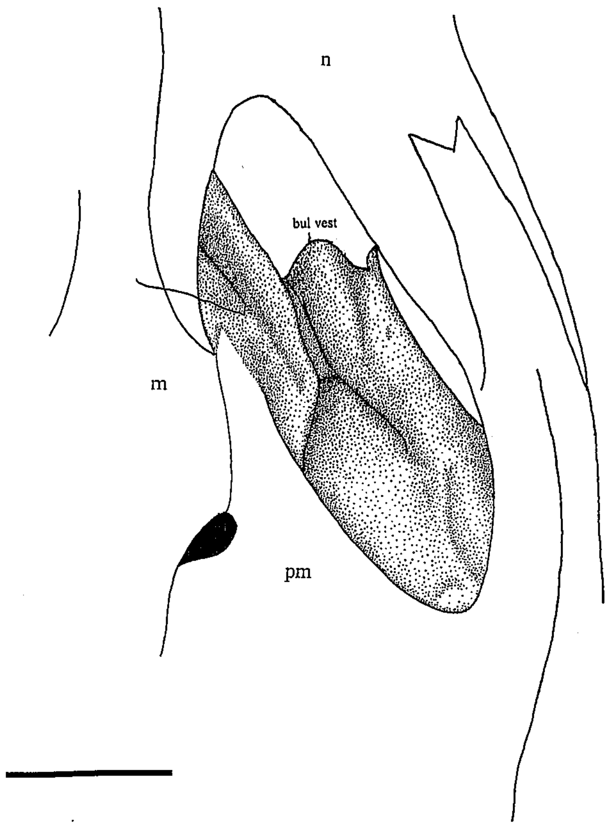

Figure 3. Anterolateral view of dorsal side of vestibular bulla through external naris in BYU 2028. Abbreviations: As in Figure 2. Scale bar equals 5 cm.

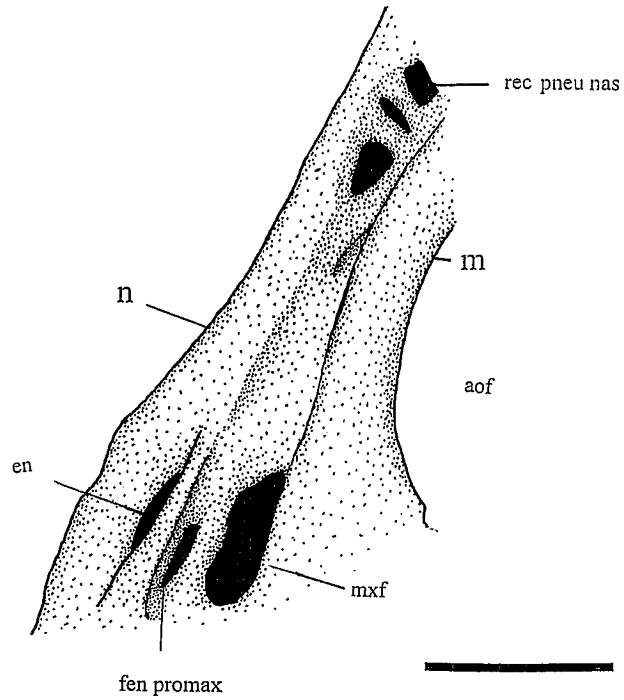

Figure 4. Posterolateral view of maxilla showing fenestrae in the ascending process. Abbreviations: fen promax, promaxillary fenestra; pmf, promaxillary fenestra; rec pneu nas, nasal pneumatic recess (recessus pneumaticus nasalis); or as in Figure 2. Scale bar equals 10 cm.

In BYU 2028, both the right and left dentaries have 18 teeth or alveoli, falling within the range of variation expected for *Allosaurus fragilis* (Madsen, 1976). On the left side, teeth 1–3, 7–11, and 15–18 are present. One, 2, 7, and 8 are broken at the tips. There is a short replacement tooth in the fourteenth alveolus. In the right dentary, 4–6, 8, and 10–14 are preserved. There is a replacement tooth in the seventeenth alveolus.

Splenial.—The right splenial (Figure 6) is thin and triangular, with an evaginated posterior end. It is similar to other specimens of *Allosaurus* (Madsen, 1976) and *Sinraptor* (Currie and Zhao, 1993). As in *Sinraptor*, the ventral margin thickens posteriorly. The anterior mylohyoid foramen is large in both mandibles, extending to the ventral edge of the splenial. The anterior end of the splenial bifurcates into two small processes, one above the other (Lisak, 1980). The higher one forms part of the ventral border to the supradentary. The lower process is longer than the first and lies in Meckel's groove.

The prearticular, coronoid, and surangular are fragmentary, so this specimen provides no new information on these bones.

DISCUSSION

Individual and ontogenetic variation in the pneumatic system of the *Allosaurus* cranial region was described previously using braincases of different sizes from Cleveland-Lloyd Dinosaur Quarry, Utah (Chure and Madsen, 1996). BYU 2028 is now used to document some of the range of morphological and paranasal pneumatic variation present in the *Allosaurus* skull. Previous descriptions of *Allosaurus* (Madsen, 1976) and *Sinraptor* (Currie and Zhao, 1993) are used as a basis for comparison. Witmer (1997) provided a discussion and illustrations of the general paranasal pneumatic system of *Allosaurus*. BYU 2028 was compared with disarticulated *Allosaurus fragilis* material from Dry Mesa Dinosaur Quarry, Colorado, Dinosaur National Monument, and previous descriptions of this species (Madsen, 1976). The paranasal pneumatic system and the nasal crest are more extensively developed than observed in other specimens of *Allosaurus*. However, most of the bones are very similar to typical *Allosaurus* elements (Madsen, 1976; Currie and Zhao, 1993). On this basis, the present specimen is regarded as an adult specimen of *Allosaurus fragilis* with some unusual characters.

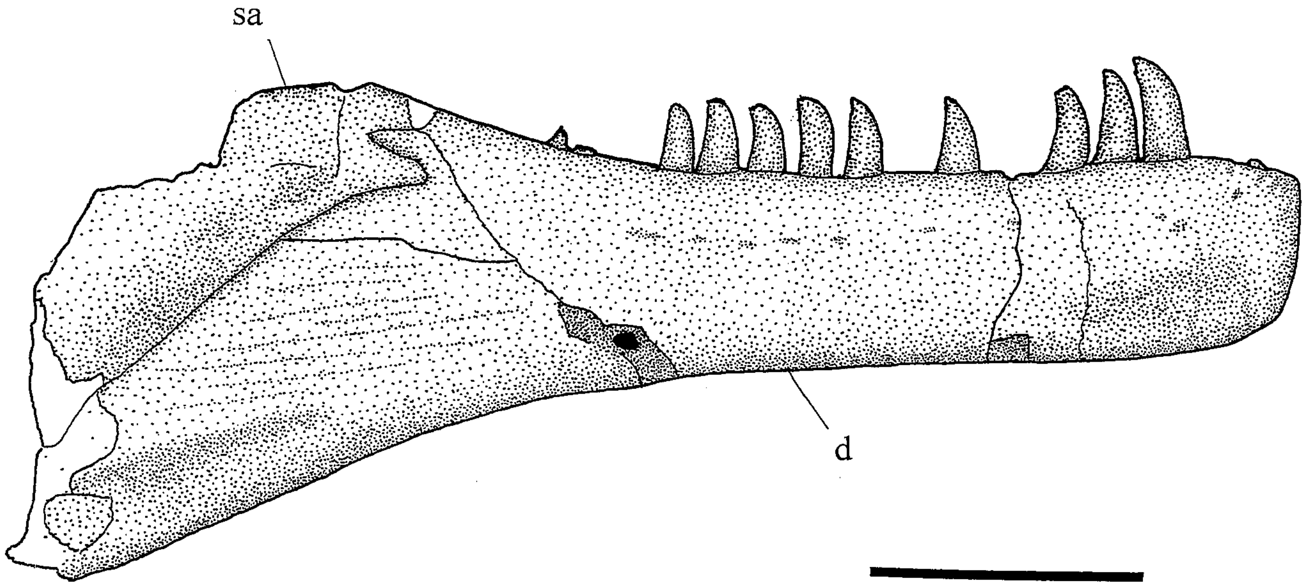

Figure 5. Allosaurus fragilis *right mandible (BYU 2028) in lateral view. Abbreviations: an, angular; d, dentary; sa, surangular. Scale bar equals 10 cm.*

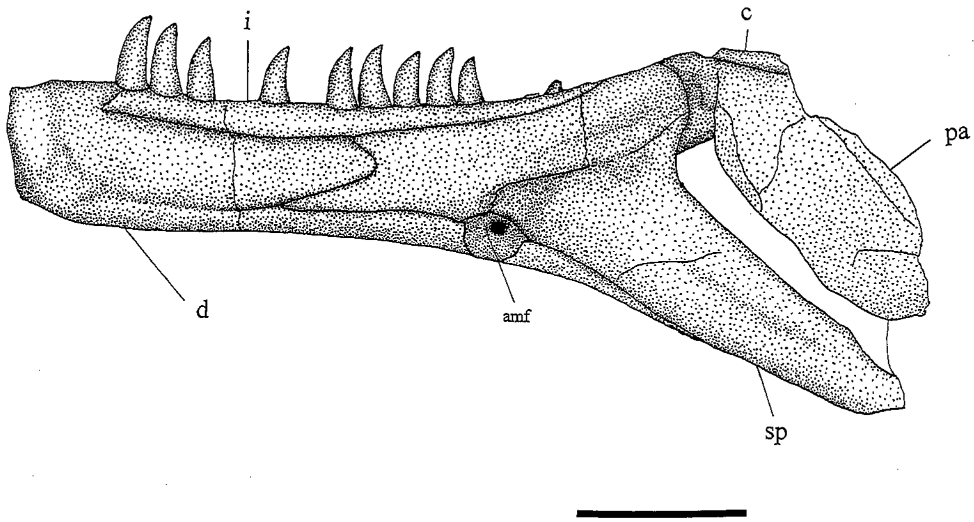

Figure 6. Allosaurus fragilis *right mandible (BYU 2028) in medial view. Abbreviations: amf, anterior mylohyoid foramen; c, coronoid; d, dentary; i, intercoronoid; pa, prearticular; sd, supradentary; sp, splenial. Scale bar equals 10 cm.*

This specimen of *Allosaurus* shows an increase in the amount of morphological and pneumatic variation seen within this taxon. The results reinforce the relative amount of variation in different parts of the *Allosaurus* skull. Morphological variation can include variation in the degree of development and ornamentation of crests on the skull. Witmer (1997) observed that the pattern of pneumatic development within the theropod clade generally increases over time, but that it is difficult to identify an orderly pattern in the development of accessory cavities. Additionally, development of paranasal pneumatic cavities can vary within a single theropod species. No other observed specimen of *Allosaurus fragilis* has such an enlarged pneumatic system in the nasal. However, the presence of pneumatic openings can vary from specimen to specimen and even from side to side as has previously been noted (Chure, pers. com. 1999). Variation of this type does not appear to be related to ontogeny. Therefore, the expanded cavities within BYU 2028 are associated with individual variation.

ACKNOWLEDGMENTS

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Conodont and Fusulinid Biostratigraphy and History of the Pennsylvanian to Lower Permian Keeler Basin, East-Central California

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ABSTRACT

The Pennsylvanian-Lower Permian Keeler Canyon Formation and lower part of the Lower Permian Lone Pine Formation in east-central California were deposited in a deep-water basin that originated in the Morrowan (Early Pennsylvanian), was fully established by the Desmoinesian (Middle Pennsylvanian), and lasted into the Sakmarian (Early Permian). Stratigraphic studies indicate that the Keeler Canyon Formation can be divided into members recognizable throughout the area of our detailed mapping. From older to younger they are the Tinemaha Reservoir, Tihvipah Limestone, Cerro Gordo Spring, and Salt Tram Members. Rocks in this basin, here referred to as the Keeler basin, contain numerous fusulinid and conodont faunas most of which were deposited by sediment-gravity flows probably originating at the margin of the Bird Spring carbonate platform to the northeast. Sixty-one species of Atokan to Sakmarian fusulinids and 38 species of Desmoinesian to Sakmarian conodonts are recognized. These, in addition to four species of Morrowan conodonts previously reported, show that every stage from the Morrowan to Sakmarian is represented in the basin. The fusulinid faunas are composed largely of taxa of the North American craton, especially the south-central USA, with important endemic constituents and some McCloud Limestone forms, representing the Eastern Klamath terrane. Conodonts are closely similar to species in the Ural Mountains region of Russia and Kazakhstan, as well as the American midcontinent. The co-occurrence of fusulinids and conodonts in the Keeler basin results in a better correlation of zones based on these two groups of fossils than generally is possible.

INTRODUCTION

The Keeler basin, one of a succession of several late Paleozoic basins in east-central California, accumulated a thick, apparently continuous section of Pennsylvanian to Early Permian deep-water marine strata representing the southwesternmost exposures of fossiliferous rock of this age in the Cordilleran miogeocline. Strata deposited in this basin, assigned to the Keeler Canyon Formation and lower member of the Lone Pine Formation, form an approximately north-south-trending belt about 70 km wide and at least 160 km long (Fig. 1). Coeval strata adjacent to the Keeler basin are represented by the shallow-water Mount Baldwin Marble to the northwest in the Sierra Nevada, which probably formed on an isolated carbonate platform, and the shallow-water Bird Spring Formation to the east in the southern Cottonwood Mountains and Panamint Range, which was part of a broad carbonate platform that fringed the western margin of the North American craton (e.g., Stone and Stevens, 1988; Stevens and Greene, 1999).

Regional mapping reveals that the Keeler Canyon Formation is more extensively exposed than the overlying Lone Pine Formation and therefore best marks the minimum extent of the Keeler basin. The Keeler Canyon Formation crops out most widely in the southern Inyo Mountains, but exposures extend northwestward to Mazourka Canyon and Tinemaha Reservoir, eastward into the Ubehebe Mine and Quartz Spring areas, and southward to the north end of the Slate Range (Figs. 1, 2).

Because both conodonts and fusulinids occur throughout the sequence, the rocks of the Keeler basin offer an unusually favorable opportunity for comparing the biostratigraphy of these two faunal groups that commonly do not occur together. The conodonts, many of which have worldwide distribution, allow correlation of the upper part of the Keeler basin section with the Gzhelian (Upper Pennsylvanian) and the type Cisuralian (Lower Permian) in the southern Ural Mountains, and the fusulinids permit comparison with Pennsylvanian and Lower Permian sections in the United States midcontinent region. The paleogeographic position of the Keeler basin near the western edge of the late Paleozoic North American continent also makes these faunas critical for evaluation of relations between those of the North American craton and those of late Paleozoic terranes that were later accreted to the continental margin. Finally, detailed age control of rocks in this region is critical for dating the initiation of regional late Paleozoic contractile tectonism thought to have marked the transition from a transform to a convergent continental margin in east-central California (Stevens et al., 1998).

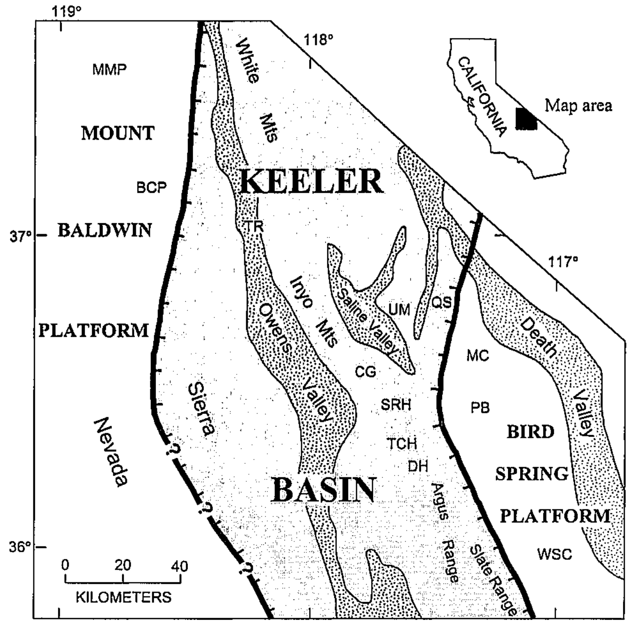


Figure 1. Paleogeographic setting of the Keeler basin in east-central California. BCP=Bishop Creek pendant; CG=Cerro Gordo; DH=Darwin Hills; MC=Marble Canyon; MMP=Mount Morrison pendant; PB=Panamint Butte; QS=Quartz Spring; SRH=Santa Rosa Hills; TCH=Talc City Hills; TR=Tinemaha Reservoir; UM=Ubehebe Mine; WSC=Warm Spring Canyon.

SCOPE

This report summarizes and updates stratigraphic and paleontologic information acquired by the authors over a period of many years. Our work has included geologic mapping of all major outcrop areas of Pennsylvanian and Permian rocks in the Inyo Mountains region, measurement of key stratigraphic sections, and paleontological studies of the fusulinids and conodonts. The paleontological data and interpretations presented here are based on the study of fusulinid (Stevens) and conodont (Ritter) samples collected by the authors. The lithostratigraphic information presented here is updated from previous reports (e.g., Stone, 1984; Stone and Stevens, 1984, 1987), although some is based on recent field work. The stratigraphic scheme used here is shown in Figure 3.

Much of this report is based on work in the Cerro Gordo Mine area of the southern Inyo Mountains where the Keeler Canyon and Lone Pine Formations are most completely and extensively exposed, and where the fusulinids are best preserved. We have mapped this area in detail (Fig. 4) and have measured and collected two stratigraphic sections to provide fusulinid and conodont control. A third stratigraphic section in this area (Section 3 on Fig. 4), measured and described by Riggs (1962) as part of a fusulinid study, was reexamined and partially recollected to provide additional fusulinid and conodont control. We also utilize a measured section of the Keeler Canyon and Lone Pine Formations in the Ubehebe Mine area that was collected for fusulinids and conodonts by Stone (1984).

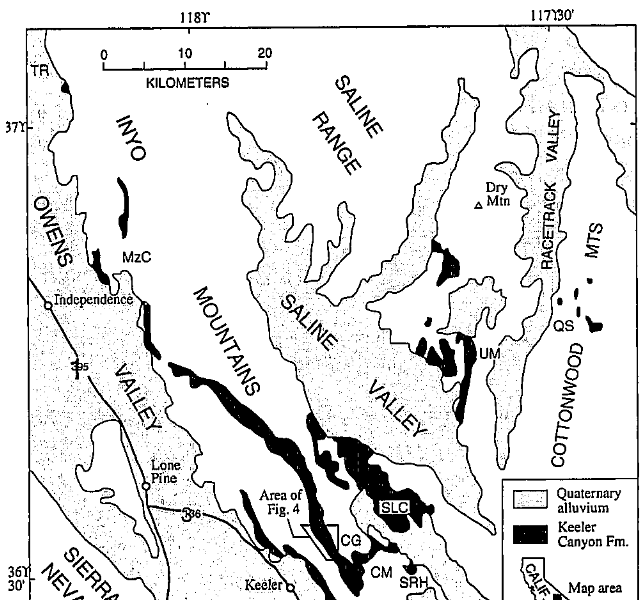


Figure 2. Major outcrops of Keeler Canyon Formation. Additional small outcrops occur as far south as the north end of the Slate Range (Fig. 1). CM=Conglomerate Mesa; MzC=Mazourka Canyon; SLC=San Lucas Canyon. For other abbreviations see caption for Figure 1.

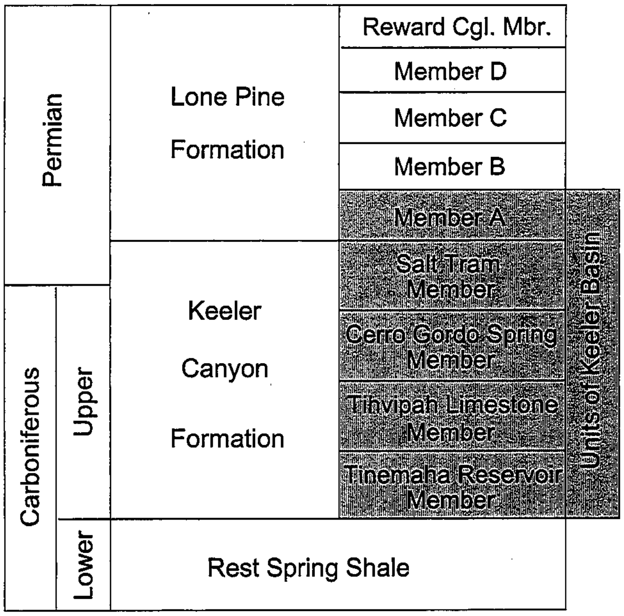


Figure 3. Stratigraphic context for units in the Keeler basin area.

The measured sections are shown in Figure 5 and are briefly described in Appendix 1. Samples from the measured sections are supplemented by spot samples from various other areas. In all, 67 fusulinid and 66 conodont collections are reported. The location and faunal content of these samples are tabulated in Appendix 2.

This study was initiated with the purpose of gaining a better understanding of the geologic history of this region, reporting on the nature of the conodont and fusulinid faunas, and providing illustrations of the major taxa encountered in our sampling. It is our intention here to provide a general outline of the paleontology of these faunas without presenting a detailed taxonomic study.

STRATIGRAPHY

Pennsylvanian and Lower Permian strata of east-central California received little attention prior to the work of Merriam and Hall (1957) who named the Keeler Canyon and Owens Valley Formations for exposures in the southern Inyo Mountains. Later Hall and MacKevett (1962) used these units in mapping of the Darwin quadrangle, Merriam (1963) and D.C. Ross (1965) mapped these formations throughout much of the southern Inyo Mountains, and Burchfiel (1969) mapped them in the Dry Mountain area east of Saline Valley. Rocks equivalent to part of the lower Keeler Canyon Formation, a distinctive unit of fine-grained limestone containing spherical black chert nodules ("golf ball beds" of Merriam and Hall, 1957), previously had been mapped and named the Tihvipah Limestone in the northern Cottonwood Mountains near Quartz Spring (McAllister, 1952), and rocks equivalent to the Keeler Canyon and Owens Valley Formations in the Ubehebe Mine area (McAllister, 1956) were mapped as Bird Spring(?) Formation. The stratigraphy of the Keeler Canyon Formation and some of its lateral variations were discussed by Stevens et al. (1979).

Stone (1984) conducted a regional study of the Keeler Canyon and Owens Valley Formations and delimited the geographic extent of the Keeler basin, contrasting rocks in this basin with those on the largely coeval carbonate shelf to the east represented by the Bird Spring Formation. In that study the Keeler Canyon Formation was divided into four informal members, the second of which coincided with the "golf ball beds" of Merriam and Hall (1957) and the Tihvipah Limestone of McAllister(1952). The two upper members were later employed by Yose (1987), Yose and Heller (1989), and R.P. Miller (1989), who studied the sedimentary facies of these units.

Stone (1984) divided the overlying Owens Valley Formation into a Lower Permian and an Upper Permian part separated by an unconformity. Later, Stone and Stevens (1987) formally raised the Owens Valley Formation to group status and introduced the name Lone Pine Formation for the Lower Permian, mostly deep-water marine strata below the unconformity. The Lone Pine Formation is now divided into four informal members (A–D) and the Reward Conglomerate member (Stone et al., 2000).

Here, the Keeler Canyon Formation is subdivided into four formal members. The complete stratigraphic scheme now used for rocks of the Keeler basin and the enclosing units is shown in Figure 3.

KEELER CANYON FORMATION

The Keeler Canyon Formation consists predominantly of evenly bedded, silty to sandy and bioclastic limestone. In most areas this formation overlies black shale of the Upper Mississippian Rest Spring Shale, commonly along a faulted contact, and is conformably overlain by the Lone Pine Formation which consists largely of mudstone with a few normally graded limestones. In the Cerro Gordo Mine area (Fig. 4), the Lone Pine Formation pinches out southeastward along strike, and the Keeler Canyon Formation is unconformably overlain by Lower-Middle (?) Triassic rocks of the Union Wash Formation.

The type section of the Keeler Canyon Formation (Merriam and Hall, 1957) is east of the Estelle Tunnel portal in the Cerro Gordo Mine area. The upper part of this section, designated Section 3 in this report (Fig. 4), was measured by Riggs (1962). The type section is not ideal as the lower part is pervasively sheared and altered, there is a large sill with other possible structural compli-

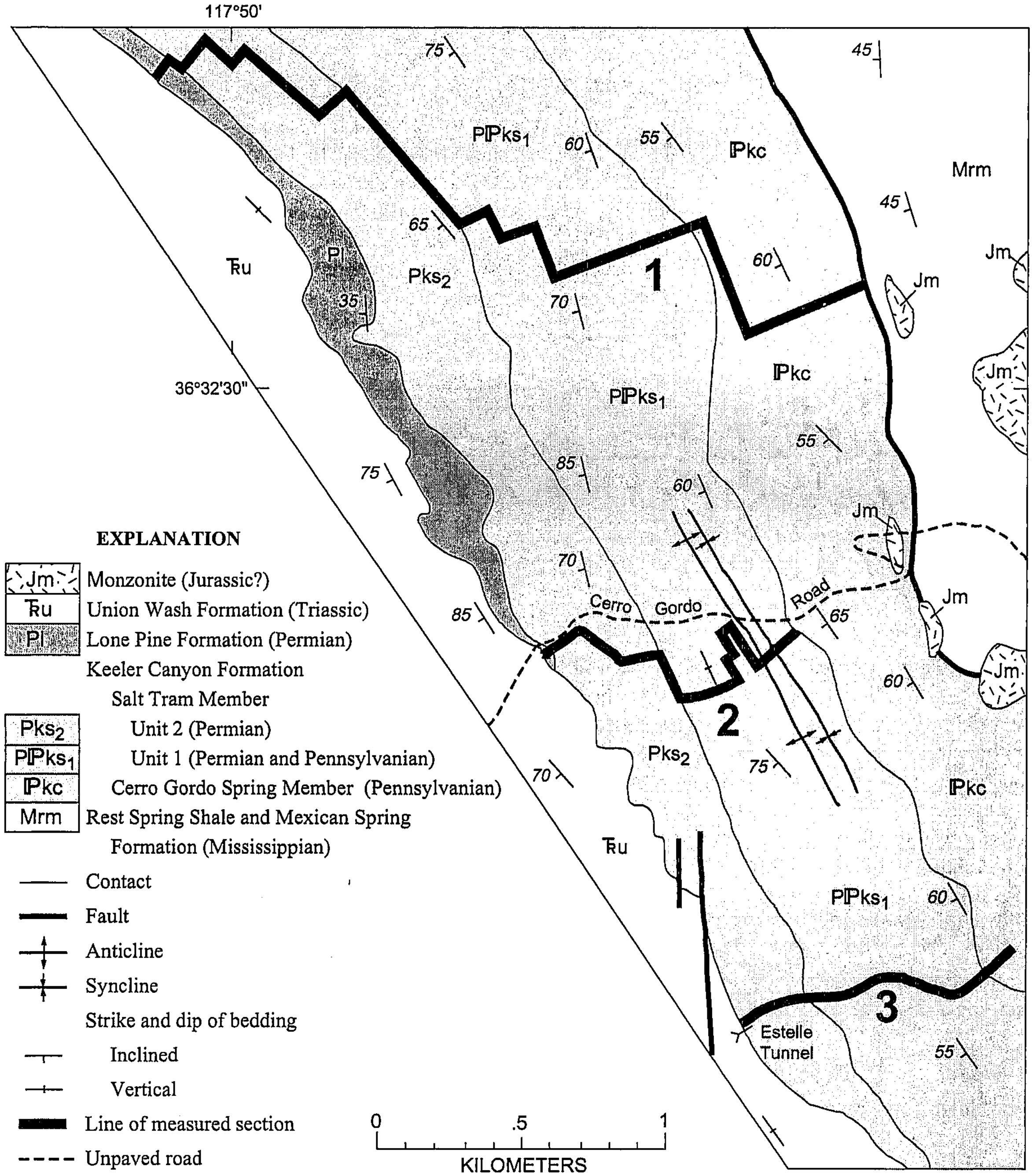


Figure 4. Geologic map of Pennsylvanian and Lower Permian rocks and the enclosing strata in the Cerro Gordo Mine area showing location of measured Sections 1, 2, and 3.

cations in the middle, and the uppermost part is missing due to pre-Triassic erosion. To supplement the type section, we here designate Section 1 of this report, located between 1 and 2.5 km northwest of the Cerro Gordo Road (Fig. 4), as a structurally simpler and more complete reference section of the Keeler Canyon Formation. In this section, the Keeler Canyon Formation is conformably overlain by the Lone Pine Formation and has its maximum known thickness of 1,261 m. The basal Keeler Canyon beds are highly disturbed along a faulted contact with the Rest Spring Shale, but the remainder of the section is mostly undisturbed except by minor folding.

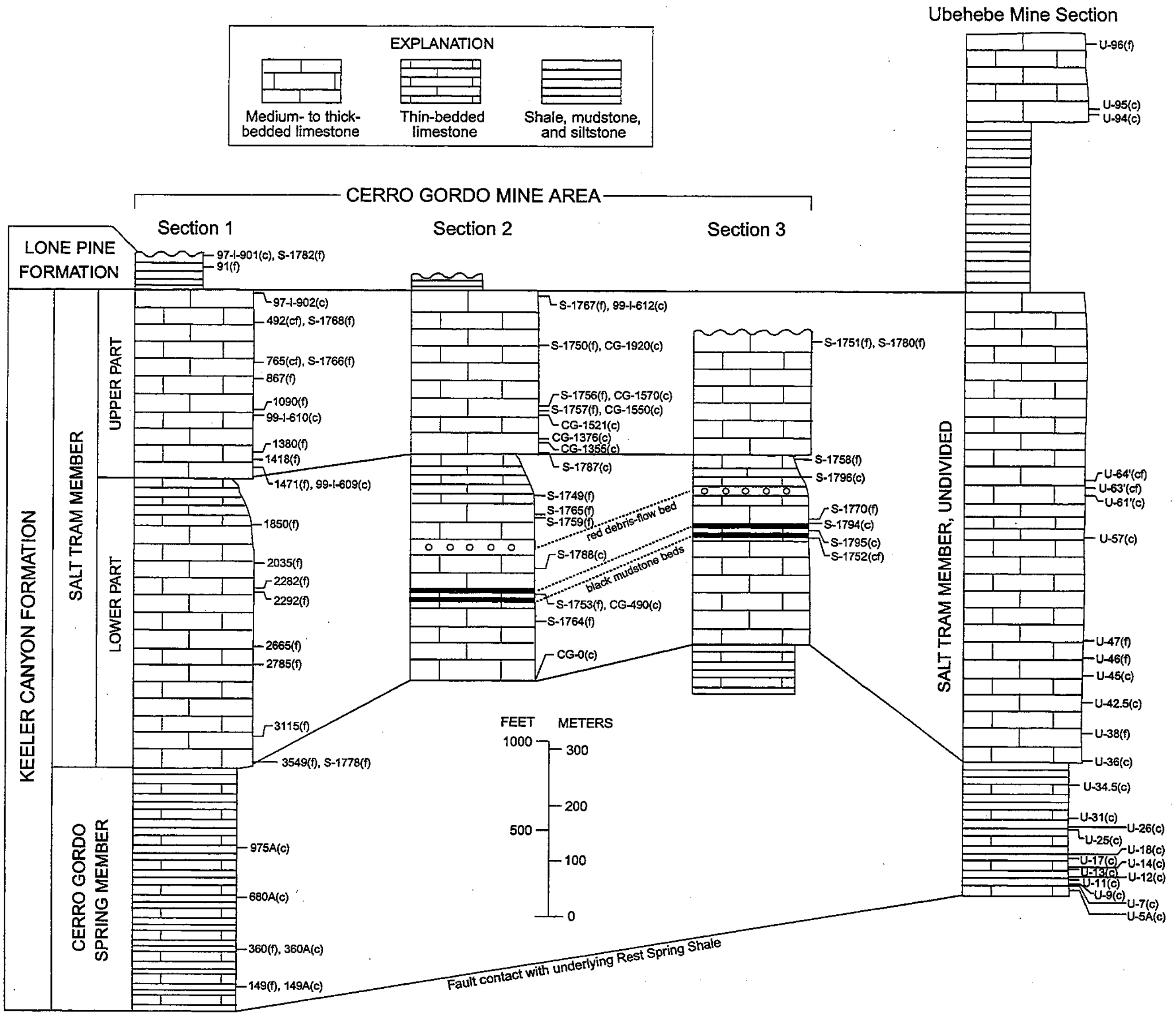


Figure 5. Lithostratigraphic correlation of sections measured in the Keeler basin. Numbers and capital letters refer to fossil samples. f indicates fusulinid sample; c indicates conodont sample. (See Appendix 2 for taxa present).

The Keeler Canyon Formation thins both northwestward and southeastward away from the Cerro Gordo Mine area (Stone, 1984); it is about 425 m thick at Coyote Spring in the vicinity of Independence 30 km to the northwest, and about 350 m thick east of Conglomerate Mesa 15 km to the southeast (Fig. 2). In the Ubehebe Mine area, the Keeler Canyon Formation has a measured thickness of 1,061 m (Stone, 1984) and is similar in lithology and completeness to sections in the Cerro Gordo Mine area (Fig. 5).

In this paper we formally name and describe four members of the Keeler Canyon Formation. They are the Tinemaha Reservoir, Tivhipah Limestone, Cerro Gordo Spring, and Salt Tram Members.

Tinemaha Reservoir Member

The lowest member of the Keeler Canyon Formation is here named the Tinemaha Reservoir Member for strata exposed near Tinemaha Reservoir southeast of Big Pine (Fig. 2). The type section is on a prominent ridge southeast of the reservoir where it is composed of about 400 m of bioclastic limestone, sandy to silty limestone, minor limestone conglomerate, and interbedded shale and siltstone (Stone, 1984). The limestone beds are laterally extensive and display graded bedding and Bouma sequences. The base of this member is placed at the base of the lowest thick limestone which conformably overlies the Rest

Spring Shale. It is conformably overlain by the Tihvipah Limestone Member. Thick exposures of the Tinemaha Reservoir Member are restricted to the type area, but very thin sequences attributable to this member have been recognized elsewhere (e.g., the southernmost Darwin Hills).

Tihvipah Limestone Member

The second member of the Keeler Canyon Formation is equivalent to the Tihvipah Limestone of McAllister (1952) and is here referred to as the Tihvipah Limestone Member. This unit is composed of medium- to dark-gray micritic limestone and light-gray to tan, silty or argillaceous limestone, both of which characteristically contain spherical to subspherical nodules of black chert generally between 0.5 and 2 cm in diameter. These cherty, fine-grained limestones differ from most other rocks in the Keeler Canyon Formation in generally lacking graded bedding and Bouma sequences. Scattered beds of bioclastic and conglomeratic limestone, however, are present locally. In addition to its type area near Quartz Spring, the Tihvipah Limestone Member has been recognized in the Conglomerate Mesa area, the Coyote Spring area near Independence, the Tinemaha Reservoir area, and locally in the Cerro Gordo area. It ranges in thickness from about 30 to 140 m.

This unit lies conformably on the Tinemaha Reservoir Member, wherever that member is present, or evidently unconformably on the Rest Spring Shale. Throughout most of the central part of the Keeler basin, the Tihvipah Limestone Member is missing because of faulting between the Rest Spring Shale and the Keeler Canyon Formation.

Cerro Gordo Spring Member

The Cerro Gordo Spring Member consists primarily of tan-weathering calcareous siltstone interbedded with medium- to dark-gray, fine-grained to bioclastic limestone. The bioclastic limestone typically occurs as graded beds 20 cm to 1.5 m thick; these beds are rich in echinodermal debris and locally contain fusulinids and conodonts. The type section of this member, which is faulted against the Rest Spring Shale, comprises the lower 428 m of Section 1 in the Cerro Gordo Mine area (Figs. 4, 5). The member name is derived from Cerro Gordo Spring near the crest of the Inyo Mountains about 6 km northwest of the Cerro Gordo Road (Fig. 4).

The Cerro Gordo Spring Member is also well developed near Ubehebe Mine, where it has a measured thickness of 231 m above a faulted base (Stone, 1984). There it contains thick limestone megabreccias described by Yose (1987) and Yose and Heller (1989). At Coyote Spring near Independence, where it is about 100 m thick (Stone, 1984), the Cerro Gordo Spring Member conformably overlies the Tihvipah Limestone Member. In the Conglomerate Mesa area, the Cerro Gordo Spring Member is poorly developed and apparently consists of about 20 m of platy gray siltstone characterized by locally abundant bedding-parallel trace fossils (Stone, 1984).

Salt Tram Member

The uppermost part of the Keeler Canyon Formation is here named the Salt Tram Member in reference to an abandoned aerial tramway once used to transport salt across the Inyo Mountains from Saline Valley into Owens Valley. The ruins of the tramway cross the crest of the range about 10 km northwest of the Cerro Gordo Road. The Salt Tram Member, which differs from the Cerro Gordo Spring Member in containing many thick, coarse-grained, graded limestones, was previously referred to informally as the Mexican Spring member or unit (Stone, 1984; Yose and Heller, 1989; R.P. Miller, 1989), but the name Mexican Spring has since been formally applied to a nearby Mississippian formation (Stevens et al., 1996).

The Salt Tram Member conformably overlies the Cerro Gordo Spring Member. The base of the Salt Tram Member is placed at a point in the upper part of the Keeler Canyon Formation where thick limestone beds become predominant. This member is the thickest of the four members and is composed primarily of evenly bedded, medium- to dark-gray, silty to sandy limestone, bioclastic limestone, and conglomeratic limestone interbedded with thin-bedded to laminated gray, tan, and pink, calcareous mudstone and shale. Limestone beds are 25 to 50 cm thick on average but are as thick as 2 m. Beds are laterally extensive and characteristically display graded bedding, Bouma sequences, and flute and groove casts. Fusulinids are common to abundant in some bioclastic limestone beds.

The type section of the Salt Tram Member comprises the upper 833 m of the Keeler Canyon Formation in Section 1 in the Cerro Gordo Mine area (Figs. 4, 5). In this area, the Salt Tram Member is divided into a lower and an upper subunit. The lower subunit contains substantial amounts of calcareous mudstone and shale and the top is marked by a thick zone of relatively thin, fine grained, recessive beds. The upper subunit contains thick packages of resistant, mostly thick-bedded limestone separated by thinner intervals of recessive mudstone and shale. This subunit contains considerably less mudstone and shale than the lower subunit.

In the Ubehebe Mine section where the Salt Tram Member cannot be subdivided, this member is 830 m thick and contains several limestone conglomerates and limestone megabreccia sheets (Stone, 1984; R.P. Miller, 1989). In the northeastern part of the Keeler basin south of Mazourka Canyon (Fig. 2) the Salt Tram Member is only about 225 m thick and is finer grained. In the Conglomerate Mesa area, limestone turbidites assigned to the Salt Tram Member are about 300 m thick and sharply overlie platy siltstone assigned to the Cerro Gordo Spring Member (Stone, 1984).

Undivided Cerro Gordo Spring and Salt Tram Members at San Lucas Canyon.

The Keeler Canyon Formation is extensively exposed in the vicinity of San Lucas Canyon on the east side of the southern Inyo Mountains (Fig. 2). These complexly folded rocks have an estimated thickness of about 1,200 m and consist primarily of thin- to medium-bedded limestone, silty limestone, and calcarenite in which graded bedding, cross lamination, and convolute lamination are locally observed (Werner, 1979). Our mapping shows that in this area the sharp basal contact of the formation with the Rest Spring Shale is probably faulted. Except for a thin, locally developed basal zone of cherty limestone that may represent the Tihvipah Limestone Member, the entire formation in this area is presumably equivalent to the Cerro Gordo Spring and Salt Tram Members. However, in contrast to the Cerro Gordo and Ubehebe Mine areas, neither member is distinctly represented here and we are unable to differentiate between them.

LONE PINE FORMATION

The Lone Pine Formation conformably overlies the Salt Tram Member of the Keeler Canyon Formation. The lower subunit of this formation (member A of Stone and Stevens, 1987) is composed primarily of fine-grained, thin-bedded calcareous mudstone, siltstone, and very fine grained sandstone. The overlying subunits of the Lone Pine Formation (members B, C, D, and the Reward Conglomerate Member) apparently were deposited after the Keeler basin had been modified by an episode of contractile deformation (Stevens and Stone, in press) and are not of primary concern to this study. These higher subunits were recently reviewed and interpreted by Stone et al. (2000).

Member A of the Lone Pine Formation is in excess of 1,000 m thick in the south-central Inyo Mountains (Stone and Stevens, 1987) but thins southward toward the Cerro Gordo Mine area. It is about 240 m thick at the type section of the Lone Pine Formation 2.5 km north of the area of Figure 4, thinning to 67 m in Section 1 where it is unconformably overlain by Early Triassic rocks. This thinning of member A resulted from pre-Triassic deformation and erosion (Stone et al., 2000). Between Section 1 and the Cerro Gordo Road, rocks assigned to the Lone Pine Formation maintain an average thickness of 60 to 70 m, the lower half of which consists of thin-bedded calcareous mudstone and siltstone typical of member A. The upper half of the sequence in this area consists of resistant, fine-grained limestone similar to some limestones in the Keeler Canyon Formation. For unknown reasons these beds are not present in Section 1 and areas farther north. To the south, just north of the Cerro Gordo Road, this upper limestone subunit is erosionally truncated beneath the Union Wash Formation, and a short distance farther south the underlying mudstone subunit is truncated (Fig. 4).

In the Ubehebe Mine area, rocks assigned to the Lone Pine Formation are about 450 m thick with the top eroded and comprise two subunits (Fig. 5). The lower subunit, about 300 m thick, consists of thin-bedded, fine-grained, recessive calcareous to siliceous mudstone, siltstone, and very fine grained sandstone similar to rocks typical of member A of the Lone Pine Formation in the southern Inyo Mountains. The upper subunit, about 150 m thick, is composed of resistant limestone turbidites similar to those of the underlying Salt Tram Member of the Keeler Canyon Formation.

In the Conglomerate Mesa area, the Lone Pine Formation is absent and the Keeler Canyon Formation is unconformably overlain by various units of the informally named sedimentary rocks of Santa Rosa Flat (Magginetti et al., 1988; Stone et al., 1989), some of which are equivalent in age to parts of the Lone Pine Formation. Over much of this area, the rocks directly above the Keeler Canyon Formation are massive echinodermal limestone comprising unit 7 of the sedimentary rocks of Santa Rosa Flat. We also have identified unit 7 limestone in a small outcrop unconformably above the Keeler Canyon Formation in San Lucas Canyon.

SEDIMENTOLOGY

Stevens (1970) was the first to interpret the Keeler Canyon Formation as a turbidite sequence composed largely of graded beds containing a transported fauna of fusulinids and other fossils alternating with very fine grained, unfossiliferous beds. Later sedimentologic, petrographic, and sedimentary facies studies (Parker, 1976; Flora, 1984; Yose, 1987; R.P. Miller, 1989; Yose and Heller, 1989) have demonstrated that the Keeler Canyon Formation represents a submarine fan or a debris apron that accumulated downslope from an extensive, long-lived carbonate shelf or platform. The overlying member A of the Lone Pine Formation has been interpreted to represent deposition in a deep-water basin plain environment mostly far removed from a shallow-water source of carbonate debris (Stone and Stevens, 1987).

Transported calcareous fossils, mostly pelmatozoan columnals, fusulinids, and bryozoans, are abundant locally in the limestone turbidites and debris-flow beds of the Keeler Canyon Formation. On some bedding surfaces fusulinids are strongly aligned, commonly in a layer only a few fusulinids thick; in some beds, fusulinids are size-sorted with different species or different developmental stages of the same species in different layers. Conodonts are moderately abundant in many of these beds.

Fossils in the bioclastic beds evidently were derived from various shallow- to moderately deep-water environments and mixed during transport. In contrast, the fine-grained beds, even the densest micrites, lack not only calcareous fossils but also conodonts. In some of these beds, however, ghosts of radiolarians and siliceous sponge spicules suggestive of deep water have been noted.

Fossils, including both fusulinids and conodonts, are rare in member A of the Lone Pine Formation except in the locally developed limestone subunits and in a few thin limestone turbidites. The only other fossils that have been reported from member A are sponge spicules and calcispheres or calcified radiolarians in some micritic limestone beds (Stone, 1984).

PALEONTOLOGY

ZONATIONS AND AGES

Ten informal fusulinid zones (F1–F10) and nine informal conodont zones (C1–C9), interval zones of Oriel et al. (1983), are recognized in the rocks of the Keeler basin (Figs. 6–8). These informal zones do not designate bodies of rock containing continuous occurrences of particular species or genera or assemblages of species, but instead include sequences of rocks, many of which are devoid of fusulinids or conodont elements, bounded by beds containing the first occurrence of stratigraphically significant species or genera.

The informal zones recognized in the Keeler basin are here correlated with a chronostratigraphic scale (Figs. 6, 7) employing a combination of American and internationally adopted names. Names of American stages for the lower part of the Pennsylvanian are used here because the International Commission on Stratigraphy has yet to implement a formal international scale. For the uppermost Pennsylvanian we use the Russian stage name Gzhelian because that stage is more complete than the American equivalent, the Virgilian. For the Permian we follow the global chronostratigraphic scale recently approved by the Subcommission on Permian Stratigraphy, International Commission on Stratigraphy (Jin et al., 1997). Thus, we use the following stage names. From oldest to youngest they are: Morrowan, Atokan, Desmoinesian, Missourian, Gzhelian, Asselian, Sakmarian, and Artinskian.

FUSULINID PALEONTOLOGY

Fusulinids have long been known from rocks of the Keeler basin but have received little attention. McAllister (1952, 1956) reported *Fusulinella* from the Tihvipah Limestone near Quartz Spring and *Triticites, Pseudofusulina,* and *Schwagerina*? from the Bird Spring(?) Formation near Ubehebe Mine, indicating an Atokan (early Middle Pennsylvanian) to Wolfcampian (Early Permian) age for these rocks that have since been reassigned to the Keeler Canyon Formation. Similarly, Merriam and Hall (1957) reported *Fusulinella, Triticites,* and *Pseudofusulina* from the Keeler Canyon Formation in the southern Inyo Mountains. Riggs (1962) described and illustrated fusulinids from 15 collections in the upper 650 m of the type section of the Keeler Canyon Formation in the southern Inyo Mountains. He assigned species to *Pseudofusulinella, Triticites, Schwagerina,* and *Pseudofusulina,* indicating a Virgilian (late Late Pennsylvanian) to Wolfcampian age. Stone (1984) presented a preliminary report on the fusulinids from the Pennsylvanian and Permian rocks in the Inyo Mountains region, including a list of 30 taxa from the Keeler Canyon Formation and member A of the Lone Pine Formation, and illustrations of 24 of the species. These fusulinids, which included *Pseudoschwagerina* in addition to other genera reported previously, were interpreted to indicate an age of Atokan to early middle Wolfcampian. Most recently Stone et al. (2000) briefly described and illustrated some fusulinids from member A of the Lone Pine Formation and from member B of that formation, which is part of the overlap assemblage that postdates deformation of the Keeler basin.

The fusulinids identified for this study are mostly from the Cerro Gordo Mine area although collections from other areas also were used. In addition to collections reported for the first time here, all collections previously reported by Stone (1984) were reexamined and several localities originally reported by Riggs (1962) were recollected. Most of the collections are from the Salt Tram Member of the Keeler Canyon Formation, in which fusulinids are locally very abundant. Fewer collections are from the Cerro Gordo Spring Member, only four are from the Tihvipah Limestone Member, and only one sample from the Tinemaha Reservoir Member contains fusulinids. Four collections of fusulinids from member A of the Lone Pine Formation also are reported.

Sixty-one fusulinid species identified for this study are listed and briefly described in Appendix 3, and are illustrated in Figures 9–11. Reduced photographs of some of the important species are shown in stratigraphic sequence in Figure 12. Many of the species encountered in our samples appear to be new, but because of the paucity of specimens of most species and poor preservation, no new

UNIT		AGE		FUSULINID		CONODONT	
				Zone	Sample	Zone	Sample
Lone Pine Formation		Lower Permian	Sakmarian	F10	91; U-96; S-1760, -1782	C9	492; 97-I-901, -902; 99-I-608, -612, -613; U-94, -95
Keeler Canyon Formation	Salt Tram Member			F9	492, 765; S-1750, -1751, -1766, -1767, -1768, -1772, -1774, -1775, -1777, -1780; 82-I-23, 24		
			Asselian	F8	867, 1090; S-1756, S-1757	C8	765; S-1787; CG-1355, -1376, -1521, -1550, -1570, -1920; U-63'?, -64'?: 82-I-24?; 99-I-609, -610
				F7	1380, 1418, 1471; S-1747?; 79-CM-84		
				F6	1850, 2035; S-0613, -0614, -0856, -1749, -1758, -1759, -1765; 79-CM-86; U-63', -64'		
		Upper Carboniferous	Gzhelian	F5	2282, 2292, 2665; S -1371, -1700, -1746?, -1752, -1753, -1764, -1770; U-46, -47	C7	CG-490; S-1752, -1794, -1795, -1796; U-45, -57, -61'; 98-I-922?
	Cerro Gordo Spring Member			F4	2785, 3115, 3549; S-1778; U-38	C6	CG-0; U-34.5, -36, -42.5; 98-I-926, 927, 928
			Missourian	F3	S-0858	C5	U-17, -18, -25, -26, -31
						C4	U-13, -14
						C3	975A; U-12
			Desmoinesian	F2	149, 360; S-1389b, S-1773; 82-I-31; GH-1, -2, -5	C2	149A, 360A, 680A; U-5A, -7, -9, -11; 82-I-28, -29, -30
	Tihvipah Ls. Member					C1	80-RS-2, -3, -4; GH-4B, -5A
			Atokan	F1	S-1208, -1225		None
	Tinemaha Res. Member		Morrowan		None		T-1

Figure 6. Correlation of fusulinid and conodont zones recognized in the Keeler basin indicating samples assigned to each zone.

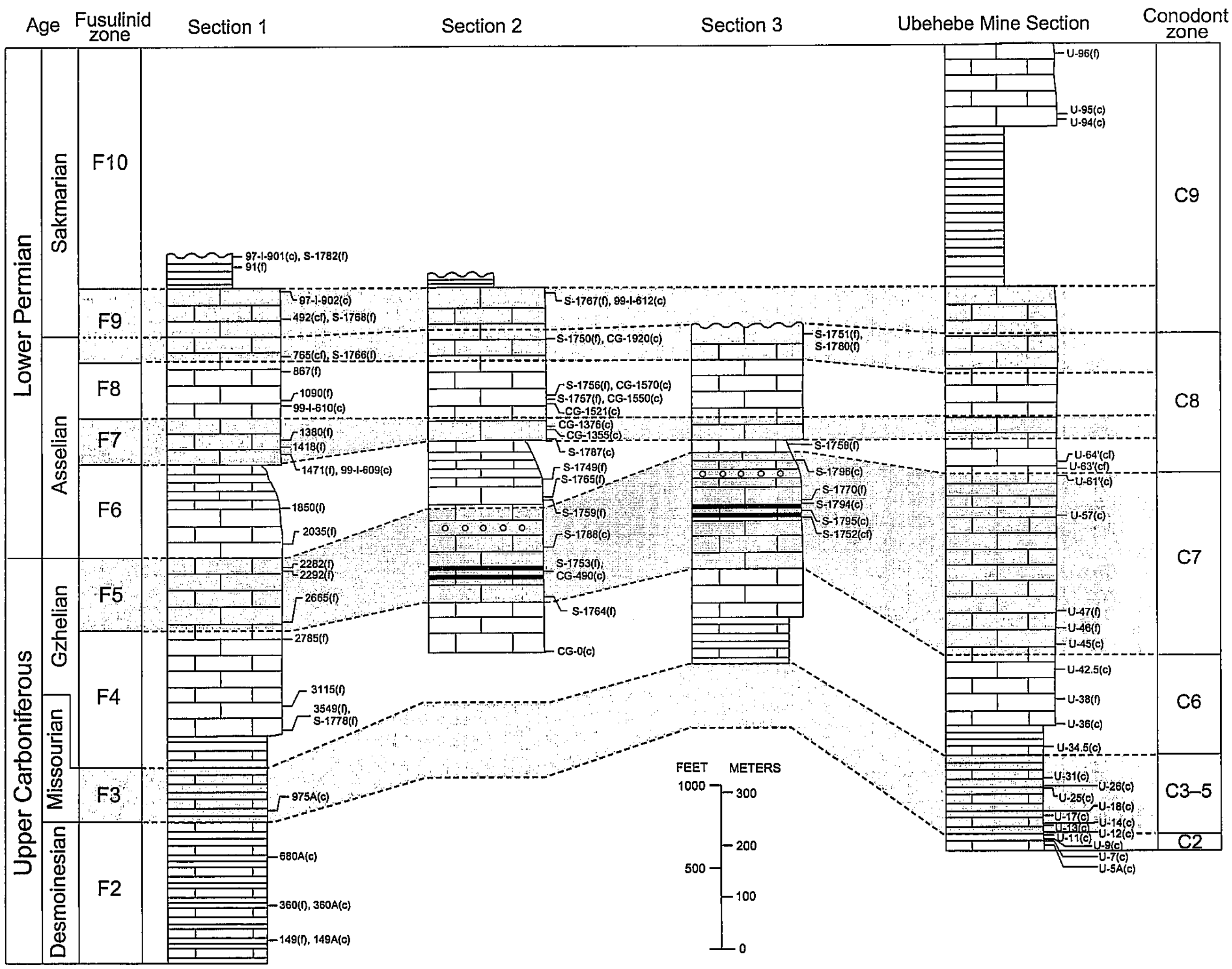


Figure 7. Stratigraphic position of fusulinid and conodont zones in measured sections in the Keeler basin.

taxa are described at this time. Instead, most specimens from our study area are compared with similar species previously described.

Local fusulinid zones and regional correlations

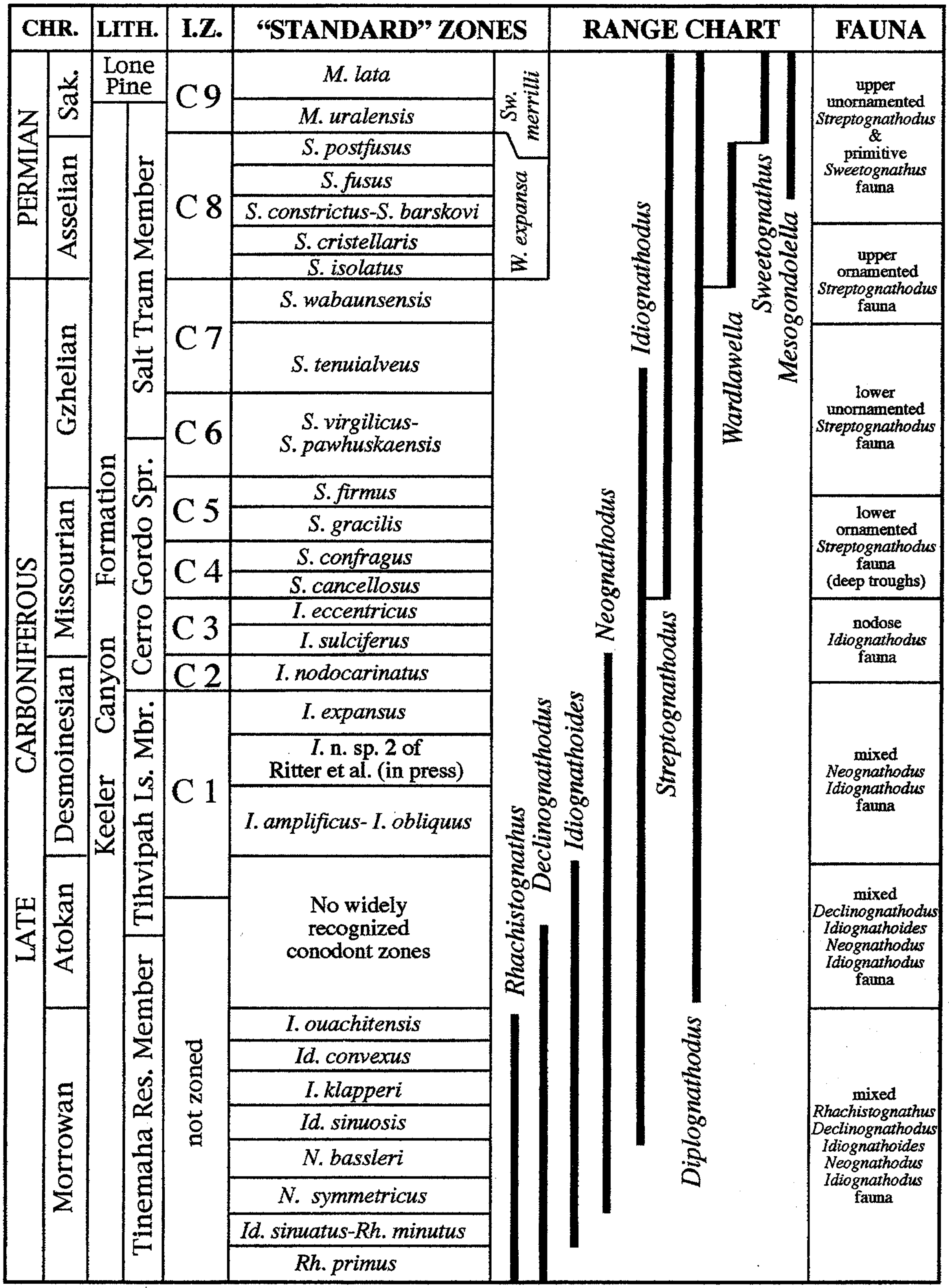
The fusulinid zones recognized here can be generally correlated with fusulinid faunas from other parts of North America (Table 1). We base our correlations mostly upon our own interpretations of fusulinid faunal relationships modified to some extent by consideration of the detailed correlations of Ross and Ross (1999).

Fusulinid Zone F1.—This zone in the Keeler Canyon Formation is conceived to be equivalent to the widely recognized Zone of *Fusulinella* (Thompson, in Loeblich and Tappan, 1964) in North America. Species in the Keeler Canyon Formation include *Fusulinella fugax* and *Pseudostaffella* cf. *P. powwowensis.*

Fusulinid Zone F2.—This zone corresponds to the Desmoinesian stage in the United States and is characterized by several species of *Beedeina* and *Wedekindellina.* Species recognized include *Beedeina* aff. *B. acme, B.* cf. *B. apachensis, B.* cf. *B. cappsensis, B.* aff. *B. haworthi, B.* aff. *B. occultifons, B.* sp. 1, *Wedekindellina* cf. *W. cabezasensis,* and *W.* sp. 1.

Fusulinid Zone F3.—This zone was conceived to correspond to the Missourian stage in the United States. Unfortunately it is recognized only on the basis of speci-

Figure 8. "Composite Standard Zonation" for conodonts correlated with stratigraphic units in the Keeler basin. CHR. = chronostratigraphy, LITH. = Lithostratigraphy, I.Z. = informal zones, Rh. = Rhachistognathus, Id. = Idiognathoides, I. = Idiognathodus, N. = Neognathodus, S. = Streptognathodus, Sw. = Sweetognathus, W. = Wardlawella.


CHR.
LITH.
I.Z.
"STANDARD" ZONES
RANGE CHART
FAUNA
PERMIAN
Sak.
Asselian
LATE CARBONIFEROUS
Gzhelian
Missourian
Desmoinesian
Atokan
Morrowan
Lone Pine
Keeler Canyon Formation
Salt Tram Member
Cerro Gordo Spr.
Tihvipah Ls. Mbr.
Tinemaha Res. Member
C 9
C 8
C 7
C 6
C 5
C 4
C 3
C 2
C 1
not zoned
M. lata
M. uralensis
S. postfusus
S. fusus
S. constrictus-S. barskovi
S. cristellaris
S. isolatus
S. wabaunsensis
S. tenuialveus
S. virgilicus-
S. pawhuskaensis
S. firmus
S. gracilis
S. confragus
S. cancellosus
I. eccentricus
I. sulciferus
I. nodocarinatus
I. expansus
I. n. sp. 2 of
Ritter et al. (in press)
I. amplificus- I. obliquus
No widely
recognized
conodont zones
I. ouachitensis
Id. convexus
I. klapperi
Id. sinuosis
N. bassleri
N. symmetricus
Id. sinuatus-Rh. minutus
Rh. primus
Sw. merrilli
W. expansa
Rhachistognathus
Declinognathodus
Idiognathoides
Neognathodus
Idiognathodus
Streptognathodus
Diplognathodus
Wardlawella
Sweetognathus
Mesogondolella
upper
unornamented
Streptognathodus
&
primitive
Sweetognathus
fauna
upper
ornamented
Streptognathodus
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Streptognathodus
fauna
lower
ornamented
Streptognathodus
fauna
(deep troughs)
nodose
Idiognathodus
fauna
mixed
Neognathodus
Idiognathodus
fauna
mixed
Declinognathodus
Idiognathoides
Neognathodus
Idiognathodus
fauna
mixed
Rhachistognathus
Declinognathodus
Idiognathoides
Neognathodus
Idiognathodus
fauna


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mens from a single random sample. None of the fusulinids at the appropriate stratigraphic position in measured sections are identifiable. Simple species of *Triticites*, including *T. burgessae*, are considered to belong to this zone.

Fusulinid Zone F4.—Zone F4 is characterized by the appearance of large species of *Triticites*, some of them highly inflated. Species present in the Keeler Canyon Formation include *Triticites californicus?*, *T.* cf. *T. hermanni*, *T.* aff. *T. hobblensis*, *T. whetstonensis*, and *T.* sp. 2.

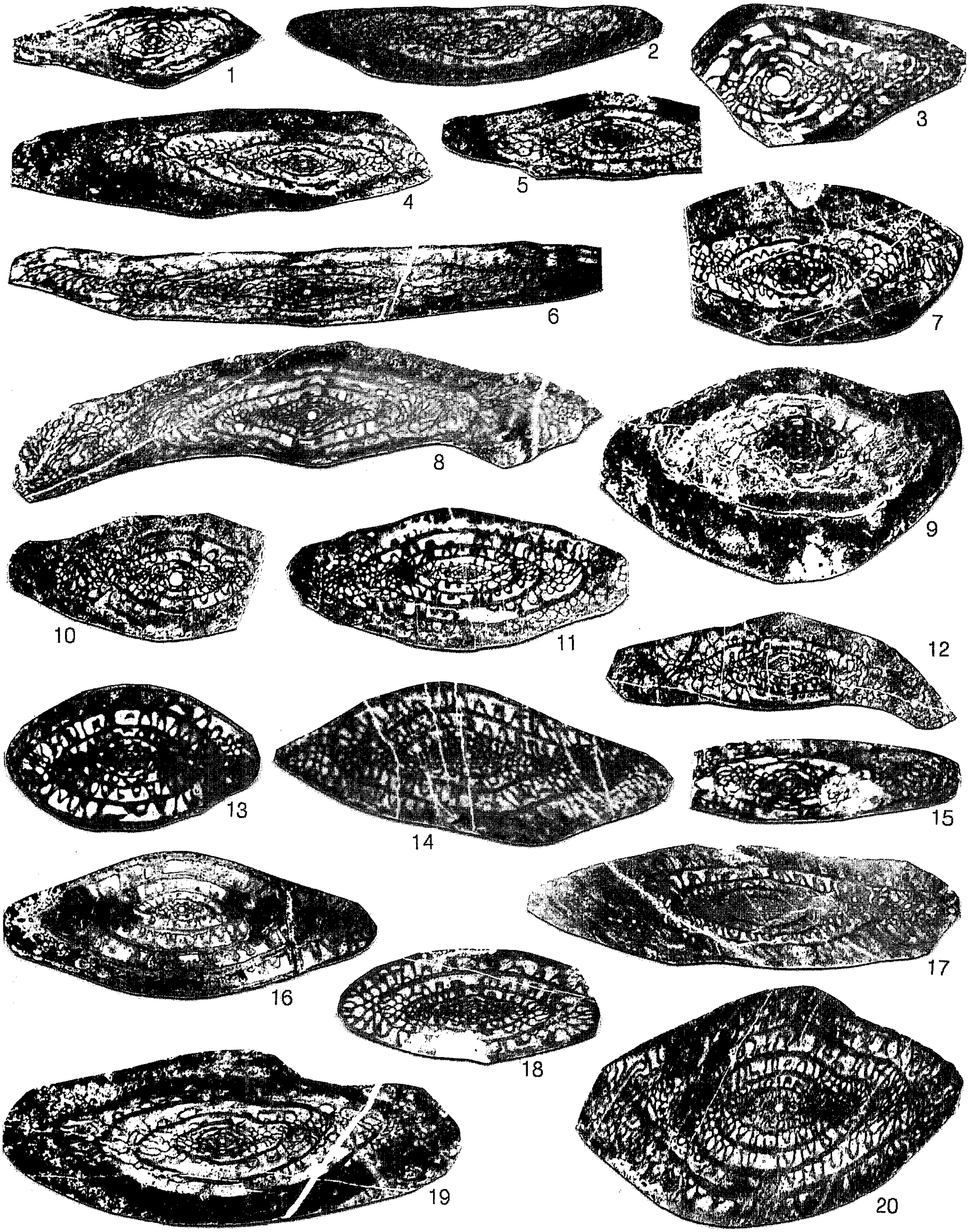
A similar fauna occurs in Beds 289–92A in the Bird Spring Formation in southern Nevada (Rich, 1961), suggesting a similar age, and *T. whetstonensis* allows correlation with the lower part of the Earp Formation in southern Arizona. *Triticites* sp. 2 in the Keeler basin is similar to *T. turgida* which occurs in bed H of the Gaptank Formation (C.A. Ross, 1965) in the Glass Mountains which Ross correlated with the middle Cisco Group of central Texas and the Shawnee Group in the midcontinent region. A form very close to *T. whetstonensis* occurs in the upper Cisco (Ross and Tyrell, 1965), which was correlated by C.A. Ross (1965) with the upper part of the Wabaunsee Group in the midcontinent. Based on the overall fauna we also correlate Fusulinid Zone F4 with the Admire Group in Kansas as shown by Thompson (1954). The presence of *Triticites* cf. *T. hermanni* in the Keeler basin suggests correlation with Zone A of the McCloud Limestone in the Klamath Mountains (Skinner and Wilde, 1965). The faunas in these rocks are typically Virgilian.

Fusulinid Zone F5.—Large, inflated species of *Triticites* continue to be the dominant forms in this zone, but they are accompanied by small, unidentified species of *Schwagerina* with low, irregularly folded septa. Besides species of *Schwagerina*, this fauna includes *Pseudofusulinella* sp. 1, *Triticites* aff. *T. beedei*, *T. cellamagnus*, *T. confertoides*, possibly *T.* cf. *T. hermanni*, *T.* aff. *T. kelleyensis*, *T. pinguis*, *T.* aff. *T. ventricosus* var. *sacramentoensis*, *T.* sp. 2, *T.* sp. 3, *T.*? sp. 4, and a form resembling *T. burgessae.*

These faunas suggest correlation with Beds 90A–62A of the Bird Spring Formation in southern Nevada (Rich, 1961), "post-Virgilian" beds of Sabins and Ross (1963) near or at the base of the Earp Formation in Arizona, and bed J of C.A. Ross (1965; Bed 2 of the Gray Limestone Member) of the Gaptank Formation in the Glass Mountains, which according to Wilde (1971) contains *Schwagerina.* Most of the Pueblo Formation in north-central Texas and the lower half of the Council Grove Group in Kansas also probably correlate with Fusulinid Zone F5 on the basis of the overall similarity of the faunas, consisting of largely of species of *Triticites* with generally small, primitive species of *Schwagerina.* It is uncertain whether or not this zone is represented in the Klamath Mountains section. The lack of primitive species of *Schwagerina* in that section suggests that an equivalent of this zone may be missing, and Skinner and Wilde's (1965) observation that there is an apparent discordance between Zones A and B there strengthens this interpretation. These faunas commonly have been considered post-Virgilian or Wolfcampian. Here, this fauna is considered Gzhelian (latest Carboniferous) on the basis of the composition of both the fusulinid and associated conodont faunas (see later).

Fusulinid Zone F6.—This zone is characterized by a wide variety of inflated species of *Triticites* and moderately large, inflated species of *Schwagerina* having regularly and highly folded septa. Species include *Pseudofusulinella* sp. 1, *Schwagerina aculeata, S. modica, S.* sp. 3, *Triticites cellamagnus, T. confertoides, T.* aff. *T. directus, T.* aff. *T. hobblensis, T. meeki, T. pinguis, T.* aff. *T. ventricosus* var. *sacramentoensis, T.* sp. 3, *T.*? sp. 4, and *Reticulosepta*? sp. 8.

Figure 9. Illustrations of fusulinid taxa recognized in this study. 1, Pseudostaffella *cf.* P. powwowensis *(Thompson) from locality S-1225, x20 (SJS 82f); 2,* Beedeina *cf.* B. apachensis *(Ross and Sabins) from locality GH-1, x10 (SJS 83f); 3,* Beedeina *cf.* B. cappsensis *(Stewart) from locality 82-I-31, x10 (SJS 84f); 4,* Beedeina *aff.* B. haworthi *(Beede) from sample 149, x10 (SJS 85f); 5,* Beedeina *aff.* B. occultifons *(Alexander) from sample 149, x10 (SJS 86f); 6,* Beedeina *sp. 1 from locality 82-I-31, x10 (SJS 87f) 7,* Beedeina *aff.* B. acme *(Dunbar and Henbest) from locality S-1773, x10 (SJS 88f) 8,* Pseudofusulinella simplex *Skinner and Wilde from locality 79-CM-84, x10 (SJS 89f) 9,* Fusulinella fugax *Thompson from locality S-1208, x20 (SJS 90f); 10,* Pseudofusulinella *sp. 1 from locality S-1747, x20 (SJS 91f); 11,* Pseudofusulinella parvula *Skinner and Wilde from locality S-1747, x20 (SJS 142f); 12,* Wedekindellina *cf.* W. cabezasensis *Ross and Sabins from locality GH-2, x10 (SJS 92f) 13,* Wedekindellina *sp. 1 from sample 360, x10 (SJS 93f); 14,* Triticites *aff.* T. beedei *Dunbar and Condra from sample 2292, x10 (SJS 94f); 15,* Triticites burgessae *Burma from locality S-0858, x10 (SJS 95f); 16,* Triticites *aff.* T. hobblensis *Thompson, Verville, and Bissell from sample 3115, x10 (SJS 96f); 17,* Triticites *aff.* T. directus *Thompson from sample 1380, x10 (SJS 97f); 18,* Triticites *cf.* T. hermanni *Skinner and Wilde from sample 3549, x10 (SJS 98f) 19,* Triticites *sp. 2 from sample 2665, x10 (SJS 99f); 20,* Triticites *aff.* T. kelleyensis *Needham from locality S-1753, x10 (SJS 100f); 21,* Triticites mulleri *Skinner and Wilde from locality S-1700, x10 (SJS 101f); 22,* Triticites meeki *Thompson from locality 79-CM-84, x10 (SJS 102f); 23,* Triticites pinguis *Dunbar and Skinner from locality S-1752, x10 (SJS 103f); 24,* Triticites *aff.* T. ventricosus *var.* sacramentoensis *Needham from locality S-0856, x10 (SJS 104f); 25,* Triticites whetstonensis *Ross and Tyrrell from sample 3549, x10 (SJS 105f); 26,* Triticites *sp. 1 from locality 79-CM-84, x10 (SJS 106f); 27,* Triticites californicus *Thompson and Hazzard? from sample 3549, x10 (SJS 107f); 28,* Triticites *sp. 3 from locality S-1770, x10 (SJS 108f); 29,* Triticites confertoides *Ross from locality S-1752, x10 (SJS 109f); 30,* Reticulosepta? *sp. 8 from locality S-1759, x10 (SJS 110f).*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Zone F6 is correlated with the highest beds in the Earp Formation assigned a post-Virgilian age by Sabins and Ross (1963). This interpretation is based on the presence of *Schwagerina vervillei* in the Earp Formation, a species quite similar to *S. aculeata* and probably about the same age. *Schwagerina vervillei* also occurs in the middle Council Grove Group in Kansas (Thompson, 1954), indicating correlation with those beds. The presence of the highly inflated species of *Schwagerina, S. ventricosa,* in Zone B in the Klamath Mountains also suggests correlation with Fusulinid Zone F6. The presence of *S. aculeata,* which in the Providence Mountains in southeastern California occurs with *Pseudoschwagerina* (Thompson et al., 1946), indicates that this zone is Permian in age.

Fusulinid Zone F7.—This zone is marked by the appearance of *Pseudoschwagerina.* Inflated specimens of *Triticites* are still common. Species include *Pseudofusulinella simplex, Pseudoschwagerina* cf. *P. needhami, P.* aff. *rhodesi, Schwagerina dunnensis,* S. sp. 1, S. sp. 3, *Triticites cellamagnus, T. meeki, T. pinguis*?, *T.* aff. *T. ventricosus* var. *sacramentoensis,* and *T.* sp. 1.

Zone F7 probably correlates with much of the Earp Formation in southern Arizona (Sabins and Ross, 1963), in which inflated species of *Triticites* are also still common. Zones C and D in the Klamath Mountains are correlated with Fusulinid Zone F7 on the basis of the first appearance of *Pseudoschwagerina* (in Zone C), and the presence of *Pseudofusulinella simplex* (in Zone D). Zone D also contains *Paraschwagerina magna,* which is similar to *P. gigantea* from the Neal Ranch Formation, suggesting correlation with part of that unit. These faunas are considered Wolfcampian throughout North America.

Fusulinid Zone F8.—This zone is marked by the appearance of a primitive species of *Eoparafusulina* resembling, but more primitive and probably slightly older than, *E. gracilis* from the Klamath Mountains. Other species include *Reticulosepta*? sp. 6, *Schwagerina* aff. *S. andresensis,* S. aff. *S. sublettensis,* and S. sp. 3. *Eoparafusulina* aff. *E. gracilis* suggests correlation with Zone E of the McCloud Limestone. Typical *Eoparafusulina* is considered Sakmarian by V. Davydov (pers. commun, 2000), but this very primitive form may instead be Asselian as suggested by the associated conodonts (see later).

Fusulinid Zone F9.—This zone is marked by the appearance of typical forms of *Eoparafusulina (E.* sp. 1), *Stewartina,* many species of *Reticulosepta,* and species of *Schwagerina* with intensely folded septa, including a form somewhat similar to *S. bellula.* Species include *Pseudofusulinella parvula, Reticulosepta* sp. 1, *R.*? sp. 2, *R.*? sp. 3, *R.*? sp. 4, *R.*? sp. 5, *R.*? sp. 6?, *R.* sp. 7, *Schwagerina* aff. *S. andresensis, S.* aff. *S. arta,* possibly *S. bellula, S.* aff. *S. sublettensis, S. turgida, S.* sp. 1, *Stewartina* sp. 1, *S.* sp. 3, *S.*? cf. *S.*? aff. *laxissima, Chusenella* cf. *C. jewetti, Pseudoschwagerina* aff. *P. parabeedi,* possibly *Pseudofusulina decora,* and *Eoparafusulina* sp. 1.

Eoparafusulina sp. 1 is similar to species of the genus described by Ross (1967) from the upper part of the Neal Ranch Formation suggesting correlation with that part of the Glass Mountains section. *Stewartina,* represented by *S. texana,* also first appears in the Neal Ranch Formation (Ross, 1963; per. comm., 2000). *Schwagerina turgida* and S. aff. *S. arta* in Fusulinid zone 9 suggest correlation with zone F in the Klamath Mountains, but the presence of the form similar to *S. bellula,* which compares with *Paraschwagerina fax* and *P. elongata,* and *Pseudofusulina decora*? suggest correlation with Zone E. We prefer correlation with Zone E because it is more compatible with our correlation of Fusulinid Zone 10.

Fusulinid Zone F10.—This zone is distinguished by delicate, inflated species of *Schwagerina,* especially S. cf. *S. bellula.* Other species represented include *Pseudofusulinella parvula, Pseudofusulina decora, Schwagerina* aff. *S. andresensis, S. turgida,* S. sp. 2, *Stewartina* sp. 2, and possibly *Reticulosepta*? sp. 6.

Fusulinid Zone F10 contains several species in common with Fusulinid Zone F9, but lacks the profusion of species of *Reticulosepta* present in the lower zone.

Schwagerina cf. *S. bellula* suggests correlation with the upper Neal Ranch Formation or the younger Lenox Hills Formation (Ross, 1963). This species is reported to extend

Figure 10. Illustrations of fusulinid taxa recognized in this study. 1, Reticulosepta *sp. 2 from sample S-1751 (SJS 111f); 2,* Reticulosepta? *sp. 6 from locality S-1750 (SJS 112f); 3,* Triticites cellamagnus *Thompson and Bissell from locality S-1749 (SJS 113f); 4,* Reticulosepta? *sp. 4 from locality S-1750 (SJS 114f); 5,* Triticites? *sp. 4 from locality S-0613 (SJS 115f); 6,* Reticulosepta? *sp. 7 from sample 492 (SJS 116f); 7,* Pseudoschwagerina *cf.* P. needhami *Thompson, 79-CM-84 (SJS 117f); 8,* Reticulosepta *sp. 1 from sample S-1751 (SJS 118f); 9,* Pseudoschwagerina *aff.* P. rhodesi *Thompson from sample 1471 (SJS 119f); 10,* Schwagerina modica *Thompson and Hazzard from sample 2035 (SJS 120f); 11,* Schwagerina *cf.* S. bellula *Dunbar and Skinner from sample S-1782 (SJS 76f); 12,* Schwagerina *aff.* S. sublettensis *Thompson, Dodge, and Youngquist from locality S-1756 (SJS 121f); 13,* Schwagerina *sp. 2 from sample U-96 (SJS 122f); 14,* Schwagerina *sp. 1 from sample S-1767 (SJS 123f); 15,* Schwagerina dunnensis *Sabins and Ross from sample 1418 (SJS 124f); 16,* Schwagerina aculeata *Thompson and Hazzard from sample 2035 (SJS 125f); 17,* Schwagerina *aff.* S. arta *Skinner and Wilde from sample 492 (SJS 126f); 18,* Schwagerina *aff.* S. andresensis *Thompson from sample S-1756 (SJS 127f); 19,* Reticulosepta? *sp. 5 from sample S-1772 (SJS 128f); 20,* Schwagerina turgida *Skinner and Wilde from sample S-1766 (SJS 129f). All figures x10.*

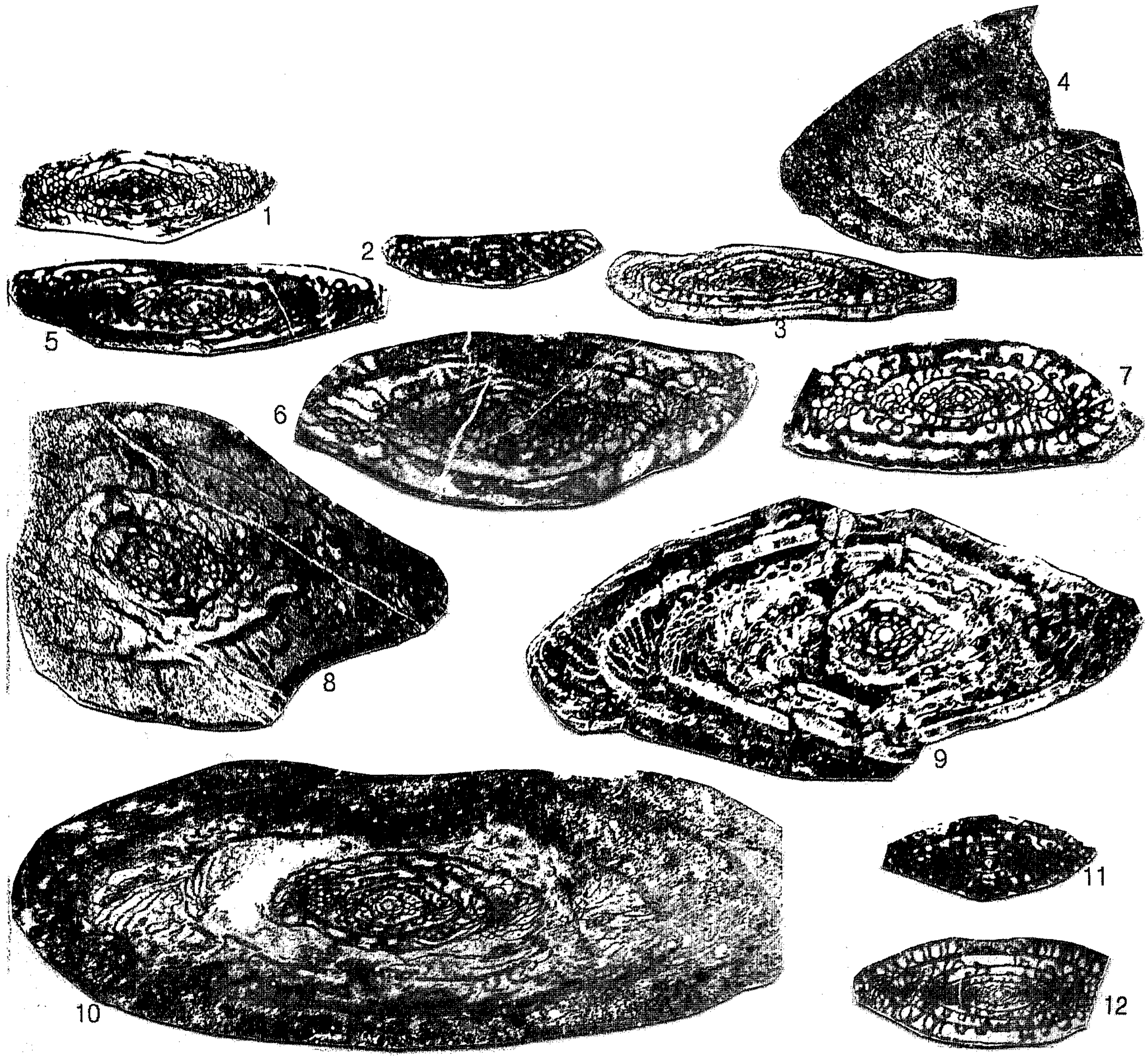
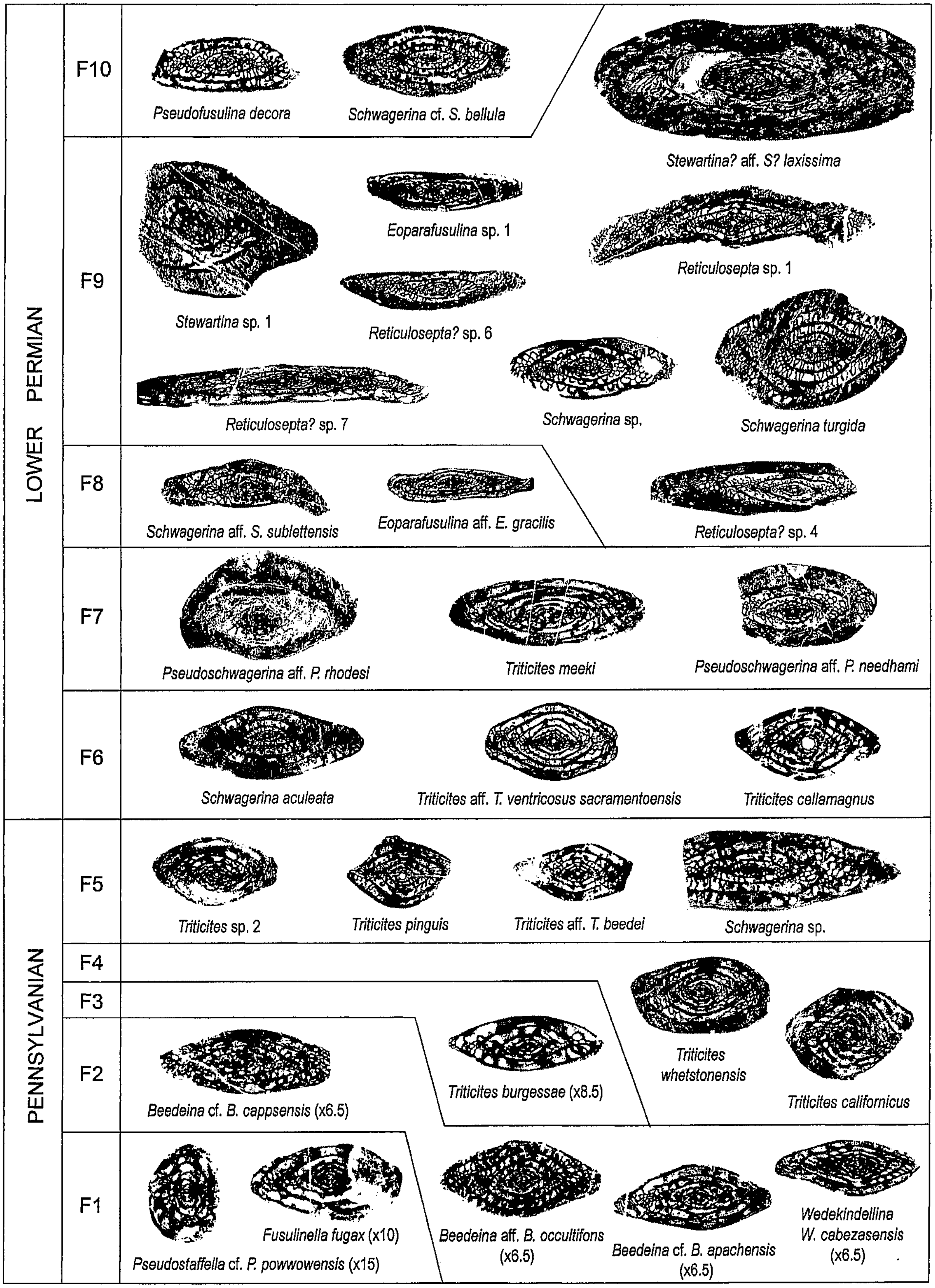


Figure 11. Illustrations of fusulinid taxa recognized in this study. 1, Reticulosepta? *sp. 3 from sample S-1780 (SJS 130f); 2,5,* Eoparafusulina *sp. 1 from sample S-1774 (SJS 131f) and locality 82-I-23 (SJS 132f), respectively; 4,* Pseudoschwagerina *aff.* P. parabeedei *Ross from sample S-1777 (SJS 133f); 3,* Eoparafusulina *aff.* E. gracilis *(Meek) from sample 867 (SJS 134f); 6,* Stewartina *sp. 3 from sample 492 (SJS 135f); 7,* Pseudofusulina decora *Skinner and Wilde from locality S-1760 (SJS 136f); 8,* Stewartina *sp. 1 from sample 765 (SJS 137f); 9,* Stewartina *sp. 3 from sample 91 (SJS 138f); 10,* Stewartina? *aff.* S.? laxissima *(Dunbar and Skinner) from locality S-1766 (SJS 139f); 11,* Schwagerina *sp. 3 from locality S-1758 (SJS 140f); 12,* Chusenella *cf.* C. jewetti *(Thompson) from locality 82-I-23 (SJS 141f). All figures x10.*

through a considerable thickness of beds in the Hueco Canyon Formation in the Franklin Mountains (Williams, 1966), but the type specimens were collected from the basal beds of the Hueco Limestone in the Hueco Mountains (Dunbar and Skinner, 1937). There, this species and *Stewartina* aff. *S. texana* occur in beds below those containing the coral *Stylastraea* sp. (Larry Wollschlager, per. commun., 1975). In the Franklin Mountains *Stylastraea* also occurs above most of the occurrences of *S. bellula*, although Williams (1966) reported it higher in the section. Similarly, in northeastern Nevada, the upper part of the Riepe Spring Limestone, which contains *Stylastraea* spp.,

Table 1. Correlation of fusulinid zones with important sections in North America modified according to some conodont data.

Series boundaries based on conodont faunas (Ural Mountains)	Correlations based largely on fusulinid faunas and stratigraphic position													
	Keeler Basin (this study)		Southern Nevada (Rich, 1961)		Arizona (Sabins and Ross, 1963)		Glass Mts., Texas C.A. Ross, 1963, 1965)		North-central Texas (C.A. Ross, per. comm., 2000)		Kansas (Thompson, 1954)		Klamath Mts., California (Skinner and Wilde, 1965)	
Sakmarian	Lone Pine Fm.	Zone F10		?		?	Neal Ranch Formation	middle and upper	Pueblo Formation	upper	Council Grove Group	upper	McCloud Limestone	Zones E and F?
	Keeler Canyon Formation	Zone F9										middle		
Asselian		Zone F8	Bird Spring Formation	bed 23A?										Zone E
		Zone F7		bed 32A?	Earp Formation	samples 15–25 "Wolfcampian"				middle				Zone D / Zone C
		Zone F6		?		sample 70b "post-Virgilian"		lower						Zone B
Gzhelian		Zone F5		beds 90A–62A		samples 11–14, 54–70a "post-Virgilian"	Gaptank Formation	bed J / *Uddenites*-bearing shale		lower		lower		?
		Zone F4		beds 289–92A		samples 10, 38–48 "Virgilian"		beds H and I		middle-upper Cisco Group		Admire Group Wabaunsee Gp. Shawnee Gp.		Zone A / ?


LOWER PERMIAN
PENNSYLVANIAN
F10
Pseudofusulina decora
Schwagerina cf. S. bellula
Stewartina? aff. S? laxissima
F9
Stewartina sp. 1
Eoparafusulina sp. 1
Reticulosepta sp. 1
Reticulosepta? sp. 6
Reticulosepta? sp. 7
Schwagerina sp.
Schwagerina turgida
F8
Schwagerina aff. S. sublettensis
Eoparafusulina aff. E. gracilis
Reticulosepta? sp. 4
F7
Pseudoschwagerina aff. P. rhodesi
Triticites meeki
Pseudoschwagerina aff. P. needhami
F6
Schwagerina aculeata
Triticites aff. T. ventricosus sacramentoensis
Triticites cellamagnus
F5
Triticites sp. 2
Triticites pinguis
Triticites aff. T. beedei
Schwagerina sp.
F4
F3
F2
Beedeina cf. B. cappsensis (x6.5)
Triticites burgessae (x8.5)
Triticites whetstonensis
Triticites californicus
F1
Fusulinella fugax (x10)
Pseudostaffella cf. P. powwowensis (x15)
Beedeina aff. B. occultifons (x6.5)
Beedeina cf. B. apachensis (x6.5)
Wedekindellina W. cabezasensis (x6.5)

was shown by Stevens et al. (1979) to lie above a zone referred to as the zone of *S. bellula.*

In most areas *Eoparafusulina linearis* makes its debut a short distance above *Stylastraea.* This species occurs in the Lenox Hills Formation, at the top of the Hueco Canyon Formation in the Franklin Mountains, and at the base of the Rib Hill Sandstone immediately above the Riepe Spring Limestone in Nevada. In both of the latter two areas, *E. linearis* lies above the zone of *Stylastraea.* Beds containing *Stylastraea* and the slightly younger beds containing *E. linearis* can be correlated throughout northeastern Nevada and West Texas. Thus, the lower Hueco Canyon Formation in the Franklin Mountains, upper Riepe Spring Limestone in Nevada, and upper Neal Ranch Formation in the Glass Mountains are approximately the same age. According to Wardlaw et al. (1998) much of the Neal Ranch is Sakmarian in age, and Wardlaw and Davydov (2000) indicate that the highest part of the Riepe Spring Limestone also is Sakmarian. Both *Stylastraea* and *E. linearis* also occur in the post-Keeler basin overlap assemblage in east-central California (Magginetti et al., 1988). Therefore, Fusulinid Zone F10 in the Keeler Canyon Formation probably correlates with the *S. bellula* zone elsewhere and is Sakmarian, an age confirmed by the associated conodont assemblages (see later).

Excellent specimens of *Schwagerina* cf. *S. bellula* and *Pseudofusulina decora* suggest correlation with Zone E of the Klamath Mountains. These faunas have been considered Wolfcampian in age in other parts of North America.

CONODONT PALEONTOLOGY

Conodonts from the Keeler Basin previously have been less extensively studied than the fusulinids. Stone (1984) reported Morrowan (Early Pennsylvanian) conodonts from near the base of the Keeler Canyon Formation (Tinemaha Reservoir Member) in the Tinemaha Reservoir area and Middle and Late Pennsylvanian conodonts from several samples in the Cerro Gordo Spring Member in the Ubehebe Mine area. Morrowan conodonts also were reported by C.D. Miller (1989) from a thin sequence of rocks assigned to the Keeler Canyon Formation in the southern Darwin Hills. More recently Ritter (1992) reported conodonts ranging in age from Missourian (Late Pennsylvanian) to Asselian (Early Permian) from the upper 850 m of the Keeler Canyon Formation in the Cerro Gordo Mine area (Section 2, Figs. 4, 5), including three species originally described from the middle Asselian of the southern Ural Mountains. No conodonts have been reported previously from member A of the Lone Pine Formation.

Figure 12. Reduced photographs of important fusulinid species arranged in stratigraphic order.

Sixty-six conodont collections containing 37 species (Figs. 13–17) were obtained from sampling of the Keeler Canyon and lower Lone Pine Formations. These samples are neither geographically nor stratigraphically uniform. For example, the Tinemaha Reservoir Member is represented by a single sample from its type locality. Six samples from the Tihvipah Limestone Member, all from near Quartz Spring, produced conodont elements. The majority of our collections resulted from systematic sampling of the Cerro Gordo Spring Member, Salt Tram Member, and Lone Pine Formation in the Cerro Gordo and Ubehebe Mine areas. At these localities, conodont-bearing beds are separated by much thicker intervals of barren strata. Faunas throughout the section are dominated by Pa elements of *Idiognathodus* and *Streptognathodus.* A minor percentage of samples from the upper two members of the Keeler Canyon Formation contained small numbers of reworked Devonian and Lower and Middle Pennsylvanian conodont elements.

Conodonts from the Keeler basin are here grouped into nine zones and correlated with a "composite standard" zonation (Fig. 8) based on the existing zonations of Barrick and Boardman (1989), Ritter (1995), and Chernykh and Ritter (1997). This zonation is based on the Pennsylvanian to Early Permian evolutionary model that follows.

Conodont evolutionary model

The Pennsylvanian and Early Permian represent a time of low conodont diversity coinciding with the rise and fall of the family Idiognathodontidae. The seminal genus *Declinognathodus* (Fig. 8) evolved from *Gnathodus girtyi* at the beginning of the Pennsylvanian Period (Sweet, 1988). With the successive addition of *Idiognathoides, Neognathodus,* and *Idiognathodus,* Idiognathodontidae reached its maximum generic diversity by late Morrowan time. Speciation events within these genera (as well as non-idiognathodontid *Rhachistognathus*) provide the primary means for zoning Morrowan strata (Fig. 8). From its late Morrowan acme, diversity began to decline beginning with the late Morrowan extinction of *Rhachistognathus,* followed by *Declinognathodus* and *Idiognathoides* during the middle and late Atokan, respectively. These evolutionary events are reflected in the transition from mixed *Rhachistognathus, Declinognathodus, Idiognathoides, Neognathodus,* and *Idiognathodus* faunas in the Morrowan Series (Fig. 8), to mixed *Declinognathodus, Idiognathoides, Neognathodus,* and *Idiognathodus* faunas in the Atokan Series, to mixed *Neognathodus* and *Idiognathodus* faunas in the Desmoinesian Series. With the demise of *Neognathodus* in the beginning of the Missourian, *Idiognathodus* was temporarily the sole surviving idiognathodontid and most useful zonal index for Desmoinesian through early

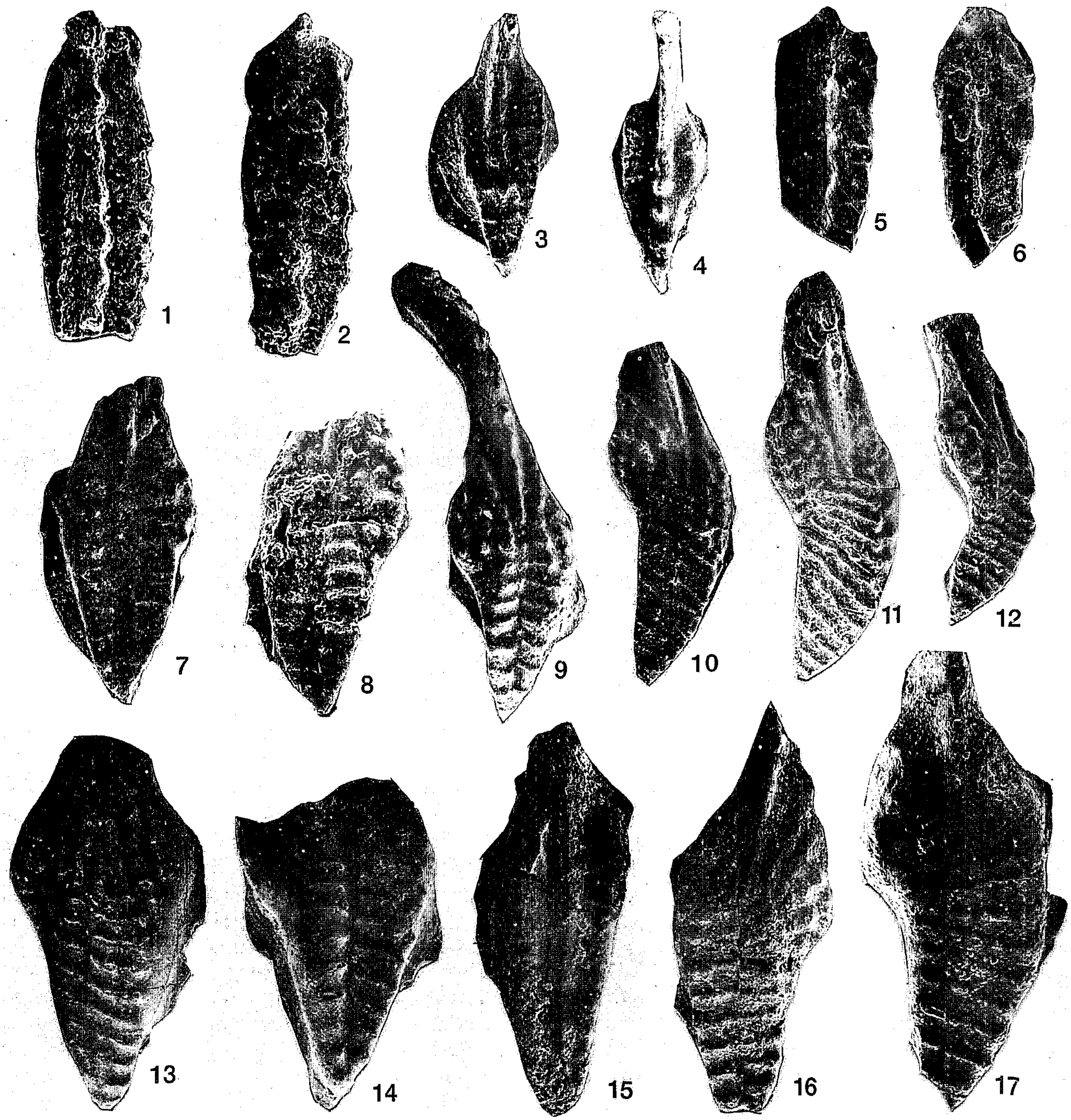


Figure 13. Desmoinesian Pa elements from the Cerro Gordo Spring Member of the Keeler Canyon Formation. All specimens X60 unless otherwise noted. 1, 2, 5, 6, Gondolella magna *Stauffer and Plummer, 1, sample 149a, X65, BYU 2K00100; 2, sample 149A, X65, BYU 2K00101; 5, sample 82-I-28, BYU 2K00102; 6, sample 82-I-28, BYU 2K00103; 3,* Neognathodus medadultimus *Merrill, sample U-9, BYU 2K00104; 4,* Neognathodus medexultimus *Merrill, sample 82-I-28, BYU 2K00105; 7–9, 13, 14,* Idiognathodus nodocarinatus *(Jones), all from sample 82-I-28 except 8, which is from sample 149A, 7, X65, BYU 2K00106; 8, X65, BYU 2K00107; 9, BYU 2K00108; 13, BYU 2K00109; 14, BYU 2K00110; 10–12,* Idiognathodus obliquus *Kozitskaya, 10, sample U-5a, X 55, BYU 2K00111; 11, sample U-7, BYU 2K00112; 12, sample U-11, BYU 2K00113; 15,* Neognathodus bothrops *Merrill, sample 82-I-30, BYU 2K00114; 16, 17,* Idiognathodus expansus *Stauffer and Plummer, 16, sample 82-I-30, BYU 2K00115; 17, sample U-11, BYU 2K00116.*

Missourian strata. During the latter part of the early Missourian, *Idiognathodus* gave rise to the fifth and final idiognathodontid genus, *Streptognathodus.*

Streptognathodus is the primary means for zoning and correlating middle Missourian through Asselian (Early Permian) strata on a global basis. Missourian streptognathodid populations were characterized by species with ornamented platforms and deep medial troughs (lower ornamented *Streptognathodus* fauna of Figure 8). These were abruptly replaced by unornamented forms in the Gzhelian (lower unornamented *Streptognathodus* fauna). From these, a remarkably variable group of broad, heavily ornamented species (upper ornamented *Streptognathodus* fauna) emerged in the latest Gzhelian and continued into the middle Asselian. Included in this group are *S. wabaunsensis, S. isolatus, S. nodulinearis, S. flangulatus,* and *S. cristellaris.* The first occurrence of *S. isolatus* (developed from *S. wabaunsensis*) defines the Carboniferous-Permian boundary (Chernykh and Ritter, 1997; Davydov et al., 1998). In the Asselian, the extinction of the nodose streptognathodids left behind a low diversity fauna of unornamented morphotypes including *S. longissimus, S. constrictus, S. fusus,* and *S. barskovi.* These were joined by the seminal species of both *Sweetognathus* and *Mesogondolella,* the chief index conodonts of the Permian System. Following Wardlow and Davydov (2000), the Asselian-Sakmarian boundary is placed at the appearance of *Sweetognathodus merrilli* (base of Conodont Zone C9).

Local conodont zones

Nine local conodont zones can be recognized and generally correlated with conodont zones previously recognized.

Conodont Zone C1.—This zone is characterized by the presence of generalized species of *Idiognathodus* and *Neognathodus.* The association of *Idiognathodus* and *Neognathodus* in the absence of *Rhachistognathus, Declinognathodus, Idiognathoides,* and *Streptognathodus* suggests a late Atokan to Desmoinesian age and corresponds with the upper Atokan to Desmoinesian mixed *Neognathodus-Idiognathodus* fauna (Fig. 8).

Conodont Zone C2.—The base of this zone, which corresponds with the upper part of the Desmoinesian stage, is defined by the first occurrence of *Idiognathodus nodocarinatus*. Associated species include *I. expansus, I. obliquus, Gondolella magna,* and *Neognathodus medexultimus.* This zone is correlated with the *I. nodocarinatus* zone of the "standard" zonation.

Conodont Zone C3.—The lower boundary of Conodont Zone C3 is marked by the first occurrence of *Idiognathodus sulciferus* of the lower Missourian *I. sulciferus* zone. *I. expansus* is still an important element of zonal faunas.

Conodont Zone C4.—The base of this middle Missourian zone coincides with the first occurrence of *Streptognathodus cancellosus*. The top is defined by the appearance of *S. elegantulus. Streptognathodus sulciferus* ranges throughout the zone and *S. confragus* appears in the upper part. Zone C4 correlates with the combined *S. cancellosus* and *S. confragus* Zones of the North American midcontinent.

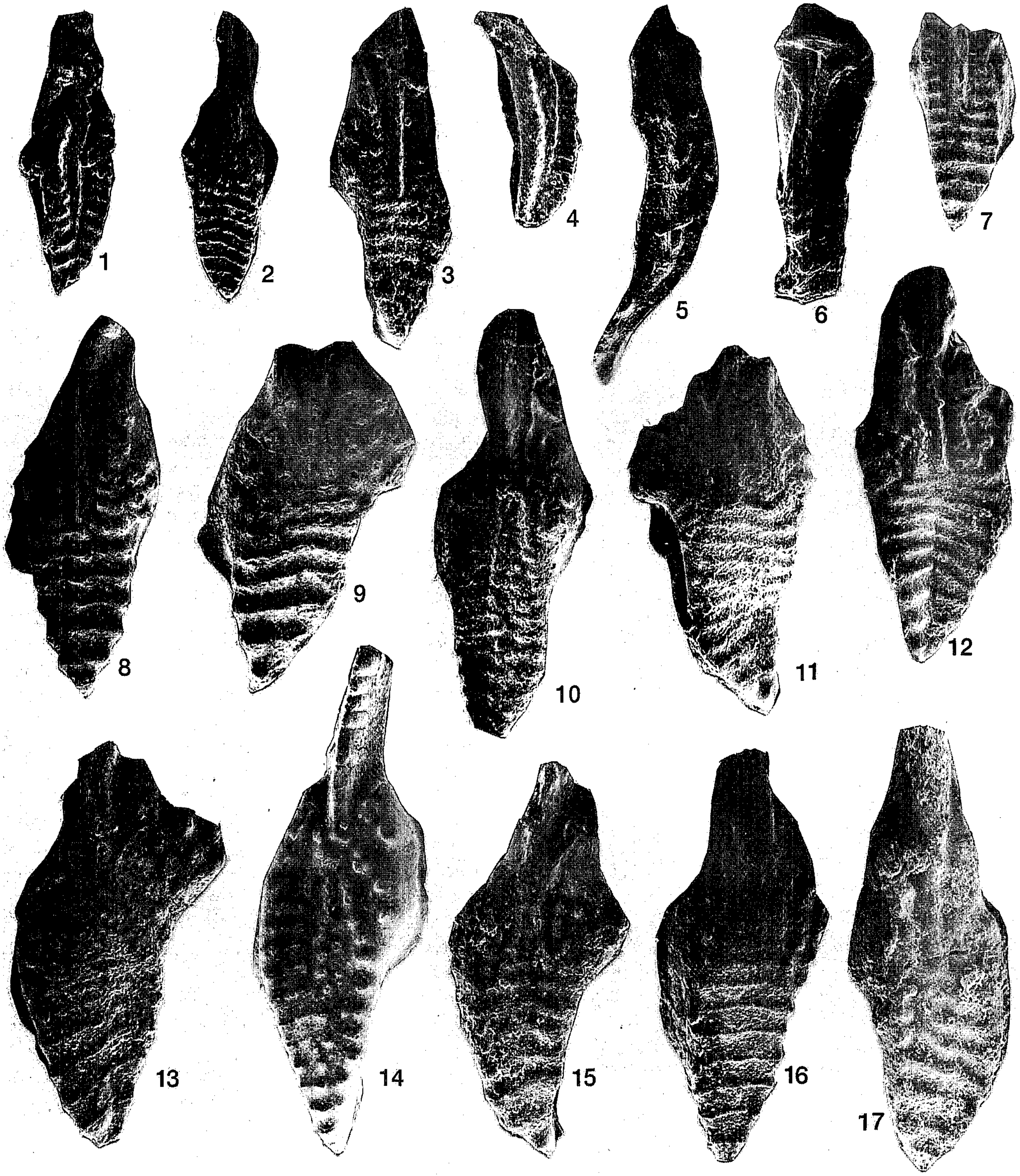
Conodont Zone C5.—The highest Missourian strata comprise Conodont Zone C5. This zone is characterized by elements of *Streptognathodus elegantulus* and *S. excelsus* in association with *Idiognathodus magnificus.* This conodont zone is correlated with the *S. gracilis* fauna of Barrick and Boardman (1989) on the basis of *S. elegantulus* and *S. excelsus.*

Conodont Zone C6.—This zone corresponds to the lower half of the Gzhelian stage and the *Streptognathodus virgilicus-S. pawhuskaensis* conodont zone of the American midcontinent as indicated by the dominance of *S. pawhuskaensis.* The appearance of this species defines the base of the *S. pawhuskaensis-S. virgilicus* zone. Accompanying *S. pawhuskaensis* are specimens of *S. virgilicus, S. excelsus,* and *S. brownvillensis.*

Conodont Zone C7.—This upper Gzhelian zone is characterized by the appearance of unornamented streptognathodids such as *Streptognathodus tenuialveus, S.* aff. *S. longilatus, S.* n.sp. A of Chernykh and Ritter (1997), and *S. costaeflabellus* in conjunction with *S. pawhuskaensis.* These Keeler Canyon faunas correspond with the middle to upper Gzhelian *S. tenuialveus* Zone of Chernykh and Ritter (1997). In both the American midcontinent and southern Ural Mountains, uppermost Gzhelian strata contain a zone of ornamented streptognathodids (*S. wabaunsensis* Zone). Due to the conodont-poor nature of latest Gzhelian rocks, this zone is not distinguishable in the Keeler basin. Hence, middle to upper Gzhelian strata are assigned to Zone C7 as defined herein.

Conodont Zone C8.—The base of this zone corresponds with the appearance of *Wardlawella expansa.* Other species include *Streptognathodus constrictus, S.* aff. *S. barskovi, S. fusus, S.* aff. *S. cristellaris, Mesogondolella dentiseparata,* and *M. belladontae.* This zone is considered to be Asselian in age and the base of this zone corresponds roughly with the Pennsylvanian-Permian boundary. Sample 765 near the top of this zone in Cerro Gordo Section 1 contains *Wardlawella expansa* and a form transitional between *W. expansa* and *Sweetognathus merrilli,* a Sakmarian species. We consider this sample to be upper Asselian.

Conodont Zone C9.—The appearance of *Sweetognathus merrilli* defines the base of conodont zone C9. *Mesogondolella lata* also occurs in these samples. *Sweetognathus merrilli* has a range of lower to upper Sakmarian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and *Mesogondolella lata* a range of upper Asselian through lower Sakmarian. Therefore Conodont Zone C9 is considered early Sakmarian in age.

Conodont correlations

On the basis of correlation of the local conodont zones with the "composite standard" zonation and with the local fusulinid zones, fusulinid-bearing stratigraphic sections throughout North America presumably can be correlated with the standard Ural Mountains section (Table 1). Conodont work in the midcontinent United States and Texas (Barrick and Boardman, 1989; Ritter, 1995; Barrick et al., 1996; Wardlaw and Davydov, 2000) is mostly consistent with these correlations. Chernykh and Ritter (1997) and Davydov et al. (1998) placed the Carboniferous-Permian boundary at the base of the Bennett Shale (middle Council Grove Group) in Kansas and within the Gray Limestone Member of the Gaptank Formation in the Glass Mountains. The former correlation is compatible with our correlations in the Keeler basin, but on the basis of the poorly known fusulinid data we tentatively place the the Gray Limestone (Bed J of C.A. Ross, 1965) in the upper Gzhelian. Wardlaw and Davydov (2000) placed the Asselian-Sakmarian boundary within the Neal Ranch Formation, a position compatible with our correlations. In the Kansas section, Wardlaw and Davydov (2000) placed the Asselian-Sakmarian boundary at the base of the Eiss Limestone (in the upper part of the Council Grove Group). Because of the lack of fusulinids in this part of the Kansas section we cannot evaluate this placement.

FAUNAL AFFINITIES

The fusulinids of the Keeler basin consist of a mixture of North American, McCloud Limestone, and endemic species, with North American cratonal species dominating. Zone F2 (Atokan) through Zone F5 (late Gzhelian) fusulinid faunas are composed of typical North American cratonic species with only a few endemic and McCloud Limestone forms. In Fusulinid Zone F6 (upper Gzhelian to lower Asselian) and again in Fusulinid Zone F9 (upper Asselian-lower Sakmarian), however, endemic fusulinids are dominant. McCloud Limestone fusulinid species are prominent in Fusulinid Zones F8 and F9 (upper Asselian and lower Sakmarian). In Zone 10, McCloud fusulinid species persist but endemic species are sparse.

Of the fusulinid species from the Keeler basin with North American cratonal affinity, many compare rather closely with those of south-central United States. Considering the proximity of the Bird Spring carbonate platform immediately east of the Keeler basin, it is surprising that only a few species from the Keeler basin compare closely with taxa from that region.

Most of the conodont species present occur in both Russia and North America and indicate that dispersal of this group was uninhibited. The major difference between faunas from these three areas is the absence of *Mesogondolella* in the North American midcontinent, probably due to environmental factors. Thus, the conodonts are more useful than the fusulinids for correlation of the American section with the Lower Permian stratotype.

CORRELATION OF BIOSTRATIGRAPHIC AND LITHOSTRATIGRAPHIC UNITS

The stratigraphic section in the Keeler basin appears to represent essentially continuous deposition from earliest Pennsylvanian time into the Sakmarian (Early Permian), as shown by the succession of stages represented in the members of the Keeler Canyon Formation and the Lone Pine Formation. The conodont faunas represent all stages of the Pennsylvanian (except the Atokan) and Lower Permian into the Sakmarian; the fusulinid faunas represent all stages from Atokan to Sakmarian.

The stratigraphic occurrence of conodonts and fusulinids in the four measured sections presented here allows correlation and dating of the stratigraphic units within the Keeler basin (Fig. 7).

KEELER CANYON FORMATION

Tinemaha Reservoir Member

Limited data on fossils are presently available from this member of the Keeler Canyon Formation. The only collection of conodonts, from the basal beds, yielded a rich

Figure 14. Missourian Pa elements from the Cerro Gordo Spring Member of the Keeler Canyon Formation. All specimens X60 unless otherwise noted. 1, 4, 7, Streptognathodus elegantulus *Stauffer and Plummer, 1, sample U-17, BYU 2K00117; 4, juvenile from sample U-25, BYU 2K00118; 7, sample U-17, BYU 2K00119; 2, 11, 13,* Idiognathodus magnificus *Stauffer and Plummer, 2, juvenile from sample U-26, BYU 2K00120; 11, sample U-25, BYU 2K00121; 13, sample U-18, BYU 2K00122; 3, 8,* Streptognathodus confragus *(Gunnell), both from sample U-14, 3, BYU 2K00123; 8, BYU 2K00124; 5, 6,* Gondolella sublanceolata *Gunnell, both from sample U-14, 5, BYU 2K00125; 6, BYU 2K00126; 9, 15, 16,* Idiognathodus sulciferus *Gunnell, 9, sample U-17, BYU 2K00127; 15, sample U-13, BYU 2K00128; 16, sample U-14, BYU 2K00129; 10,* Streptognathodus cancellosus *(Gunnell), sample U-13, X65, BYU 2K00130; 12,* Streptognathodus excelsus *Stauffer and Plummer, sample U-36, BYU 2K00131; 14,* Idiognathodus *n. sp. A of Barrick et al., 1996, sample 975a, BYU 2K00132; 17,* Idiognathodus eccentricus *(Ellison), sample U-12, BYU 2K00133.*


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fauna containing *Idiognathoides convexus, I. sinuatus,* and *Declinognathodus* (Stone, 1984). The joint occurrence of these species suggests correspondence with the upper Morrowan *I. convexus* Zone. The presence of the fusulinids *Pseudostaffella* and *Fusulinella*? (of Fusulinid Zone 1) higher in the section indicates that deposition continued into the Atokan.

Tihvipah Limestone Member

Zone C1 conodonts were recovered from samples of the Tihvipah Limestone Member near Quartz Spring in the Cottonwood Mountains (Fig. 2). Fusulinids from this unit form parts of Zones F1 and F2, and include *Fusulinella* from near Tinemaha Reservoir, *Fusulinella, Wedekindellina,* and *Beedeina* from exposures near Quartz Spring, and *Beedeina* and *Wedekindellina* from the northern Santa Rosa Hills. Ross and Sabins (1965) reported a very similar assemblage from the basal beds of the Desmoinesian in southeast Arizona.

Previously the Tihvipah Limestone Member was considered entirely Atokan in age (Merriam and Hall, 1957; McAllister, 1952) based on the presence of *Fusulinella.* New collections suggest, however, that deposition of the Tihvipah Limestone began in the upper part of the Atokan and extended into the Desmoinesian.

Cerro Gordo Spring Member

Conodonts have been recovered from this member in both the Cerro Gordo region and the Ubehebe Mine Section. Specimens representing Conodont Zone C2, corresponding with the late Desmoinesian *Idiognathodus nodocarinatus* Zone, occur in Cerro Gordo Section 1 (samples 149A, 360A, and 680A) and several samples from the lower part of the member 4.1 km northwest of Cerro Gordo.

Sample 975A from Section 1 represents Zone C3. Fifteen samples from the Cerro Gordo Spring Member in the Ubehebe Mine section produced conodonts showing that this member ranges from late Desmoinesian to early Gzhelian in age. The lowest four samples (U-5A through U-11) are dominated by Pa elements of *Idiognathodus nodocarinatus* of Zone C2. Sample U-12 higher in the section is characterized by conodonts of Zone C3. Slightly higher in the section (samples U-13, U-14), Zone C4, represented by *S. confragus,* appears. Four higher samples (U-17 to U-26) belong to Zone C5. The uppermost sample from the Cerro Gordo Spring Member (U-34.5) yielded Zone C6 conodonts.

In contrast to the conodont faunas, the fusulinid faunas are sparse in the Cerro Gordo Spring Member. Several species of *Beedeina* and a species of *Wedekindellina* from Section 1 represent Zone F2 and demonstrate a Desmoinesian age as also shown by the conodont collections. The single fusulinid collection representing the Missourian Zone F3 (S-0858) is from the upper part of the Cerro Gordo Spring Member near its type section.

Salt Tram Member (lower part)

Conodonts are moderately abundant in the coarse-grained turbidites of the lower part of the Salt Tram Member near Ubehebe Mine and in all three sections in the Cerro Gordo area. At Ubehebe Mine the lower part of the member (samples U-34.5 to U-42.5) contains Zone C6 conodonts. A fauna from the overlying beds (sample U-45) contains conodonts of Zone C7.

In section 3 near Cerro Gordo, samples S-1752, S-1794, and S-1795 contain elements of Zone C6. Sample CG-0 from Section 2 contains Zone C6 Pa elements and samples CG-490 and S-1788 higher in the section represent Zone C7. Samples U-63′ and U-64′ have yielded conodonts provisionally placed in Zone C8.

The lower part of the Salt Tram Member contains considerable numbers of fusulinids, mostly in the Cerro Gordo area, here grouped into Fusulinid zones F4–F6. Thus, we interpret the lower part of the Salt Tram Member to span the Gzhelian-Asselian boundary. Several fusulinid samples from the Salt Tram Member in the Conglomerate

Figure 15. Gzhelian Pa elements from the uppermost Cerro Gordo Spring and lower Salt Tram Members of the Keeler Canyon Formation. Specimens X 60 unless otherwise indicated. 1, 7, 11, 14, Streptognathodus virgilicus *Ritter, 1, sample S-1752, X65, BYU 2K00134; 7, sample CG-0, BYU 2K00135; 11, sample 98-I-928, BYU 2K00136; 14, sample S-1794, X65, BYU 2K00137; 2,* Streptognathodus tenuialveus *Chernykh and Ritter, sample U-45, BYU 2K00138; 3,* Streptognathodus *aff.* S. longilatus *Chernykh and Ritter, sample S-1794, X65, BYU 2K00139; 4, 9, 10, 12, 15, 16, 21–23,* Streptognathodus pawhuskaensis *(Harris and Hollingsworth), 4, sample U-34.5, BYU 2K00140; 9, sample 98-I-926, BYU 2K00141; 10, sample 98-I-927, BYU 2K00142; 12, sample CG-0, BYU 2K00143; 15, sample CG-0, BYU 2K00144; 16, sample 98-I-926, X75, BYU 2K00145; 21, sample CG-490, BYU 2K00146; 22, sample U-36, X65, BYU 2K00147; 23, sample 79-CM-88, BYU 2K00148; 5,* Streptognathodus costaeflabellus *Chernykh and Ritter, sample CG-490, BYU 2K00149; 6.* Streptognathodus *n. sp. 1, sample U-45, BYU 2K00150; 8, 13, 18,* Idiognathodus magnificus *Stauffer and Plummer, 8, sample CG-490, BYU 2K00151; 13, sample S-1752, X65, BYU 2K00152; 18, sample CG-490, BYU 2K00153; 17,* Streptognathodus brownvillensis *Ritter, sample S-1794, BYU 2K00154; 19,* Streptognathodus excelsus *Stauffer and Plummer, sample U-34.5, BYU 2K00155; 20,* Streptognathodus *n. sp. A of Chernykh and Ritter, 1997, sample S-1795, BYU 2K00156.*


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Mesa area are assigned to zones F5 and F6 and are interpreted as correlative with the middle and upper parts of this subunit.

Salt Tram Member (upper part)

Numerous conodont faunas from the upper part of the Salt Tram Member were obtained from the Cerro Gordo Mine Sections 1 and 2. At Section 1, five productive beds spanning the entire upper Salt Tram Member were collected. The lowest fauna (sample 99-I-609) contains Zone C8 elements. Somewhat higher in the section, the unusual fauna in sample 765 noted earlier is considered to mark the top of the Asselian. Samples 492 and 97-I-902 near the top of the Salt Tram Member contain Zone C9 conodonts including *Sweetognathus merrilli.*

Five beds in the lower half of the upper Salt Tram Member were also productive at Section 2. These contain Zone C8 species. Two samples from the upper half of the upper Salt Tram Member, including one from the top of the member, yielded specimens of elongate, unornamented streptognathodids of uncertain taxonomic affinity and age. These specimens represent an as yet unnamed species belonging to the upper fauna of unornamented *Streptognathodus* (Fig. 8).

Fusulinid faunas grouped into Zones F7–F9 are abundant in the upper part of the Salt Tram Member, which spans the Asselian-Sakmarian boundary. The highest fusulinid sample from the Salt Tram Member in the Conglomerate Mesa area (79-CM-84) is assigned to Zone F7 and therefore is interpreted as correlative with the lower part of this subunit.

Undivided Cerro Gordo Spring and Salt Tram Members at San Lucas Canyon

Four conodont samples and one fusulinid sample from the upper part of the Keeler Canyon Formation at San Lucas Canyon were examined. The conodont samples, which range from 30 to 625 m below the top of the formation, all contain *Streptognathodus pawhuskaensis,* and the fusulinid sample (S-1746, about 360 m below the top) contains *Triticites pinguis.* Together these fossils indicate a Gzhelian age probably including parts of conodont Zones C6 and C7. Thus, these rocks are approximately equivalent to the lower and middle parts of the lower Salt Tram Member. Conodonts from the unconformably overlying unit 7 of the sedimentary rocks of Santa Rosa Flat (sample 98-I-921) include *Sweetognathus whitei* indicative of an Early Permian (Artinskian) age, which is compatible with the latest Wolfcampian age determined for this unit in the Conglomerate Mesa area by Magginetti et al. (1988) on the basis of fusulinids.

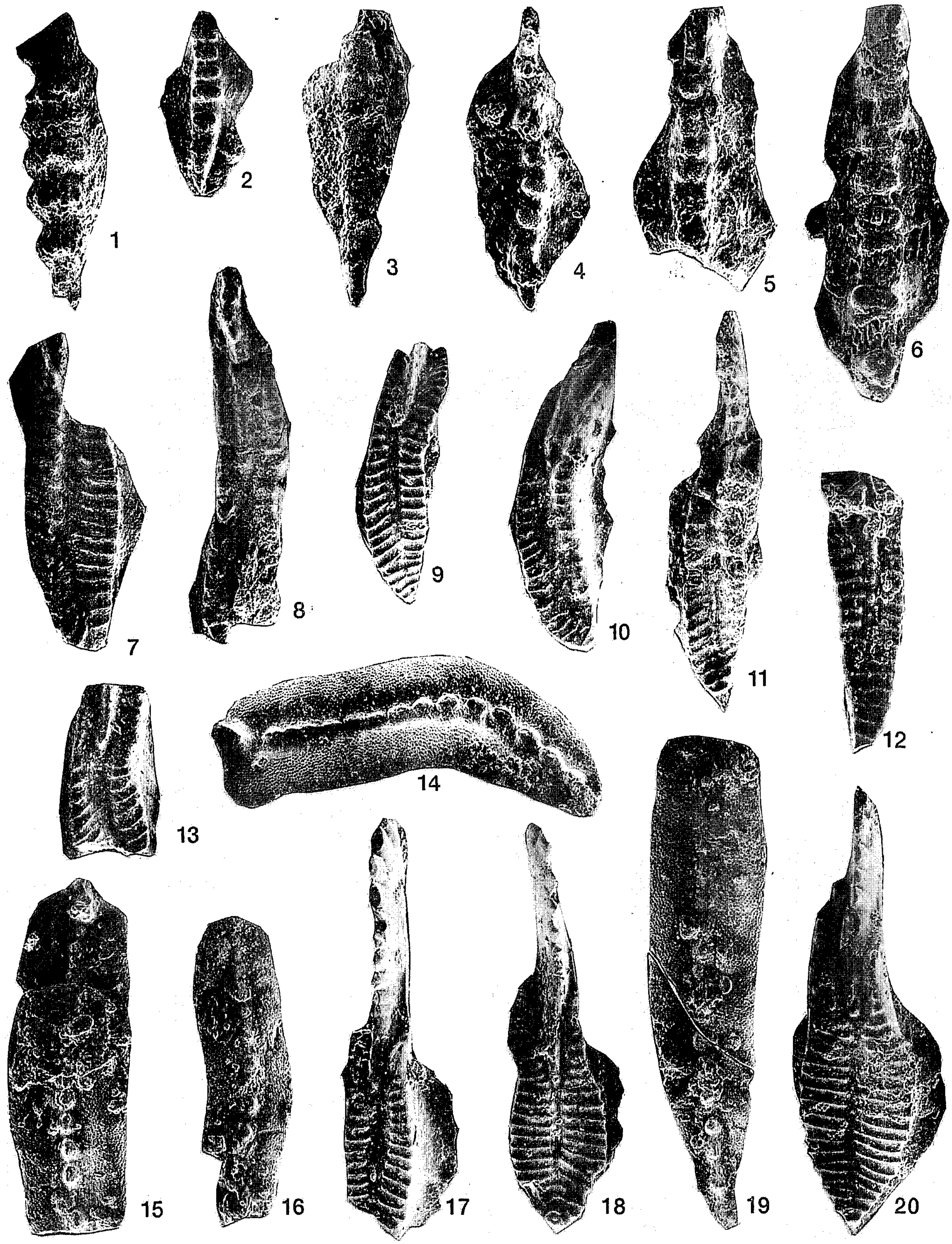
LONE PINE FORMATION

The Lone Pine Formation is represented by sparse conodont faunas obtained from the uppermost portion of the preserved section at Section 1, from two spot localities in the vicinity of the Cerro Gordo Mine, and two horizons at Ubehebe Mine. The Lone Pine faunas, along with those in the uppermost part of the Salt Tram Member, are assigned to Zone C9, which is correlated with the *Sweetognatus merrilli* conodont zone. An early Sakmarian age is indicated. Fusulinid Zone F10 from the lower part of the Lone Pine Formation corresponds with the upper part of Conodont Zone C9. This fauna is rather poor. The presence of *Schwagerina* cf. *S. bellula,* however, is consistent with the early Sakmarian age suggested by the conodonts.

GEOLOGIC HISTORY OF THE KEELER BASIN

The Keeler basin is defined by the regional distribution of the deep-water Keeler Canyon Formation and member A of the Lone Pine Formation. In the northern and central parts of the basin the Keeler Canyon Formation overlies older basinal strata of the Chesterian (Upper Mississippian) Rest Spring Shale, which in turn overlies the deep-water Mississippian Kearsarge and Mexican Spring Formations

Figure 16. Asselian Pa elements from the upper Salt Tram Member of the Keeler Canyon Formation. All figures X60 unless otherwise indicated. 1, 2, 5, Wardlawella expansa *(Perlmutter), 1, sample 99-I-609, BYU 2K00157; 2, sample 765, BYU 2K00158; 5, sample 765, BYU 2K00159; 3, 8, 20, 22,* Streptognathodus fusus *Chernykh and Reshetkova, 3, sample 99-I-609, BYU 2K00160; 8, sample 99-I-609, BYU 2K00161; 20, sample CG-1521, BYU 2K00162; 22, sample CG-1521, BYU 2K00163; 4, specimen transitional between* Wardlawella expansa *and* Sweetognathus merrilli *Kozur, sample 765, BYU 2K00164; 6, 10, 11, 17, 23,* Mesogondolella dentiseparata *Chernykh, 6, sample CG-1521, BYU 2K00165; 10, sample 82-I-24, BYU 2K00166; 11, sample 99-I-610, BYU 2K00167; 17, sample CG-1521, BYU 2K00168; 23, sample CG-1550, BYU 2K00169; 7,* Streptognathodus *aff.* S. barskovi *(Kozur), sample CG-1355, BYU 2K00170; 9,* Mesogondolella belladontae *Chernykh, sample 99-I-609, BYU 2K00171; 12, 18, 19,* Streptognathodus longissimus *Chernykh and Reshetkova, 12, sample CG-1570, BYU 2K00172; 18, sample CG-1570, BYU 2K00173; 19, sample CG-1521, BYU 2K00174; 13,* Streptognathodus constrictus *Chernykh and Reshetkova, sample CG-1376, BYU 2K00175; 14, 16,* Streptognathodus fuchengensis *Zhao, 14, sample 765, X65, BYU 2K00176; 16, sample CG-1521, BYU 2K00177, 15,* Streptognathodus *aff.* S. cristellaris *Chernykh and Reshetkova, sample CG-1550, BYU 2K00178; 21,* Streptognathodus *sp. indet., CG-1920, BYU 2K00179.*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of early Late Mississippian (Meramecian) age (Stevens et al., 1996). Thus, this part of the Keeler basin originated in the Mississippian and probably was a southwestern extension of the Antler foreland basin of central Nevada (Poole and Sandberg, 1991). In Nevada, however, the Antler foreland basin rocks generally pass upward into shallow-water carbonate rocks of Pennsylvanian age in contrast to east-central California where deep-water sedimentation continued through the Pennsylvanian and into Early Permian time, evidently reflecting continued subsidence of this part of the basin.

We consider the Keeler basin to have originated when the western margin of the North American continent was truncated (Stone and Stevens, 1988). This event resulted in a change in trend of facies belts in east-central California from southwestward, with depositional belts representing progressively deeper water to the west, to southeastward. South of about the latitude of Lone Pine, part of the older shelf was down-dropped, resulting in deposition of the deep-water Keeler Canyon Formation above Late Mississippian shallow-shelf rocks. The change in trend of the Keeler basin in this region (Fig. 1) reflects these events.

Throughout its early history (Morrowan through most of the Desmoinesian) the Keeler basin accumulated mostly fine-grained limestone, probably deposited in moderately deep water. The major exception is in the Tinemaha Reservoir area where a thick, but very local turbidite sequence (Tinemaha Reservoir Member) was deposited. Thin sequences of coeval fine-grained calcareous rocks were deposited locally elsewhere. Abundant quartz sand and silt associated with the limestone turbidites near Tinemaha Reservoir suggest that their source was somewhere on the Bird Spring shelf rather than from the closer Mount Baldwin platform, the limestones of which are quartz free (Stevens and Greene, 1999).

During the latter part of the Atokan and early Desmoinesian time, a thin sequence of cherty micritic limestone of the Tihvipah Limestone Member was deposited throughout most if not all of the Keeler basin. The rate of sediment accumulation evidently continued to be very slow. The Tihvipah Limestone is not a turbidite sequence although debris-flow deposits composed of coarse-grained carbonate detritus derived from shallow water occur locally. This unit probably represents deposition in relatively deep, quiet water.

Limestone turbidites and calcareous siltstone of the Cerro Gordo Spring Member represent the first widely distributed turbidite sequence in the Keeler basin. This member accumulated from Desmoinesian into early Gzhelian time. These strata reflect deposition in relatively deep water downslope from the adjacent Bird Spring carbonate shelf. Yose (1987) and Yose and Heller (1989) interpreted the Cerro Gordo Spring Member as a basin-margin sequence that accumulated as a line-sourced debris apron. Rates of sediment accumulation apparently increased in the late Desmoinesian, decreased greatly in the early and middle Missourian, and increased again in the late Missourian and early Gzhelian.

The thick sequence of silty to sandy limestone turbidites that comprise the Salt Tram Member of the Keeler Canyon Formation accumulated from Gzhelian into Sakmarian time. This member has been interpreted both as a submarine fan sequence (Parker, 1976; Stone, 1984) and as a debris apron sequence (Flora, 1984; R.P. Miller, 1989) derived from the Bird Spring carbonate shelf. Regardless, the Salt Tram Member clearly reflects an extended episode of deposition during which mixed carbonate and terrigenous sediment gravity flows carried shallow-water material downslope into the Keeler basin. Paleocurrent data from this member indicate southward flow in the Ubehebe Mine area and southwestward flow in the Cerro Gordo area. The rate of sediment accumulation was high throughout middle Gzhelian to middle Sakmarian time.

The origin of the turbidites in which the fusulinids and conodonts occur is not precisely known. In the upper part of the Asselian and in the Sakmarian a number of endemic species not known from nearby platform rocks are present. Paleocurrent measurements (Stevens et al., 1979; Parker, 1976; Stone, 1984; Flora, 1984) show transport to the south at Ubehebe Mine and southwest in the southern Inyo Mountains. The only possible source rocks of the appropriate age to the northeast are limestones of the Tippipah Limestone on the Nevada Test Site, more than 100 km away. The top of section there, however, is only as

Figure 17. Sakmarian Pa elements from the Salt Tram Member of the Keeler Canyon Formation and Lone Pine Formation. All figures X60 unless otherwise noted. 1, Sweetognathus whitei *(Rhodes), sample 98-I-921, X100, BYU 2K00180; 2–6,* Sweetognathus merrilli *Kozur, 2, sample 492, BYU 2K00181; 3, sample 99-I-608, X85, BYU 2K00182; 4, sample 902, BYU 2K00183; 5, sample 902, BYU 2K00184; 6, sample 492, BYU 2K00185; 7,* Adetognathus paralautus *Orchard, sample U-94, BYU 2K00186; 8, 12, indeterminate species of elongate* Streptognathodus*, 8, sample 99-I-612, BYU 2K00187; 12, sample 99-I-608, BYU 2K00199; 9, 10, 11, 13,* Streptognathodus *n. sp. 1, 9, sample 97-I-901, BYU 2K00188; 10, sample 97-I-901, BYU 2K00189; 11, sample 99-I-612, BYU 2K00190, 13, sample U-94, BYU 2K00191; 14–16, 19,* Mesogondolella lata *Chernykh, 14, deformed specimen, sample U-94, BYU 2K00192; 15, sample 99-I-608, X50, BYU2K00193; 16, sample 99-I-608, BYU 2K00194; 19, sample 99-I-608, BYU 2K00195; 17, 18, 20,* Streptognathodus *n. sp. 2, all three from sample 97-I-901, 17, BYU 2K00196; 18, BYU 2K00197, 20, BYU 2K00198.*

young as early Asselian (V.I. Davydov, oral commun., 1999), so comparison of most Permian faunas is impossible. The Gzhelian and early Asselian fusulinids at the Nevada Test Site, however, are not closely similar to those in the Keeler basin (C.H. Stevens, unpub. data), so these shelf limestones apparently were not the source of the Keeler Canyon turbidites. Apparently the carbonate shelf that gave rise to the turbidites in the upper part of the Keeler Canyon Formation is not now exposed.

Following deposition of the Salt Tram Member the Keeler basin evidently was largely cut off from its source of limestone turbidites, and the predominantly fine-grained strata of member A of the Lone Pine Formation accumulated in a basin-plain environment. During this time up to about 1000 m of very fine, siliciclastic sediment of member A of the Lone Pine Formation was deposited in the south-central Inyo Mountains. This change in sediment type and rate of accumulation may have been related to development of the Last Chance thrust that eventually resulted in emplacement of the Keeler Canyon Formation against the older Mississippian shelf margin to the east (Stevens and Stone, in press), marking the end of the Keeler basin depositional sequence. We interpret the faulted contact that characterizes the base of the Keeler Canyon Formation throughout the region as part of the Last Chance thrust.

After thrusting, shallow-marine carbonate rocks of unit 7 of the sedimentary rocks of Santa Rosa Flat overlapped the uplifted Keeler Canyon Formation in the Conglomerate Mesa and San Lucas Canyon areas. In contrast, deep-water sedimentation continued in the western part of the former Keeler basin, resulting in deposition of member B of the Lone Pine Formation. Shelf limestones of unit 7 and the overlying unit 8 are correlative with the limestone turbidites of member B and may have been their source (Stone et al., 2000).

SUMMARY AND TECTONIC SIGNIFICANCE

The limestone-rich Keeler Canyon Formation, here divided into four formal members, and the lower part of the dominantly siliciclastic Lone Pine Formation were deposited in a basin close to the late Paleozoic continental margin in east-central California from the Morrowan (Early Pennsylvanian) to Sakmarian (Early Permian) time. This basin, here called the Keeler basin, cut across earlier facies belts, probably the result of an earlier continental truncation to the west. Deposition was terminated by an orogenic event that resulted in development of the Last Chance thrust in the latest Sakmarian.

Strata of the Keeler basin contain numerous fusulinid and conodont faunas, most of which were deposited by sediment-gravity flows that probably originated at the margin of the Bird Spring carbonate platform to the northeast. The fusulinid faunas are composed of taxa with North American affinities, with endemic constituents, and with elements of the McCloud Limestone of northwestern California. The conodonts are closely similar to species in the Ural Mountains of Russia and Kazakhstan, as well as midcontinent USA.

The Keeler basin was one of a succession of sedimentary basins that developed along the continental margin during the latter part of the Paleozoic in east-central California (Stone and Stevens, 1988). The history of this basin reflects initial subsidence and subsequent compressional uplift along the margin following its truncation, probably by transcurrent faulting, in early Pennsylvanian time. This structural event was followed by a series of events involving basin subsidence and subsequent uplift in later Early Permian to earliest Triassic time (Stevens et al., 1998). This structural history apparently reflects a protracted period of tectonic instability and variability as the continental margin changed from the dominantly passive margin that had characterized most of the Paleozoic to the active, convergent margin that would become fully developed by the Late Triassic and continue through the remainder of the Mesozoic.

APPENDIX 1: MEASURED SECTIONS

Sections in Cerro Gordo Mine area

Note: All sections are in the Cerro Gordo Peak 7.5′ quadrangle.

Section 1. Measured on slopes and ridges northwest of Cerro Gordo Road by C.H. Stevens and Jerry Lewis in 1964; reexamined by C.H. Stevens and Paul Stone in 1999. Base of section is 1 km northwest of road at elev. 8240 ft; top of section is 2.5 km northwest of road at elev. 6920 ft. Base of section is reached by a jeep road leading northwest from Cerro Gordo Mine. Section extends from base of Keeler Canyon Formation, which is faulted against Rest Spring Shale, to top of Lone Pine Formation, which is unconformably overlain by Union Wash Formation. Unit thicknesses: Cerro Gordo Spring Member of Keeler Canyon Formation, 428 m; Salt Tram Member of Keeler Canyon Formation, 833 m (lower part, 516 m; upper part, 317 m); Lone Pine Formation, 67 m.

Section 2. Measured along south side of Cerro Gordo Road by S.M. Ritter in 1991; reexamined by S.M. Ritter, C.H. Stevens, and Paul Stone in 1999. Base of section is adjacent to road at elev. 7040 ft; top of section is adjacent to road at elev. 6520 ft. Section extends from base of Salt Tram Member of Keeler Canyon Formation to top of Lone

Pine Formation, which is unconformably overlain by Union Wash Formation. Unit thicknesses: Salt Tram Member of Keeler Canyon Formation, 643 m (lower part, 387 m; upper part, 255 m); Lone Pine Formation, 22 m. In canyon 0.3 km northwest of measured section, Lone Pine Formation is 63 m thick, the upper 30 m of which consists of limestone that is truncated by unconformity with Union Wash Formation between here and Cerro Gordo Road. About 0.1 km south of measured section, Lone Pine Formation is truncated by unconformity with Union Wash Formation.

Section 3. Measured in canyon east of Estelle Tunnel by Riggs (1962); reexamined by C.H. Stevens, Paul Stone, and S.M. Ritter in 1999. Base of section is 1 km east-northeast of Estelle Tunnel at elev. 7080 ft; top of section is adjacent to Estelle Tunnel at elev. 6100 ft. Section extends from within Cerro Gordo Spring Member of Keeler Canyon Formation to top of Keeler Canyon Formation, which is unconformably overlain by Union Wash Formation. Unit thicknesses: Cerro Gordo Spring Member of Keeler Canyon Formation, 87 m (partial thickness); Salt Tram Member of Keeler Canyon Formation, 549 m (lower part, 330 m; upper part, 219 m). Note: Base of section is about 0.4 km farther up the canyon from Estelle Tunnel and 500 ft higher in elevation than shown on the location map of Riggs (1962, fig. 4).

Ubehebe Mine section

Measured in canyon west of Ubehebe Mine by Stone (1984). Base of section is 2.3 km west-northwest of Ubehebe Mine, elev. 3360 ft, in the Teakettle Junction 7.5′ quadrangle; top of section is 3.75 km west-southwest of Ubehebe Mine, elev. 2680 ft, in the Ubehebe Peak 7.5′ quadrangle. Section extends from base of Keeler Canyon Formation, which is faulted against the Rest Spring Shale, into the Lone Pine Formation. Unit thicknesses: Cerro Gordo Spring Member of Keeler Canyon Formation, 232 m; Salt Tram Member of Keeler Canyon Formation, 829 m; Lone Pine Formation, 182 m (partial thickness). Top of section is at synclinal fold hinge. Approximately 1.5 km to the south, lower shaly subunit of Lone Pine Formation is about 300 m thick and is conformably overlain by upper limestone subunit which has a maximum exposed thickness of about 150 m in core of large syncline.

APPENDIX 2: FOSSIL LOCALITIES

Note: Fusulinid and conodont taxa identified at each locality are listed. Fusulinid zone (**F1–10**) and/or conodont zone (**C1–9**) are indicated at end of each listing.

Measured section 1,
Cerro Gordo Mine area

Keeler Canyon Formation, Cerro Gordo Spring Member:

149 45 m (149 ft) above base of section. Fusulinids: *Beedeina* aff. *B. haworthi*, *B.* aff. *B. occultifons.* (**F2**)

149A Approximately same locality as 149. Conodonts: *Idiognathodus nodocarinatus*, *I. expansus*, *I. obliquus*, *Gondolella magna.* (**C2**)

360 110 m (360 ft) above base of section. Fusulinids: *Wedekindellina* sp. 1. (**F2**)

360A Approximately same locality as 360. Conodonts: *Idiognathodus obliquus*, *I. expansus.* (**C2**)

680A Approximately 207 m (680 ft) above base of section. Conodonts: *Gondolella magna*, *Idiognathodus expansus* (**C2**)

975A Approximately 297 m (975 ft) above base of section. Conodonts: *Idiognathodus* n. sp. A of Barrick et al. (1996). (**C3**)

Keeler Canyon Formation, Salt Tram Member, lower part:

1850 852 m (2795 ft) above base of section. Fusulinids: *Pseudofusulinella* sp., *Schwagerina* sp. (**F6**)

2035 803 m (2634 ft) above base of section. Fusulinids: *Triticites* aff. *T. ventricosus* var. *sacramentoensis*, *T.* sp. 3?, *Schwagerina aculeata*, *S. modica.* (**F6**)

2282 738 m (2422 feet) above base of section. Fusulinids: *Triticites cellamagnus?*, *Schwagerina* sp. (**F5**)

2292 736 m (2415 ft) above base of section. Fusulinids: *Triticites* aff. *T. beedei*, *T. pinguis*, *T.* sp. 3, *Schwagerina* sp. (**F5**)

2665 641 m (2104 ft) above base of section. Fusulinids: *Triticites hermanni?*, *T. pinguis*, *T.* sp. 2, *Pseudofusulinella* sp. (**F5**)

2785 611 m (2005 ft) above base of section. Fusulinids: *Triticites californicus?*, *T. hermanni*, *T.* sp. 2 (**F4**)

3115 532 m (1587 ft) above base of section. Fusulinids: *Triticites* aff. *T. hobblensis.* (**F4**)

3549 436 m (1429 ft) above base of section. Fusulinids: *Triticites californicus?*, *T.* cf. *T. hermanni*, *T.* aff. *T. hobblensis*, *T. whetstonensis.* (**F4**)

S-1778 Same locality as 3549. Fusulinids: *Triticites pinguis*, *T.* cf. *T. hermanni.* (**F4**)

Keeler Canyon Formation, Salt Tram Member, upper part:

492 1226 m (3957 ft) above base of section. Fusulinids: *Reticulosepta* sp. 1, *R.*? sp., 4, *R.* sp. 6, *R.*? sp. 7, *Schwagerina* aff. *S. arta*, *S. turgida*, *S.* sp. 1, *Pseudofusulinella* sp., *Pseudosch-*

wagerina sp., *Eoparafusulina*? sp., *Stewartina* sp. 3. Conodonts: *Sweetognathus merrilli.* **(F9, C9)**

765 1136 m (3726 ft) above base of section. Fusulinids: *Schwagerina turgida, Reticulosepta*? sp. 4, *Stewartina* sp. 1. Conodonts: *Wardlawella expansa, Streptognathodus fuchengensis, S.* spp.; and transitional form between *W. adenticulata* and *Sweetognathus merrilli.* **(F9, C8)**

867 1110 m (3642 ft) above base of section. Fusulinids: *Pseudofusulinella* sp., *Eoparafusulina* aff. *E. gracilis.* **(F8)**

1090 1054 m (3458 ft) above base of section. Fusulinids: *Reticulosepta* ? sp. 6, *R.*? sp. 7, *Eoparafusulina*? sp. **(F8)**

1380 977 m (3206 ft) above base of section. Fusulinids: *Pseudofusulinella* sp., *Triticites cellamagnus, T.* aff. *T. directus, T. pinguis*?, *Reticulosepta*? sp., *Schwagerina* sp., *Pseudoschwagerina* cf. *P. needhami*? **(F7)**

1418 968 m (3175 ft) above base of section. Fusulinids: *Pseudofusulinella* sp., *Triticites* aff. *T. ventricosus sacramentoensis, Schwagerina dunnensis*. **(F7)**

1471 955 m (3131 ft) above base of section. Fusulinids: *Triticites* sp., *Pseudoschwagerina* aff. *P. rhodesi, Schwagerina dunnensis, S.* sp. 3. **(F7)**

S-1766 Same locality as 765. Fusulinids: *Reticulosepta*? sp. 4, *R.*? sp. 7, *Schwagerina turgida, Stewartina*? aff. *S.*? *laxissima.* **(F9)**

S-1768 Same locality as 492. Fusulinids: *Reticulosepta*? sp. 7. **(F9)**

97-I-902 Top of uppermost bed in Keeler Canyon Formation, 1261 m (4138 ft) above base of section. Conodonts: *Sweetognathus merrilli.* **(C9)**

99-I-609 Approximately same locality as 1471. Conodonts: *Streptognathodus fusus, Mesogondolella belladontae, Wardlawella expansa.* **(C8)**

99-I-610 73 m (240 ft) above 99-I-609, approximately 1028 m (3371 ft) above base of section. Conodonts: *Mesogondolella dentiseparata, Streptognathodus longissimus.* **(C8)**

Lone Pine Formation:

91 1305 m (4281 ft) above base of section. Fusulinids: *Pseudofusulinella* sp., *Triticites* sp. (reworked), *Cuniculinella*? sp., *Schwagerina turgida*?, *S.* sp. 2, *Reticulosepta* sp., *Stewartina* sp. 2. **(F10)**

97-I-901 10.5 m (34 ft) below top of section. Conodonts: *Streptognathodus* n. sp. 1, *S.* n. sp. 2. **(C9)**

S-1782 Same locality as 97-I-901. Fusulinids: *Pseudofusulinella parvula, Chusenella* sp., *Schwagerina* cf. *S. bellula, S.* aff. *S. andresensis, S.* sp. 2. **(F10)**

Measured section 2,
Cerro Gordo Mine area

Keeler Canyon Formation, Salt Tram Member, lower part:

CG-0 Base of section. Conodonts: *Streptognathodus pawhuskaensis, S. virgilicus.* **(C6)**

CG-490 149 m (490 ft) above base of section. Conodonts: *Idiognathodus magnificus, Streptognathodus pawhuskaensis, S. costaeflabellus.* **(C7)**

S-1749 322 m (1055 ft) above base of section. Fusulinids: *Triticites cellamagnus, T.* sp. 3. **(F6)**

S-1753 Same locality as CG-490. Fusulinids: *Triticites* aff. *T. kelleyensis, T. confertoides*?, *Pseudofusulinella* sp. 1. **(F5)**

S-1759 285 m (935 ft) above base of section. Fusulinids: *Pseudofusulinella* sp. 1, *Triticites meeki, T.* sp. 3, *Reticulosepta*? sp. 8. **(F6)**

S-1764 99 m (325 ft) above base of section. Fusulinids: *Triticites burgessae*? **(F5)**

S-1765 288 m (945 ft) above base of section. Fusulinids: *Triticites* aff. *T. directus*?, *T.* aff. *T. hobblensis*? **(F6)**

S-1788 Ridge southeast of measured section approximately 198 m (650 ft) above base of section. Conodonts: *Streptognathodus pawhuskaensis.* **(C7)**

Keeler Canyon Formation, Salt Tram Member, upper part:

CG-1355 413 m (1355 ft) above base of section. Conodonts: *Streptognathodus* aff. *S. barskovi.* **(C8)**

CG-1376 420 m (1376 ft) above base of section. Conodonts: *Streptognathodus constrictus* (primitive). **(C8)**

CG-1521 464 m (1521 ft) above base of section. Conodonts: *Streptognathodus fusus, S. fuchengensis, S. longissimus, Mesogondolella dentiseparata.* **(C8)**

CG-1550 473 m (1550 ft) above base of section. Conodonts: *Streptognathodus* aff. *S. cristellaris, Mesogondolella belladontae.* **(C8)**

CG-1570 479 m (1570 ft) above base of section. Conodonts: *Streptognathodus longissimus, Mesogondolella* sp. **(C8)**

CG-1920 585 m (1920 ft) above base of section. Conodonts: *Streptognathodus* spp. (**C8**)

S-1750 Same locality as CG-1920. Fusulinids: *Reticulosepta*? sp. 4, *R.*? sp. 6, *R.*? sp. 7, *Schwagerina* cf. *S. bellula*? (**F9**)

S-1756 Same locality as CG-1570. Fusulinids: *Reticulosepta*? sp. 6, *Schwagerina* aff. *S. andresensis, S.* aff. *S. sublettensis, S.* sp. 3. (**F8**)

S-1757 Same locality as CG-1550. Fusulinids: *Reticulosepta*? sp. 6?, *Schwagerina* sp. 3. (**F8**)

S-1767 Base of upper bed in Keeler Canyon Formation, 640 m (2098 ft) above base of section. Fusulinids: *Pseudofusulina* sp., *Reticulosepta*? sp. 6, *R.*? sp. 7, *Schwagerina turgida, S.* sp. 1, *Pseudofusulina decora*?. (**F9**)

S-1787 Ridge southeast of measured section approximately 387 m (1270 ft) above base of section. Conodonts: *Streptognathodus fusus.* (**C8**).

99-I-612 Same locality as S-1767. Conodonts: *Streptognathodus virgilicus* (reworked), *S.* n. sp. 1, *S. pawhuskaensis* (reworked). (**C9**)

S-1787 Ridge southeast of measured section approximately 387 m (1270 ft) above base of section. Conodonts: *Streptognathodus* aff. *S. postfusus.* (**C8**)

Measured section 3,
Cerro Gordo Mine area

Keeler Canyon Formation, Salt Tram Member, lower part:

S-1752 276 m (906 ft) above base of section, same locality as C-72 of Riggs (1962). Fusulinids: *Pseudofusulinella* sp., *Triticites confertoides, T. pinguis, T.* aff. *T. ventricosus* var. *sacramentoensis, T.* sp. 3. Conodonts: *Streptognathodus pawhuskaensis, S. virgilicus, Idiognathodus magnificus*? (reworked) (**F5, C7**)

S-1758 Approximately 415 m (1360 ft) above base of section, near locality C-50A of Riggs (1962); just below base of upper part of Salt Tram Member. Fusulinids: *Triticites cellamagnus, Schwagerina* sp. 3. (**F6**)

S-1770 302 m (990 ft) above base of section, same locality as C-67 of Riggs (1962). Fusulinids: *Triticites confertoides, T.* sp. 3, *T.*? sp. 4, *Reticulosepta*? sp. (**F5**)

S-1794 297 m (975 ft) above base of section, same locality as C-69 of Riggs (1962). Conodonts: *Streptognathodus brownvillensis, S.* aff. *S. longilatus, S. virgilicus.* (**C7**)

S-1795 348 m (1141 ft) above base of section. Conodonts: *Streptognathodus* n. sp. A of Chernykh and Ritter (1997). (**C7**)

S-1796 Approximately 361 m (1185 ft) above base of section, 13.5 m above red debris-flow deposit. Conodonts: *Streptognathodus* spp. (**C7**)

Keeler Canyon Formation, Salt Tram Member, upper part:

S-1751 623 m (2044 ft) above base of section, same locality as C-7 of Riggs (1962). *Reticulosepta* sp. 1, *R.* sp. 2, *R.*? sp. 5, *Schwagerina* aff. *S. andresensis, S.* aff. *S. sublettensis, Pseudoschwagerina* aff. *P. parabeedi.* (**F9**)

S-1780 Same locality as S-1751. Fusulinids: *Reticulosepta* sp. 2, *R.*? sp. 3, *R.*? sp. 6, *Schwagerina* sp. (**F9**)

Ubehebe Mine section

Keeler Canyon Formation, Cerro Gordo Spring Member:

U-5A 11 m (36 ft) above base of section. Conodont: *Idiognathodus obliquus.* (**C2**)

U-7 18 m (59 ft) above base of section. Conodonts: *Idiognathodus expansus, I. obliquus, Gondolella magna.* (**C2**)

U-9 20 m (66 ft) above base of section. Conodonts: *Neognathodus medadultimus.* (**C2**)

U-11 28 m (92 ft) above base of section. Conodonts: *Idiognathodus obliquus, I. expansus* (gerontic). (**C2**)

U-12 30 m (98 ft) above base of section. Conodonts: *Idiognathodus sulciferus, I. eccentricus, I. expansus.* (**C3**)

U-13 45 m (148 ft) above base of section. Conodonts: *Idiognathodus sulciferus, I. expansus, I.* n. sp. A of Barrick et al. (1996), *Streptognathodus cancellosus.* (**C4**)

U-14 48 m (157 ft) above base of section. Conodonts: *Idiognathodus sulciferus, Streptognathodus confragus, Gondolella sublanceolata.* (**C4**)

U-17 61 m (200 ft) above base of section. Conodonts: *Idiognathodus magnificus, Streptognathodus excelsus, S. elegantulus.* (**C5**)

U-18 68 m (223 ft) above base of section. Conodonts: *Idiognathodus magnificus,* reworked *Idiognathoides* sp., *Gondolella* sp. (**C5**)

U-25 115 m (377 ft) above base of section. Conodonts: *Streptognathodus excelsus, S. elegantulus, Idiognathodus magnificus.* (**C5**)

U-26 119 m (390 ft) above base of section. Conodonts: *Streptognathodus excelsus, S. elegantulus, I. magnificus.* (**C5**)

U-31 137 m (450 ft) above base of section. *Idiognathodus* sp., *Neognathodus bothrops* (reworked). (**C5**)

U-34.5 197 m (646 ft) above base of section. Conodonts: *Streptognathodus pawhuskaensis, S. excelsus.* **(C6)**

Keeler Canyon Formation, Salt Tram Member:

U-36 233 m (764 ft) above base of section. Conodonts: *Streptognathodus pawhuskaensis, S. excelsus.* **(C6)**

U-38 280 m (918 feet) above base of section. Fusulinids: *Triticites* aff. *T. kelleyensis, T.* sp. 3. **(F4)**

U-42.5 344 m (1128 ft) above base of section. Conodonts: *Streptognathodus pawhuskaensis.* **(C6)**

U-45 390 m (1279 ft) above base of section. Conodonts: *Streptognathodus tenuialveus, S. costaeflabellus, Palmatolepis* sp. (reworked). **(C7)**

U-46 418 m (1371 ft) above base of section. Fusulinids: *Triticites pinguis*? **(F5)**

U-47 445 m (1459 feet) above base of section. Fusulinids: *Triticites cellamagnus.* **(F5)**

U-57 631 m (2070 ft) above base of section. Conodonts: *Streptognathodus tenuialveus, S. virgilicus* (reworked). **(C7)**

U-61′ 708 m (2322 ft) above base of section. Conodonts: *Diplognathodus* sp., narrow *Streptognathodus.* **(C7)**

U-63′ 722 m (2368 ft) above base of section. Fusulinids: *Schwagerina modica*?, *S. aculeata.* Conodonts: Reworked *Icriodus* sp. **(F6, C8?)**

U-64′ 733 m (2404 ft) above base of section. Fusulinids: *Schwagerina aculeata*? Conodonts: *Streptognathodus* sp. **(F6, C8?)**

Lone Pine Formation, upper limestone subunit (1.5 km south of measured section):

U-94 Near base of subunit. Conodonts: *Streptognathodus* n. sp.. 1, *Mesogondolella lata, Adetognathus paralautus.* **(C9)**

U-95 Near base of subunit. Conodonts: *Streptognathodus pawhuskaensis* (reworked?). **(C9?)**

U-96 Near top of subunit. Fusulinids: *Pseudofusulina decora*?, *Triticites pinguis* (reworked), *Reticuloseptra*? sp. 6?, *Schwagerina* cf. *S. bellula*?, *S.* sp. 2. **(F10)**

Spot localities, Cerro Gordo Mine area

Note: All localities are in Cerro Gordo Peak 7.5′ quadrangle.

Keeler Canyon Formation:

S-0858 Upper part of Cerro Gordo Spring Member, west of Cerro Gordo Road. Fusulinids: *Triticites burgessae.* **(F3)**

S-1772 Salt Tram Member, upper part, 5 m below top, about 0.3 km northwest of measured section 2 and Cerro Gordo Road, near floor of wash at elev. 6560 ft. Fusulinids: *Reticuloseptra*? sp. 5, R.? sp. 6, *Schwagerina* aff. *S. andresensis*?. **(F9)**

S-1773 Cerro Gordo Spring Member, imprecisely located along line of measured section 1. Fusulinids: *Beedeina* aff. *B. acme.* **(F2)**

S-1774 Same locality as 82-I-24; field loc. 99-I-1022. Fusulinids: *Reticuloseptra*? sp. 6, *R.*? sp. 7, *Schwagerina* aff. *S. sublettensis, Eoparafusulina*? sp. **(F9)**

S-1775 Same locality as 82-I-23; field. loc. 99-I-1021. Fusulinids: *Pseudofusulinella* sp., *Schwagerina* aff. *S. sublettensis*?. **(F9)**

S-1777 Salt Tram Member, upper part, about 10 m below S-1774; probably same stratigraphic level as sample 765 in measured section 1; field loc. 99-I-1023. Fusulinids: *Schwagerina* aff. *S. sublettensis, Pseudoschwagerina* aff. *P. parabeedei.* **(F9)**

82-I-23 Salt Tram Member, about 40 m below top; downhill to west from 82-I-24 at about elev. 7400 ft; probably same stratigraphic level as sample 492 in measured section 1. Fusulinids: *Pseudofusulinella parvula, Chusenella* cf. *C. jewetti, Eoparafusulina* sp. 1, *Schwagerina* aff. *S. sublettensis*?, *S. modica.* **(F9)**

82-I-24 Salt Tram Member, about 130 m below top, near crest of hill at elev. 7520 ft, 0.5 km S.50°W. of hill 7664, about 4.5 km northwest of Cerro Gordo Mine, north across canyon from measured section 1. Fusulinids: *Triticites* sp., *Reticuloseptra*? sp. 3. Conodonts: *Streptognathodus* spp., *Mesogondolella dentiseparata.* **(F9, C8?)**

82-I-28 Cerro Gordo Spring Member, about 30 m above base, in canyon 0.7 km N.65°E. of hill 7664 at elev. 7840 ft, about 4.1 km northwest of Cerro Gordo Mine. Conodonts: *Idiognathodus nodocarinatus, Neognathodus medexultimus, Gondolella magna.* **(C2)**

82-I-29 Cerro Gordo Spring Member, very close to 82-I-28. Conodonts: *Idiognathodus expansus.* **(C2)**

82-I-30 Cerro Gordo Spring Member, 1 m above base, down section from 82-I-28 and 29, 0.8 km N.65°E. of hill 7664 at elev. 7880 ft. Conodonts: *Neognathodus bothrops, Idiognathodus expansus.* **(C2)**

82-I-31 Cerro Gordo Spring Member, 2 m above base, 1 km S.75°E. of Morning Star Mine at elev. 8200 ft. Fusulinids: *Beedeina* cf. *B. cappsensis, B.* sp. 1, *Fusulinella fugax* (reworked), *Wedekindellina* cf. *W. cabezasensis*?. (**F2**)

Lone Pine Formation:

S-1760 Upper limestone unit, near northern end of exposure, 0.5 km S.80°W. of hill 7294 at elev. 6900 ft, about 2 km northwest of measured section 2 and Cerro Gordo Road. Fusulinids: *Pseudoschwagerina*? sp., *Pseudofusulina decora.* (**F10**)

99-I-608 Same locality as S-1760. Conodonts: *Sweetognathus merrilli, Mesogondolella lata.* (**C9**)

99-I-613 Upper limestone subunit, near top, about 0.3 km northwest of Cerro Gordo Road at elev. 6600 ft. Conodonts: *Mesogondolella lata, Sweetognathus merrilli.* (**C9**)

Spot localities,
Conglomerate Mesa area

S-0613 Keeler Canyon Formation, uppermost part, near S-0614. Fusulinids: *Triticites*? sp. 4. (**F6**)

S-0614 Keeler Canyon Formation, uppermost part, beneath unit 7 of sedimentary rocks of Santa Rosa Flat north of Conglomerate Mesa, on ridge north of hills 7236 and 7231 at about elev. 7000 ft, Nelson Range 7.5′ quadrangle. Fusulinids: *Triticites confertoides, T.* sp. 3. (**F6**)

S-1371 Keeler Canyon Formation, lowest fusulinid-bearing bed observed, northern Santa Rosa Hills east of Conglomerate Mesa, 0.25 km N.60°W of hill 6724 at about elev. 6400 ft, Nelson Range 7.5′ quadrangle. Fusulinids: *Triticites* aff. *T. beedei.* (**F5**)

S-1700 Boulder of Keeler Canyon Formation in float, in canyon near end of jeep road north of Conglomerate Mesa, near southeast corner of Cerro Gordo Peak 7.5′ quadrangle. Fusulinids: *Triticites mulleri, T.* sp. 3. Fusulinid zone uncertain.

S-1747 Keeler Canyon Formation, upper part, on same ridge as 79-CM-84 and about 100 m stratigraphically lower, 150 m west of hill 7315; field loc. 79-CM-85. Fusulinids: *Pseudofusulinella* sp. 1, *Triticites pinguis* (reworked), *Reticulosepta*? sp., *Schwagerina dunnensis*?, *S.* sp. *1.* (**F7?**)

79-CM-84 Keeler Canyon Formation, uppermost part, about 50 m below contact with unit 7 of sedimentary rocks of Santa Rosa Flat north of Conglomerate Mesa, on ridge just west and below summit of hill 7315, Nelson Range 7.5′ quadrangle. Fusulinids: *Pseudofusulinella simplex, Triticites meeki, T.* sp. 1, *Pseudoschwagerina* cf. *P. needhami, Schwagerina* sp. 1?. (**F7**)

79-CM-86 Keeler Canyon Formation, upper part, on same ridge as S-1747 and about 100–200 m stratigraphically lower, 0.3 km west of hill 7315. Fusulinids: *Triticites* sp. 3?. Conodonts: *Streptognathodus pawhuskaensis* (probably reworked). (**F6**)

79-CM-88 Keeler Canyon Formation, uppermost part, 15 m below contact with Leonardian-age limestone of sedimentary rocks of Santa Rosa Flat, on northeast side of ridge 0.75 km east of hill 7602 at elev. 7080 ft near southeast corner of Cerro Gordo Peak 7.5′ quadrangle. Conodonts: *Streptognathodus pawhuskaensis* (probably reworked). Conodont zone uncertain.

Spot localities,
San Lucas Canyon area

Note: Localities are in a side canyon draining into San Lucas Canyon from the east. Side canyon begins at a sharp bend in San Lucas Canyon 0.4 km S.75°E. of hill 5607, Nelson Range 7.5′ quadrangle. Keeler Canyon Formation in this area has an estimated thickness of 1040 m and is overlain by Permian limestone interpreted to represent unit 7 of the sedimentary rocks of Santa Rosa Flat, which crops out in one small area near the head of the side canyon 0.25 km S.60°W of hill 6121.

98-I-921 Unit 7, sedimentary rocks of Santa Rosa Flat. Conodonts: *Sweetognathus whitei.* (**higher than C9**)

98-I-922 Keeler Canyon Formation, about 30 m below top. Conodonts: *Streptognathodus pawhuskaensis.* (**C7?**)

98-I-926 Keeler Canyon Formation, about 520 m below top. Conodonts: *Streptognathodus pawhuskaensis.* (**C6**)

98-I-927 Keeler Canyon Formation, about 610 m below top. Conodonts: *Streptognathodus pawhuskaensis.* (**C6**)

98-I-928 Keeler Canyon Formation, about 625 m below top. Conodonts: *Streptognathodus pawhuskaensis, S. virgilicus.* (**C6**)

S-1746 Keeler Canyon Formation, about 360 m below top. Fusulinids: *Triticites pinguis.* (**F5**)

Spot localities,
Tinemaha Reservoir area

S-1208 Keeler Canyon Formation, upper part of exposed section (Tihvipah Limestone Member), on ridge about 3 km S.80°E. of southeast corner of Tinemaha Reservoir, Tinemaha Reservoir 7.5′ quadrangle. Fusulinids: *Pseudostaffella* sp., *Fusulinella fugax.* **(F1)**

S-1225 Keeler Canyon Formation, Tinemaha Reservoir Member, lower part, same ridge as S-1208. Fusulinids: *Fusulinella*? sp., *Pseudostaffella* cf. *P. powwowensis.* **(F1)**

T-1 Keeler Canyon Formation, Tinemaha Reservoir Member, near base, same ridge as S-1225. (USGS loc. 28920-PC). Conodonts: *Adetognathus* sp., *Declinognathodus noduliferus, Idiognathodus delicatus, Idiognathoides convexus, I. sinuatus, Neognathodus* spp. Conodonts identified by John Repetski, *in* Stone (1984). **(lower than C1)**

Spot localities,
Quartz Spring area

Note: All samples are from Tihvipah Limestone Member of Keeler Canyon Formation which forms several isolated exposures that overlie Rest Spring Shale on probable low-angle fault contacts (McAllister, 1952). Localities are in White Top Mountain 7.5′ quadrangle.

80-RS-2 Hill 7070 directly east of Rest Spring (about 4 km east of Quartz Spring), near top of exposed section. Conodonts: *Idiognathodus* spp. **(C1)**

80-RS-3 Same area as 80-RS-2, middle part of section. Conodonts: *Idiognathodus* spp. **(C1)**

80-RS-4 Same area as 80-RS-2, lower part of section. Conodonts: *Idiognathodus* spp., *Neognathodus* sp. **(C1)**

GH-1 Hill (elev. 5840+ ft) about 2.5 km north of Quartz Spring (in "Gap Hills" of McAllister, 1952), near top of exposed section which is about 140 m thick. Fusulinids: *Beedeina* cf. *B. apachensis, Fusulinella* sp. **(F2)**

GH-2 Same locality as GH-1 except 10 m lower in section. Fusulinids: *Fusulinella* sp., *Wedekindellina* cf. *W. cabezasensis.* **(F2)**

GH-4B Same area as GH-1, 15 m above base of section. Conodonts: Juvenile *Idiognathodus* sp. and *Neognathodus* sp. **(C1)**

GH-5 Same area as GH-1, 44 m above base of section. Fusulinids: *Beedeina* aff. *B. occultifons.* **(F2)**

GH-5A Just below GH-5. Conodonts: Juvenile *Idiognathodus* sp. and *Neognathodus* sp. **(C1)**

Spot localities,
northern Santa Rosa Hills

S-0856 Limestone boulder in lower conglomerate unit of Owens Valley Group, west side of Santa Rosa Hills. Fusulinids: *Triticites* aff. *T. ventricosus* var. *sacramentoensis.* **(F6)**

S-1389b Tihvipah Limestone, equivalent to Tihvipah Member of Keeler Canyon Formation. Fusulinids: *Beedeina* cf. *B. apachensis, Wedekindellina* cf. *W. cabezasensis.* **(F2)**

APPENDIX 3

Brief descriptions of fusulinid species occurring in the Keeler Canyon and Lone Pine Formations. Species are listed in alphabetical order.

Beedeina aff. *B. acme* (Dunbar and Henbest)

Our single specimen is similar to the type of *Beedeina acme*, but it is somewhat more elongate and the chomata appear to be restricted to the inner 2 or 3 volutions.
Occurrence: S-1773. Fusulinid zone F2.

Beedeina cf. *B. apachensis* (Ross and Sabins)

This form has a simple test with chomata that become massive in the outer volutions as in *Beedeina apachensis.* This species differs from *B. apachensis* in its overall larger size.
Occurrence: S-1389b, GH-1. Fusulinid zone F2.

Beedeina cf. *B. cappsensis* (Stewart)

Only one specimen of this species is available for study, but in all respects it resembles this rather broadly defined species.
Occurrence: 82-I-31. Fusulinid zone F2.

Beedeina aff. *B. haworthi* (Beede)

This species is smaller, generally is more elongate, and has larger chomata than the specimens illustrated by Dunbar and Henbest (1942). It does, however, closely resemble some of the more elongate forms.
Occurrence: 149. Fusulinid zone F2.

Beedeina aff. *B. occultifons* (Alexander)

This species is close to but slightly larger than *Beedeina occultifons.* It also resembles *B. euryteines,* but that species probably has better developed chomata which can not be distinguished in our specimens because of poor preservation.
Occurrence: 149, GH-5. Fusulinid zone F2.

Beedeina sp. 1

This small, delicate species bears little resemblance to any other described species. *Fusulina* sp. 26 of Cassity and Langenheim (1966) is most similar, but that species is more elongate than the present one.
Occurrence: 82-I-31. Fusulinid zone F2.

Chusenella cf. *C. jewetti* (Thompson)

This form rather closely resembles *Chusenella jewetti* except that in the latter species the volutions generally are more highly arched.
Occurrence: 82-I-23. Fusulinid zone F9.

Eoparafusulina aff. *E. gracilis* (Meek)

This species resembles *Eoparafusulina gracilis* in many respects, but differs in that the early volutions are less elongate, the specimen essentially lacks axial filling, and it has thinner and more delicately folded septa. This species could be a percusor to *E. gracilis.*
Occurrence: 867. Fusulinid zone F8.

Eoparafusulina sp. 1

Specimens of this species bear a general resemblance to *Eoparafusulina gracilis,* but the former have a larger proloculus and thicker walls.
Occurrence: 82-I-23. Fusulinid zone F9.

Fusulinella fugax Thompson

The specimens examined closely resemble *Fusulinella fugax* in their general form and with diaphanotheca developed only in the outer volutions. Fusulinid zone F1.
Occurrence: S-1208; 82-I-31 (reworked?).

Pseudofusulina decora Skinner and Wilde

The specimens at hand resemble *Pseudofusulina decora* in all respects.
Occurrence: S-1760, S-1767?, U-96?. Fusulinid zone F9?, F10.

Pseudofusulinella parvula Skinner and Wilde

Our specimens correspond with *Pseudofusulinella parvula* very well.
Occurrence: S-1782, 82-I-23, also in collection C-38 of Riggs (1962). Fusulinid zones F9, F10.

Pseudofusulinella simplex Skinner and Wilde

Our specimen is very similar to *Pseudofusulinella simplex,* differing only in having a slightly larger tunnel angle.
Occurrence: 79-CM-84. Fusulinid zone F7.

Pseudofusulinella sp. 1.

Our forms bears a strong resemblance to *Pseudofusulinella acuta* Skinner and Wilde, but that species is much larger.
Occurrence: S-1747, S-1753, S-1759. Fusulinid zone F5, F6.

Pseudoschwagerina cf. *P. needhami* Thompson

This form is larger than most specimens of *Pseudoschwagerina needhami* and the outer volutions expand somewhat more rapidly. Otherwise, it is quite similar.
Occurrence 1380?, 79-CM-84. Fusulinid zone F7.

Pseudoschwagerina aff. *P. parabeedei* Ross

The specimen examined is similar to *Pseudoschwagerina parabeedei* but differs in having more prominent chomata, and more volutions in the juvenarium (3-4), inshowing continued increase in height of the final volutions, and in having thicker walls. The present specimen has a larger proloculus and much smaller chomata than *P.* aff. *P. rhodesi.*
Occurrence: S-1751, S-1777. Fusulinid zone F9.

Pseudoschwagerina aff. *P. rhodesi* Thompson

In *Pseudoschwagerina rhodesi* the juvenarium has only about 3 volutions and is much smaller than in our specimens. In addition, the outer volutions do not expand as rapidly as in our specimens.
Occurrence: 1471. Fusulinid zone F7.

Pseudostaffella cf. *P. powwowensis* (Thompson)

The overall character and proportions of the California specimens are quite similar to those of *Pseudostaffella powwowensis.*
Occurrence: S-1225. Fusulinid zone F1.

Reticulosepta sp. 1.

This form has cuniculi and well developed chomata. It is smaller, more delicate, and more elongate than *Reticulosepta elongata* Magginetti, Stevens, and Stone.
Occurrence: 492, S-1751. Fusulinid zone F9.

Reticulosepta sp. 2.

Although cuniculi have not been observed in this species, fragments of fusulinids with cuniculi occur in the sample. This species is much smaller than *R.* sp. 1 in all dimensions, and the inner volutions are less elongate.
Occurrence: S-1751, S-1780. Fusulinid zone F9.

Retculosepta? sp. 3

This species is characterized by a delicate, fusiform test with small chomata extending throughout. The tunnel angle is much wider than that of *Reticulosepta* sp. 2.
Occurrence: S-1780, 82-I-24. Fusulinid zone F9.

Reticulosepta? sp. 4.

This species differs from *R.* sp. 1 in that the chomata

apparently do not persist into the final volutions and no cuniculi have been observed.
Occurrence: 492, 765?, S-1750, S-1766. Fusulinid zone F9.

Reticulosepta? sp. 5
This species is unusual in that it possesses a poorly developed juvenarium which is characteristic of *Stewartina*. The development of chomata beyond the juvenarium, however, suggests *Reticulosepta*. Cuniculi occur in the sample, but it is uncertain whether or not they occur in this species.
Occurrence: S-1772. Fusulinid zone F9.

Reticulosepta? sp. 6.
No cuniculi have been observed in this species, but its other characteristics suggest *Reticulosepta*. Chomata are less massive than in typical species and are generally confined to the inner volutions. This species is similar to *R.*? sp. 5 but the specimens are much less elongate.
Occurrence: 492, 1090, S-1756, S-1757?, S-1750, S-1767, S-1772, S-1774, S-1780, U-96?. Fusulinid zone F8, F9, 10?.

Reticulosepta? sp. 7.
This species is characterized by its extreme elongation. In most specimens chomata are limited to the first few volutions.
Occurrence: 492, 1090, S-1750, S-1766, S-1767, S-1768, S-1774. Fusulinid zone F9.

Reticulosepta? sp. 8
This species is characterized by its very, well developed, wide chomata that extend through all volutions.
Occurrence: S-1759. Fusulinid zone F6.

Schwagerina aculeata Thompson and Hazzard
The specimen figured here is similar in all respects to the type of *Schwagerina aculeata* except that the former has fewer more tightly coiled initial volutions.
Occurrence: 2035, U-63′, U-64′?. Fusulinid zone F6.

Schwagerina aff. *S. andresensis* Thompson
This species resembles *Schwagerina andresensis*, but our specimens are smaller with more pointed and more tightly coiled inner volutions.
Occurrence: S-1751, S-1756, S-1772, S-1782. Fusulinid zone F8, F9, F10.

Schwagerina aff. *S. arta* Skinner and Wilde
Our specimen is very poorly preserved, but it is generally similar to *Schwagerina arta*.
Occurrence: 492. Fusulinid zone F9.

Schwagerina cf. *S. bellula* Dunbar and Skinner
Our specimens differ from the types of *Schwagerina bellula* in having very small chomata on the first 2 or 3 volutions and less regularly folded septa. A slight increase in chamber height after the first 2 or 3 volutions suggest a poorly developed juvenarium.
Occurrence: S-1750?, S-1782, U-96?. Fusulinid zone F9?, F10.

Schwagerina dunnensis Sabins and Ross
In all respects this form corresponds to the types of *Schwagerina dunnensis*.
Occurrence: 1418, 1471, S-1747? Fusulinid zone F7.

Schwagerina modica Thompson and Hazzard
The present specimens resemble the type specimens in all respects.
Occurrence: 2035, U-63′, 82-I-23. Fusulinid zone F6.

Schwagerina aff. *S. sublettensis* Thompson, Dodge, and Youngquist
This species resembles *Schwagerina sublettensis* in most respects. It is similar to *S. providens* Thompson and Hazzard except that it is smaller and more delicate.
Occurrence: S-1751, S-1756, S-1774, S-1775?, S-1777, 82-I-23?. Fusulinid zone F8, F9.

Schwagerina turgida Skinner and Wilde
The present specimens are very similar to the types from the McCloud Limestone differing only in having slightly smaller proloculi. Some specimens are slightly more elongate at all stages of growth.
Occurrence: 91?, 492, 765, S-1766, S-1767. Fusulinid zone F9, F10.

Schwagerina sp. 1
This species resembles *Schwagerina turgida* in many respects, but it has a more elongate test and a much smaller proloculus.
Occurrence: S-1767, 492, 79-CM-84. Fusulinid zone F7, F9.

Schwagerina sp. 2
This species is similar to *Schwagerina* cf. *S. bellula* Dunbar and Skinner in having tiny chomata on the first 3 or 4 volutions, but it has more regularly folded septa, no indication of a juvenarium, and the test is shorter and has more rounded poles. It resembles *S. pseudoprinceps* Skinner and Wilde in many respects, but it has less pointed poles and less highly arched chambers.
Occurrence: 91, S-1782, U-96. Fusulinid zone F10.

Schwagerina sp. 3

This form differs from all other described species of the genus. It bears some similarity to *Chusenella jewetti* Thompson, but the early volutions are less tightly coiled and it has more tapered poles.
Occurrence: 1471, S-1757, S-1758. Fusulinid zone F6, F7, F8.

Stewartina? aff. *S.*? *laxissima* (Dunbar and Skinner)

This specimen is similar to the species cited above. It differs mainly in that it has an apparent juvenarium composed of 4 to 5 volutions compared to 2 to 3 in *Stewartina*? *laxissima,* it has a thicker wall, it is less elongate, and it has more prominent chomata.
Occurrence: S-1766. Fusulinid zone F9.

Stewartina sp. 1

This unusual specimen has a very large juvenarium of about 3 volutions with well developed chomata. This species is unlike any previously described species.
Occurrence: 765. Fusulinid zone F9.

Stewartina sp. 2

This specimen differs from all previously described species. It is closest to *Stewartina*? *acutosaxis* Magginetti, Stevens, and Stone except that in the present species the outer volutions expand much more slowly.
Occurrence: 91. Fusulinid zone F10.

Stewartina sp. 3

The general form and structure of this species suggests *Stewartina convexa* Thompson. The present species, however, has a larger juvenarium and is smaller in all other dimensions.
Occurrence: 492. Fusulinid zone F9.

Triticites aff. *T. beedei* Dunbar and Condra

This species is similar to *Triticites beedei* except that the overall size of the test is smaller and the proloculus is larger.
Occurrence: 2292, S-1371. Fusulinid zone F5.

Triticites burgessae Burma

The specimens available are very close to the type specimens.
Occurrence: S-0858, S-1764?. Fusulinid zone F3, F5?

Triticites californicus Thompson and Hazzard?

The poorly preserved specimens at hand match the types reasonably well.
Occurrence: 2785, 3549. Fusulinid zone F4.

Triticites cellamagnus Thompson and Bissell

The specimens examined are similar to the type specimens of *Triticites cellamagnus,* but many specimens have an even larger than normal proloculus for this species.
Occurrence: 1380, 2282?, S-1749, S-1758, U47. Fusulinid zone F5, F6, F7.

Triticites confertoides Ross

Our specimens are very similar to the types, differing only in having a slightly larger proloculus.
Occurrence S-0614, S-1753, S-1770, S-1752. Fusulinid zone F5, F6.

Triticites aff. *T. directus* Thompson

The present specimens are similar to the above species except that the inner volutions are less elongate.
Occurrence: 1380, S-1765?. Fusulinid zone F6, F7.

Triticites cf. *T. hermanni* Skinner and Wilde

The specimens studied are poorly preserved, but they resemble *T. hermanni* rather closely.
Occurrence: 2665?, 2785, 3549, S-1778. Fusulinid zone F4, F5?.

Triticites aff. *T. hobblensis* Thompson, Verville, and Bissell

The specimens of this species are poorly preserved, but in a general way they resemble *Triticites hobblensis* except that they are less elongate.
Occurrence: 3115, 3549, S-1765 Fusulinid zone F4, F6.

Triticites aff. *T. kelleyensis* Needham

Our specimen is smaller, but otherwise is similar to the above species.
Occurrence: S-1753, U38. Fusulinid zone F4, F5.

Triticites meeki Thompson

This specimen is virtually identical with a specimen of *Triticites meeki* figured by Thompson (1954, pl. 12, fig. 7).
Occurrence: S-1759, 79-CM-84. Fusulinid zone F6, F7.

Triticites mulleri Skinner and Wilde

These specimens are similar to the types of this species in all respects.
Occurrence: S-1700. Fusulinid zone uncertain.

Triticites pinguis Dunbar and Skinner

This form appears to be quite variable and numerous taxa have been erected to cover this variability. Some of the present forms are almost identical to the types of *Triticites pinguis.*
Occurrence: 1380?, 2292, 2665 S-1746, S-1747 (reworked), S-1752, S-1778, U-46?, U-96 (reworked). Fusulinid zone F5, F6, F7?.

Triticites aff. *T. ventricosus* var. *sacramentoensis* Needham

The present specimens resemble the above variation in their general characters. Our specimens, however, have more rounded early volutions that are more tightly coiled. Occurrence: 1418, 2035, S-0856, S-1752. Fusulinid zone F5, F6, F7.

Triticites whetstonensis Ross and Tyrrell

This specimen is similar to the types of this species except that it appears to have slightly less pointed poles. Occurrence: 3549. Fusulinid zone F4.

Triticites sp. 1

These specimens are unlike any other described species, especially in the very rapid increase in height of the outer volutions.
Occurrence: 79-CM-84. Fusulinid zone F7.

Triticites sp. 2

This species most closely resembles *Triticites turgida* Dunbar and Henbest. However, it also resembles *T. confertus* Thompson, but has a much larger proloculus and more folding in the axial region. It is shorter, generally has a larger proloculus, and has more highly developed chomata than *T. elegantoides* Ross.
Occurrence: 2665, 2785. Fusulinid zone F4, F5.

Triticites sp. 3

This inflated species has high, thin chomata that distinguishes it from other highly inflated forms such as *Triticites californicus.*
Occurrence: 2035, 2292, S-0614, S-1700, S-1749, S-1752, S-1759, S-1770, 79-CM-86?, U-38. Fusulinid zone F5, F6.

Triticites? sp. 4

This species differs from other described species in having a very wide tunnel angle bordered by small chomata.
Occurrence: S-0613, S-1770. Fusulinid zone F5, F6.

Wedekindellina cf. *W. cabezasensis* Ross and Sabins

The present specimens are very similar to *Wedekindellina cabezasensis,* differing only in having slightly less axial filling and a slightly larger proloculus.
Occurrence: S-1389b, 82-I-31?, GH-2. Fusulinid zone F2.

Wedekindellina? sp. 1

The wall structure in the specimens available is very poorly preserved, but the wall probably contains a diaphanotheca. This unusual form is characterized by its large size.
Occurrence: 360. Fusulinid zone F2.

APPENDIX 4

Brief description of conodont species concepts as used herein pertaining only to Pa elements and their occurrence. Multielement taxonomy is not discussed, owing to the paucity of Pb, M, and S elements in the Keeler Canyon faunas.

Adetognathus paralautus Orchard

A species of *Adetognathus* with a broad posterior platform possessing long transverse ridges, similar to the figured holotype of Orchard (1984).
Occurrence: U-94.

Gondolella magna Stauffer and Plummer

Species with distinct transverse ridges, resulting in crenulated upper lateral surfaces of platform.
Occurrence: 149A, 680A, 82-I-28, U-7.

Gondolella sublanceolata Gunnell

Elongate platform with only faint transverse ridges.
Occurrence: U-14.

Idiognathodus eccentricus (Ellison)

Ornamented idiognathodid with a continuous longitudinal trough that extends from the inner adcarinal trough to near the posterior end.
Occurrence: U-12.

Idiognathodus expansus Stauffer and Plummer

Broadly biconvex Pa element with fine transverse ridges and a short carina; adcarinal grooves are short with steep anterior margin; anterior lobe weakly developed and relegated to the anterior end.
Occurrence: U-7, U-11, U-12, U-13, 82-I-30, 82-I-29, 149A, 360A, 680A.

Idiognathodus magnificus Stauffer and Plummer

Pa element characterized by large, laterally projecting inner anterior accessory lobe which distorts the inner platform profile in oral view.
Occurrence: CG-490, U-17, U-18, U-25, U-26; S-1752 (reworked).

Idiognathodus nodocarinatus (Jones)

Pa element with a very short carina and deep trough that extends the length of the broad platform; transverse ridges typically, but not always offset across the median trough; accessory lobes well developed.
Occurrence: 82-I-28, 149A.

Idiognathodus obliquus Kozitskaya

Dextral Pa element displays distinct inward curvature

of the posterior platform with concomitant development of oblique transverse ridges. Well developed inner and outer accessory lobes.
Occurrence: U-5A, U-7, U-11, 149A, 360A.

Idiognathodus sulciferus Gunnell

This species is distinguished by the straight, elongate, triangular platform outline with coarse nodes and widely spaced transverse ridges. Adcarinal ridges are typically long and flaring.
Occurrence: U-12, U-13, U-14.

Idiognathodus n. sp. A of Barrick et al., 1996

Slightly curved Pa element with a long triangular platform bearing coarse nodes and widely spaced adcarinal ridges. On each side a longitudinal groove extends from the adcarinal trough to near the posterior end of the platform, isolating a row of medial nodes.
Occurrence: 975A, U-13.

Mesogondolella belladontae Chernykh

Narrow, prolongated species with low, discrete denticles and a large horn-like cusp that is terminally positioned.
Occurrence: 99-I-609, CG-1550.

Mesogondolella dentiseparata Chernykh

Species possessing a symmetrical platform with a rounded posterior margin and discrete carinal denticles.
Occurrence: CG-1521, 82-I-24, 99-I-610.

Mesogondolella lata Chernykh

Symmetrical platform with angular posterior corner and a relatively small cusp. Platform tapers posteriorly and possesses a medial row of small, closely set denticles that increase in height anteriorly.
Occurrence: U-94, 99-I-608, 99-I-613.

Neognathodus bothrops Merrill

Pa element possesses lateral parapets that continue symmetrically to the posterior tip of the platform. Posterior terminus of carina separated from posterior tip by small gap.
Occurrence: 82-I-30; U-31=reworked.

Neognathodus medadultimus Merrill

Neognathodid in which the outer parapet merges with the carina just anterior of the posterior terminus.
Occurrence: U-9.

Neognathodus medexultimus Merrill

Asymmetrical platform; reduced outer parapet merges with carina approximately at midlength of platform.
Occurrence: 82-I-28

Streptognathodus aff. *S. barskovi* (Kozur)

Dextral elements possess a symmetrical platform well developed anterior parapets, a shallow trough, and numerous elongate transverse ridges. The figured specimen is somewhat narrower than typical *S. barskovi,* but otherwise conforms to the species concept.
Occurrence: CG-1355.

Streptognathodus brownvillensis Ritter

Elongate platform with medial row of nodes that correspond in position with short transverse ridges.
Occurrence: S-1794.

Streptognathodus cancellosus (Gunnell)

Slender biconvex Pa element with high outer platform margins that join with adcarinal ridges, inner adcarinal ridge forms a frill; lobes generally absent, platform surface concave with one or two longitudinal rows of nodes that extend near posterior tip.
Occurrence: U-13.

Streptognathodus confragus (Gunnell)

Slender Pa element with high anterior platform margins, including an inner frill. Lobes absent or greatly reduced. Carina extends to platform midlength, posterior of which are several continuous transverse ridges.
Occurrence: U-14.

Streptognathodus constrictus Chernykh and Reshetkova

Narrow Pa element with slight to pronounced constriction roughly at position of carinal terminus. Stratigraphically lower forms lack well developed adcarinal ridges. Later forms bear flared parapets. Specimens from the Keeler Canyon reflect the more primitive morphology.
Occurrence: CG-1376.

Streptognathodus costaeflabellus Chernykh and Ritter

Pa element characterized by a moderately broad platform with a straight inner platform margin and strongly convex outer margin in posterior one-third of platform and reclined posterior transverse ridges.
Occurrence: CG-490, U-45.

Streptognathodus aff. *S. cristellaris* Chernykh and Reshetkova

This species was established by Chernykh and Reshetkova (1987) for Asselian forms with a broad platform and inner accessory lobe bearing ridge-like ornamentation oriented normal to the platform axis. Advanced forms possess greatly reduced accessory nodes similar to that figured herein. Node reduction reflects a late stage in the evolutionary history of the nodose *S. wabaunsensis*-*S. isolatus*-*S. cristellaris* lineage.

Occurrence: CG-1550.

Streptognathodus elegantulus Stauffer and Plummer

Unornamented Pa element with a shallow V-shaped trough and relatively short, ridge-like carina. On the holotype there is a slight constriction on the inner side of the platform adjacent to the posterior end of the carina resulting in development of an inner anterior frill.
Occurrence: U-17, U-25, U-26

Streptognathodus excelsus Stauffer and Plummer

This species is typically broad with a shallow V-shaped trough and well developed inner and outer accessory lobes.
Occurrence: U-17, U-25, U-26, U-34.5, U-36.

Streptognathodus fuchengensis Zhao

This concept is applied herein to streptognathodids with a nearly flat platform surface that increases in width posteriorly. The platform displays a distinct inward curvature and rounded posterior termination.
Occurrence: 765, CG-1521.

Streptognathodus fusus Chernykh and Reshetkova

Nearly symmetrical Pa element with a shallow, slit-like median trough and elongate transverse ridges oriented normal to the platform axis. The inner parapet is larger than its inner counterpart.
Occurrence: 99-I-609, CG-1521, S-1787.

Streptognathodus aff. *S.longilatus* Chernykh and Ritter

As originally conceived, this is an unornamented streptognathodid with long adcarinal ridges and a relatively broad posterior platform bearing a distinct constriction in the anterior one-third. The specimen from S-1794 lacks the long adcarinal ridge, but resembles *S. longilatus* in platform shape and age.
Occurrence: S-1794.

Streptognathodus longissimus Chernykh and Reshetkova

Unornamented streptognathodid with an elongate, narrow sinistral Pa platform element. Carina is short and adcarinal ridges are generally well developed.
Occurrence: CG-1521, CG-1570, 99-I-610.

Streptognathodus pawhuskaensis (Harris and Hollingsworth)

Unornamented streptognathodid with a deep U-shaped trough.
Occurrence: U-34.5, U-36, U42.5, 98-I-922, 98-I-926, 98-I-927, 98-I-928, CG-0, CG-490, S-1752, S-1788, 79-CM-86, 79-CM-88; U-95 and 99-I-612=reworked.

Streptognathodus tenuialveus Chernykh and Ritter

Species of narrow unornamented *Streptognathodus* with nearly symmetrical platform and flat oral surface.
Occurrence: U-45, U-57.

Streptognathodus virgilicus Ritter

Unornamented species with shallow V-shaped trough and elongate transverse ridges. Platform ranges from wide to narrow.
Occurrence: 99-I-612 and U-57 (reworked); S-1752, S-1794, CG-0, 98-I-928.

Streptognathodus n. sp. 1

Elongate, unornamented species with short carina, well developed parapets, and a slight inward flexure of the axis. This species resembles *S. simplex* and *S. elongatus*, but is younger (Sakmarian) than the type materials of these species (late Gzhelian). They resemble specimens from the Sakmarian Eiss Limestone of Kansas (Boardman, personal communication, 2001).
Occurrence: 97-I-901, 99-I-612, U-94.

Streptognathodus n. sp. 2

Broad unornamented species with a distinct inner frill in the anterior portion of the platform. Trough slit-like and narrow with numerous elongate transverse ridges. This species resembles Asselian *S. fusus* and *S. postfusus*, but is herein tentatively distinguished by its Sakmarian age. Similar morphotypes were collected from the Sakmarian Eiss Limestone in Kansas (Boardman, personal communication, 2001).
Occurrence: 97-I-901.

Streptognathodus n. sp. A of Chernykh and Ritter, 1997

Streptognathodid with an oblique anterior termination and symmetrical trough.
Occurrence: S-1795.

Sweetognathus merrilli Kozur

Sweetognathid with no gap between the carina and denticles of the free blade. This feature is hard to evaluate in many of our specimens due to poor preservation of the platform anterior.
Occurrence: 492, 99-I-608, 97-I-902, 99-I-613.

Sweetognathus whitei (Rhodes)

Sweetognathid with elongate transverse ridge oriented normal to platform axis.
Occurrence: 98-I-921.

Wardlawella expansa (Perlmutter)

Small Pa element with fused carina ornamented with micro-pustules. This species evolved from *Diplognathodus* and was the evolutionary link to most Permian gnathodids.

Occurrence: 99-I-609, 76.

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The Crazy Hollow Formation (Eocene) of Central Utah

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ABSTRACT

The Late Eocene Crazy Hollow Formation is a fluviatile and lacustrine unit that was deposited locally in the southwest arm of Lake Uinta during and after the last stages of the lake that deposited the Green River Formation. Most exposures of the Crazy Hollow are located in Sanpete and Sevier Counties. The unit is characterized by a large variety of rock types, rapid facies changes within fairly short distances, and different lithofacies in the several areas where outcrops of the remnants of the formation are concentrated. Mudstone is dominant, volumetrically, but siltstone, shale, sandstone, conglomerate and several varieties of limestone are also present. The fine-grained rocks are mostly highly colored, especially in shades of yellow, orange and red. Sand grains, pebbles and small cobbles of well-rounded black chert are widespread, and "salt-and-pepper sandstone" is the conspicuous characteristic of the Crazy Hollow. The salt-and-pepper sandstone consists of grains of black chert, white chert, quartz and minor feldspar. The limestone beds and lenses are paludal and lacustrine in origin; some are fossiliferous, and contain the same fauna found in the Green River Formation.

With trivial exceptions, the Crazy Hollow Formation lies on the upper, limestone member of the Green River Formation, and the beds of the two units are always accordant in attitude. The nature of the contact differs locally: at some sites there is gradation from the Green River to the Crazy Hollow; at others, rocks typical of the two units intertongue; elsewhere there is a disconformity between the two. A variety of bedrock units overlie the Crazy Hollow at different sites. In the southeasternmost districts it is overlain by the late Eocene formation of Aurora; in western Sevier County it is overlain by the Miocene-Pliocene Sevier River Formation; in northernmost Sanpete County it is overlain by the Oligocene volcanics of the Moroni Formation. At many sites bordering Sanpete and Sevier Valleys the Crazy Hollow beds dip beneath Quaternary sediments that fill the two valleys.

The Crazy Hollow Formation ranges from 0 to 1,307 feet (0–398 m) thick in the region, but is usually much thinner than the maximum value. At most outcrops it is only a few scores of feet (12–50 m) thick. Its age is middle Eocene, for it is only a little younger than the underlying Green River Formation. The unit developed by the washing of detritus into the basin of the southwest arm of Lake Uinta from the various source rocks in the highlands surrounding the basin. The limestone beds and lenses formed in ponds and small lakes that developed in the basin from time to time during and following the draining and evaporation of Lake Uinta.

The qualities of the Crazy Hollow Formation are descibed in detail for 10 different areas of outcrops in the Sanpete and Sevier Valleys and vicinity.

INTRODUCTION

It is now more than 50 years since the upper Eocene Crazy Hollow Formation was first proposed and described by Spieker (1949), at a time when its regional extent was not known. In the years since, the mapping, lithology, age and sedimentary history of the formation have been much advanced. This paper brings together what has been learned over the half century and presents, for the first time, a regional picture of the Crazy Hollow and its significance.

The Crazy Hollow Formation was named by Spieker (1949) for the "red and orange sandstone, siltstone, and shale, white sandstone, and pepper-and-salt sandstone that overlies the Green River Formation and underlies [mixed sedimentary and pyroclastic beds]" near Salina, Sevier County, Utah. The type locality is in a still-unnamed steep gulch that extends headward (southward) from the south wall of Salina Canyon (Fig. 1) into the middle of section 5, T. 22 S., R. 1 E., Salt Lake Base Line and Meridian (all grid designations cited refer to this same baseline and meridian). Spieker dubbed the gulch "Crazy Hollow" because of the much-faulted and complex stratigraphy in that drainage. He measured no type section. The mouth of Crazy Hollow is about one half mile (0.8 km) west of the mouth of Soldier Canyon, which is named on the topographic and geologic maps of the Salina quadrangle (Willis, 1986) and is served by a good road.

Spieker noted that the formation is widely exposed in nearby areas both north and south of Salina Canyon. It is widespread in the highlands south of Crazy Hollow to about 6 miles (9.6 km) from Salina Canyon, and from the upper reaches of Soldier Creek into T. 23 and T. 24 S., R. 1 E., the Lost and Gooseberry Creek drainages (McGookey, 1960). It extends about 6 miles (9.6 km) north from Crazy Hollow (Willis, 1986; Witkind et al., 1987). Spieker (1949) considered that the Crazy Hollow lies disconformably on the limestone beds of the upper Green River Formation and that it is overlain disconformably by pyroclastic beds in the Salina area, the only place then known to him where superjacent bedrock lies on the formation. He called those mixed sedimentary and pyroclastic beds [now the formation of Aurora] by a provisional name—Gray Gulch—that never achieved currency. He said that the Crazy Hollow is also recognizable in Sanpete Valley as far north as Spring City, and elsewhere (Spieker, 1949). It is now known to crop out, in patches, at many places in Sevier and Sanpete Counties; very small parts of the unit are also present in the southeast corner of Juab County and in southeastern Millard County (Fig. 1). We also now know that limestone and conglomerate are present in the Crazy Hollow at many places.

The Crazy Hollow is present as large patches in a number of places, (Areas 1 to 10 in Fig. 1), but in many of those places the areas of outcrop are themselves patchy, as shown in some of the numbered areas in Figure 1. The formation contains a wide variety of lithofacies, and the several patches of outcrop (Areas 1 to 10) locally have different lithofacies. Erosion, overlying Quaternary deposits, and faulting make numerous smaller patches of Crazy Hollow outcrop within each area; Areas 1 and 3 show this especially. This part of central Utah was the basin of the southwest arm of Lake Uinta, in which the Green River Formation of Utah was deposited. The mostly fluviatile Crazy Hollow sediments apparently spread only locally over the upper surface of the Green River beds as the southwest arm of Lake Uinta drained and dried. The perimeter around the remaining Crazy Hollow beds contains an area of about 1,500 square miles. There is little likelihood that the formation once completely covered the more extensive Green River Formation, although the existing areas of Crazy Hollow outcrop were doubtless larger before the effects of post-Eocene tectonics and erosion. There are no regionally extensive thick deposits of subaerial sediments covering the Green River Formation in central Utah, as there are in the Uinta Basin of northeastern Utah, once a more central part of Lake Uinta. Quite different and more active tectonics produced thick middle Tertiary deposits over the Green River Formation there—to as much as 8,000 feet (2,438 m) thick (Hintze, 1988).

Most of the existing outcrops of the Crazy Hollow Formation on the west (Fig. 1) lie on the lower flanks of the Pavant Range and the southern Valley Mountains and the southern Gunnison Plateau (San Pitch Mountains). On the east they lie on the lower reaches of the Fish Lake and Wasatch Plateaus. Most outcrops in Sanpete Valley, between Sterling and Fairview, are low on the dip slope of the Wasatch monocline. It is reasonable to suppose that the Crazy Hollow Formation may be more extensive in the subsurface, but published subsurface works do not distinguish it. A water well drilled just northeast of Ephraim in the late 1960s or early 1970s showed coarse salt-and-pepper sand above the Green River beds (G. E. Moore. Jr., personal communication, 2000), but there are no nearby outcrops of Crazy Hollow beds.

LITHOLOGY

Although mudstone is volumetrically the most abundant rock in the Crazy Hollow Formation, the "signature" rock types—salt-and-pepper sandstone and conglomerate—will be described first. Mineralogical details in this section are from Norton (1986; see also Weiss, 1982).

Salt-and-pepper sandstone and conglomerate

These rocks are so named because of the conspicuous speckled or dusky appearance afforded by the mixture of white, light gray and black grains. Fresh sandstone ranges from very pale orange to light olive gray. The rock is light colored because "salt" grains prevail over "pepper." Norton (1986) found that the black grains are about 15 percent of the rock in northern areas (central Sanpete County) and as much as 20 percent in southern areas (Sevier County). Light grains are quartz, chert and feldspar, and the black grains and pebbles are very dark gray or black chert (Fig. 2). There is less black chert in the formation in far northern Sanpete County (Fograsher, 1956). The typical composition of salt-and-pepper sandstone is 50 percent quartz (90 percent of which is monocrystalline), 45 percent lithic fragments and 5 percent feldspar (albite and K-spar). The salt-and-pepper sandstone is a chert litharenite or feldspathic litharenite, and most lithic fragments are chert—both light gray and black. Collophane has been observed in some pebbles (T. F. Lawton, written communication, 2000). Quartz and white or light-gray chert are common in many of the Paleozoic, Mesozoic and Tertiary bedrock units of the region, but the black chert probably came from dark, cherty carbonates in the Mississippian Deseret Limestone or the Permian Park City Formation in the upper plate of the Sevier overthrust belt.

Such units are still exposed in some of the eastern ranges of the Basin and Range province, not far west of Sevier and Sanpete Counties. Biek (1991) reported well-rounded pebbles of quartzite and black chert in the Triassic Ankareh Formation near Nephi, at the south end of the Wasatch Range (Mount Nebo). The Ankareh, of course, extends far northward into the main Wasatch Range. It seems reasonable that black chert pebbles in the Ankareh may have come from the older rocks to the west to reside in the Nebo allochthon; from there some may have contributed to the Crazy Hollow Formation during a second cycle. Outcrops of the Ankareh Formation also are known from the west side of Juab Valley, across from Mount Nebo, in the West Hills (Meibos, 1983) and Long Ridge (Muessig, 1951).

Some quartz grains have characteristics of metamorphic origin, and heavy-mineral separations show small amounts of igneous minerals (zircon, tourmaline) in the sandstone (Norton, 1986). Plagioclase feldspars with albite twinning make up 40 percent of the feldspars. Most feldspar is not twinned and microcline is rare. The igneous grains and feldspars may have been reworked from sandstone in the Colton Formation, or possibly were late imports from the southeast (cf. Stanley and Collinson, 1979; Dickinson et al., 1986).

The salt-and-pepper sandstone is weakly cemented by calcite and has little strength. The finer the grain size, the better the cementation, usually; some fine-grained examples show cavernous or honeycomb weathering. Many sandstone beds exhibit weakly developed trough and tabular cross-bedding in thin to medium beds.

Oddly, the large grains "pebbles and small cobbles" are virtually all of black chert (Fig. 2). Conglomerate is not abundant in the Crazy Hollow, except in northern Sanpete County, and most conglomerate beds are thin. Pebble-supported fabric is the exception rather than the rule. Many sandstone beds have pebble bands or floating pebbles and small cobbles of black chert. Black chert pebbles are locally common in well-cemented mudstone or siltstone, like raisins in cake.

WHITE OR "CLEAN" SANDSTONE

Beds of pale-yellowish-gray or very light gray sandstone are present in many areas and are the principal deposit of the formation locally, as on the south end of the high top of the Gunnison Plateau (Fig. 1: Area 7A), in the southwest quarter of the Manti quadrangle.[1] The "clean" sandstone is mineralogically and structurally quite like that of the salt-and-pepper sandstone, except for the fewer and smaller grains of black chert. These are also litharenites or feldspathic litharenites, but without conspicuous black chert, and are the main sandstones in northern Sanpete County (Fograsher, 1956). Norton (1986) noted that most white sandstone beds in the southern districts are lensatic and many in the northern districts are broad blankets. Curiously, pebbles and larger grains of quartz or white and light-gray chert are uncommon, so that there are no white or "clean" conglomerates.

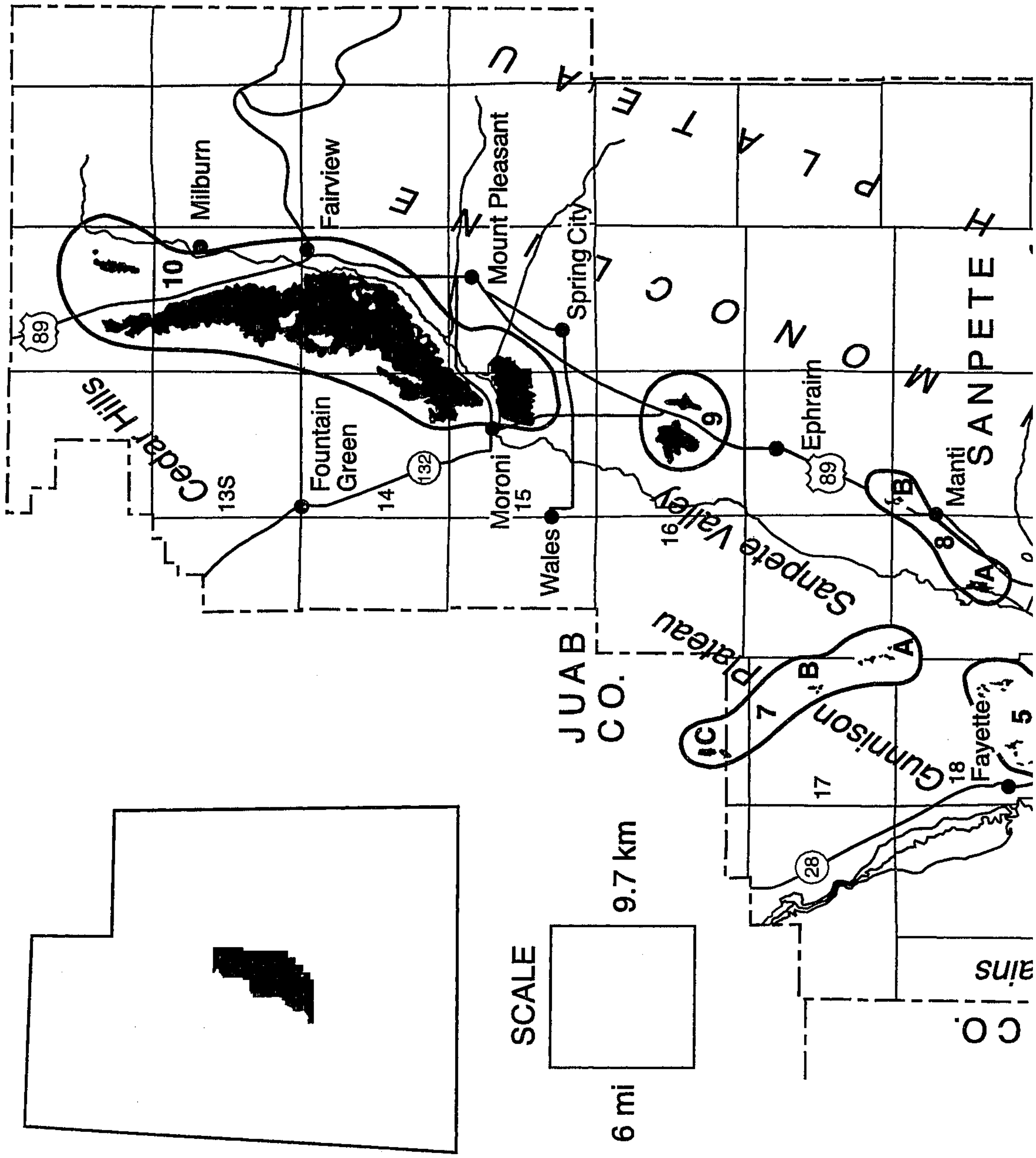
QUARTZITE CONGLOMERATE

In far northern Sanpete County, north and northwest of Fairview city, on the southeast flank of the Cedar Hills, the Crazy Hollow Formation contains medium to thick beds of coarse quartzite pebble and cobble conglomerate (Fograsher, 1956). The well-rounded clasts, from several Proterozoic quartzite formations, are reworked from Cretaceous conglomerates in Hop Creek Ridge in the central Cedar Hills, not far west of the area.

MUDSTONE AND SILTSTONE

Mudstone and siltstone of various colors make up the bulk (80–85 percent) of the Crazy Hollow Formation in most of the numbered areas and lettered subareas (Fig. 1), (Norton, 1986), except in northern Sanpete County (Area 10), where it is about half of the formation (Fograsher, 1956). Locally however, particularly where the formation is thin, there is little or no mudstone or siltstone, as in Subareas 7A, 7B, and Area 9. All of the mudrocks are sandy

[1]All quadrangles named are 7.5-minute quadrangles unless otherwise specified.


Milburn
Fairview
Mount Pleasant
Spring City
Fountain Green
Moroni
Wales
Ephraim
Manti
Fayette
Cedar Hills
Sanpete Valley
Gunnison Plateau
SANPETE
JUAB CO.
SCALE
9.7 km
6 mi

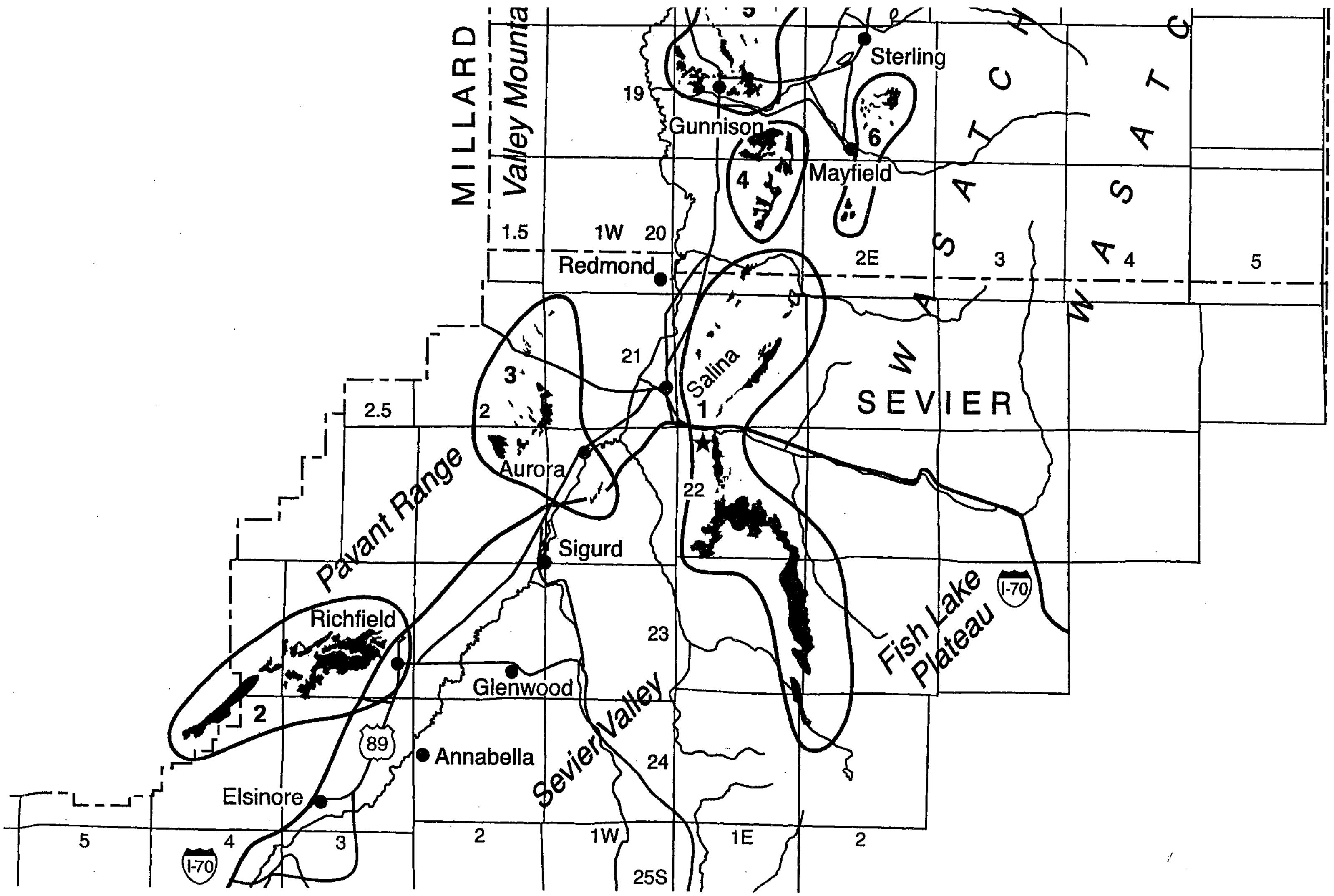


Figure 1. Map of Sanpete County and part of Sevier County, Utah, with the geologic map of the Crazy Hollow Formation represented by solid black areas. Coherent areas of outcrop patches of the formation are outlined and numbered 1 through 10. Crazy Hollow—the type area—is marked by a star in Area 1. The patches within the numbered areas closely approximate the shapes of outcrops of the Crazy Hollow Formation mapped on the many geologic maps, both published and in various theses and dissertations, from which this map was compiled. Very small outcrops are exaggerated slightly so they may show at the small scale of the map. The base of the map is adapted from the 1:500,000 map of Utah.

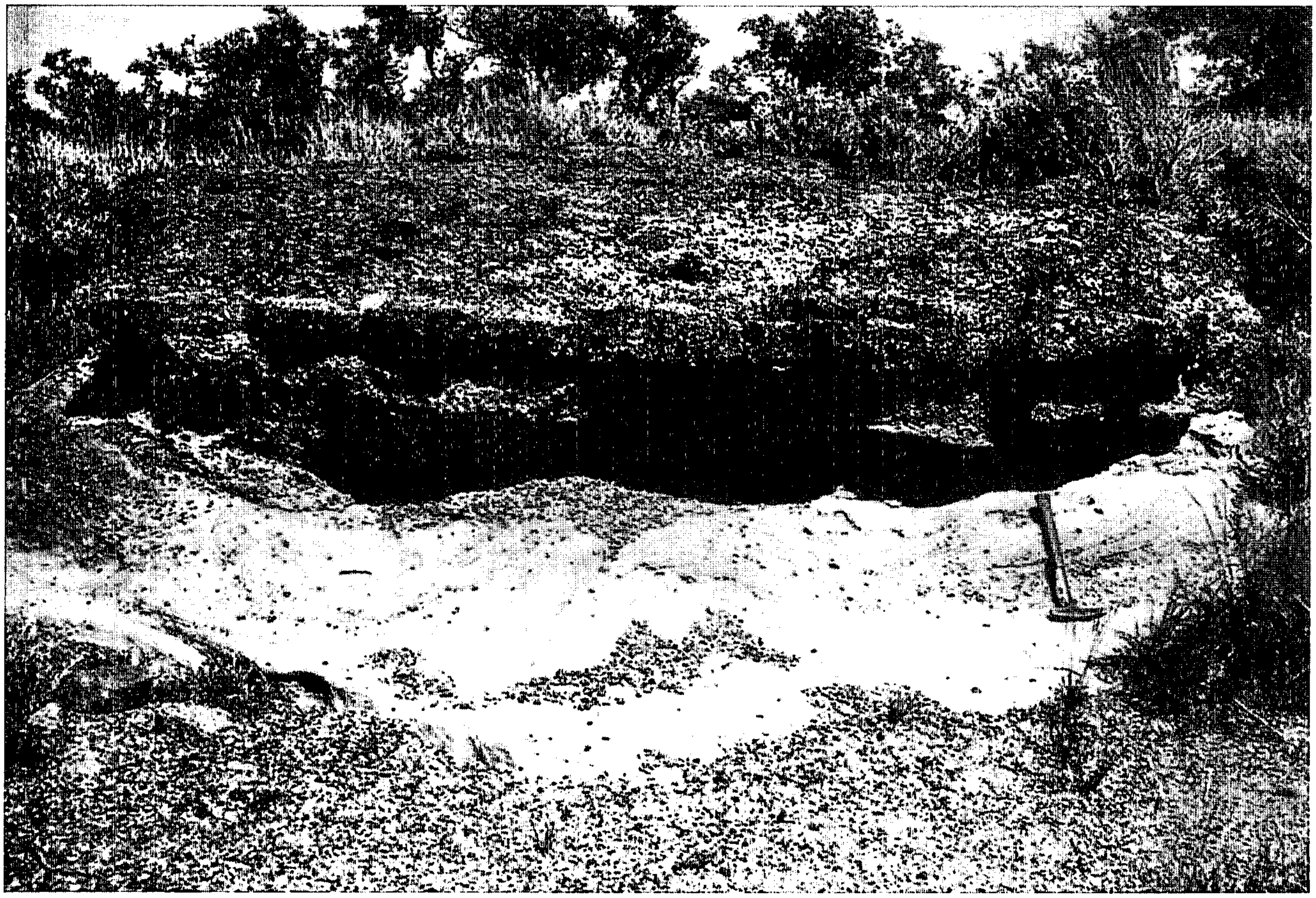


Figure 2. Outcrop of salt-and-pepper sandstone and pebble conglomerate in Subarea 7A (Fig. 1). The small black spots in the foreground are pebbles of black chert lying on the sandstone slope and the soil below it. This is part of the largest of the five outcrops in Subarea 7A, and is in the S1/2SE1/4 section 14, T. 17 S., R. 1 E. Photo by S. R. Mattox.

to some degree; any with more than 50 percent sand are regarded as sandstone. Although Spieker (1949) and several of his students used the term "shale," few of the mudrocks of the Crazy Hollow have the fissility expected of true shales. These beds are colored by traces of iron in various states; most are moderate reddish-brown to very pale orange, but gray, lavender, purple and green also are present. Most of the mudrocks are weakly calcareous and very readily eroded; fresh rock of this sort is covered at most places by regolith and soil having the color of the fresh bedrock beneath it.

CARBONATE ROCKS

Carbonate rocks make up only about 10 percent of the Crazy Hollow Formation regionally, but they are quite varied in appearance and composition. Limestone and dolomitic limestone prevail, but some is limy dolomite. Norton (1986) found that there is very little dolomite in the northern districts, but that in the southern districts the fraction of dolomite in hand samples ranges from 0 to 80 percent. Most limestone and dolomitic limestone beds are yellowish gray, but pale-red and medium-gray limestones are also present locally. Most of the carbonate beds are micrite or intraclastic, with some mud or sand. Norton (1986) referred to some as sandy limestones, but the average carbonate fraction in all types is 85 percent. A few beds contain nodules of light-colored chert, but this is not common. Thicknesses differ widely; most units in measured sections range from less than 2 feet (0.5 m) to 12–14 feet (3.6–4.3 m), but one unit in Norton's measured section near Willow Creek (section 33, T. 20 S., R. 1 E.) is 137 feet (42 m) thick (Norton, 1986).

Except in far northern Sanpete County, most limestone beds contain few macrofossils. A few thin beds of medium-gray or brown biomicrite do contain macrofossils, including gastropods and charophytes (as near Sterling—Fig. 1: Subarea 8A). La Rocque (1956) reported a few clams and snails from the Crazy Hollow Formation; however, his samples were collected and brought to him by student geologists, so the localities of his fossiliferous Crazy Hollow samples cannot now be known. La Rocque did show that the fauna is the same as that of the Green River Formation, so that no age difference can be presumed from the fossils. Although sparse vertebrate remains are known from the upper Green River Formation (Nelson et al., 1980), none have been observed or reported from the Crazy Hollow Formation.

Thin and medium limestone beds—brown or light gray—in northern Sanpete County are fossiliferous at many outcrops (Fograsher, 1956). They contain principally gastropods and bivalves, but also ostracodes, "plant remains" [probably leaves], and rare "fish remains." Jensen (1988) reported the same suite of biota in the Fairview quadrangle from his upper member of the Green River Formation, which includes what is here called Crazy Hollow beds. Even so, limestone is no more abundant, relatively, there than elsewhere in the region.

RELATIONS OF THE CRAZY HOLLOW TO OTHER FORMATIONS

Spieker (1949) said that the Crazy Hollow Formation lies disconformably on the limestones of the upper member of the Green River Formation. He also believed that overlying bedrock—the so-called Gray Gulch mixed sedimentary and pyroclastic rocks in the Salina-Gooseberry Creek area (Fig. 1: Area 1)—was disconformable on the Crazy Hollow. At the time he knew of only that one superjacent unit. Fograsher (1956) found that the volcanic deposits of the Moroni Formation lie disconformably on the Crazy Hollow Formation on the southeast flank of the Cedar Hills, in the far north of Sanpete County (Area 10). Work by other Ohio State University students found additional outcrops of the Crazy Hollow, mostly in Sanpete and Sevier Valleys, and they all endorsed Spieker's view that the formation is disconformable on the Green River Formation. The beds that Spieker called Gray Gulch in 1949 have been renamed [formation of Aurora (Willis, 1987, 1988)], and the nomenclature of the units lying on the Crazy Hollow along the west side of Sevier Valley (Areas 2 and 3) has also been revised. We will deal first with the base of the Crazy Hollow.

SUBJACENT FORMATIONS

That the Crazy Hollow lies disconformably on the upper limy member of the Green River Formation is now established for many outcrops in Sanpete and Sevier Counties. The contact is not exposed in northern Sanpete County, but Fograsher (1956) interpreted clasts of cherty limestone like that in the Green River Formation as evidence of at least local erosion and disconformity.

Norton (1986) pointed out that there are many examples regionally of the close relationship between the two formations. For example, Willis (1986) found interfingering of the Green River and Crazy Hollow Formations locally in the Salina quadrangle. Farther west, on the west flanks of the Gunnison Plateau, the prevailing condition is structural accordance of the two units, but scour and small-scale intertonguing of the two formations are also present (Fig. 3). Local sharp contacts that suggest scour are common (Weiss, 1982; Mattox and Weiss, 1989; Mattox, 1992).

It is clear that the lithofacies of the upper, limestone member of the Green River Formation changes westward across the Gunnison Plateau, toward the margin of Lake Uinta and the more clastic lake-marginal sediments (Mattox, 1987; Weiss et al., 2000). These western lithofacies of the Green River are more clastic than those typical of the formation in Sanpete Valley, which lies approximately where the deepest part of the southwest arm of Lake Uinta was. The westward changes in the upper Green River makes it more like the Crazy Hollow beds, which led to the similarity between the two at many localities (Weiss, 1982; Norton, 1986; Weiss et al., 2001).

At a few localities the Crazy Hollow Formation lies on or against rock units older than the Green River Formation, as at Big Hollow, southwest of Richfield (sections 3 and 4, T. 24 S., R. 4 W., in Area 2 of Fig. 1), where it lies on coarse conglomerate of the upper Flagstaff Limestone (Schneider, 1964; Norton, 1986; Steven et al., 1990). The Crazy Hollow is faulted down against the upper member of the Jurassic Arapien Shale 2.6 miles (4 km) north of the village of Sterling (Subarea 8A). Nearby it lies disconformably on exposures of the Green River, but local diapirism of the Jurassic Arapien Shale has distorted the area (Subarea 8A), cut out the Green River beds locally, and raised the Arapien against dipping Crazy Hollow beds (Weiss, 1994). The Crazy Hollow lies unconformably on the Arapien Shale northeast of Salina (Area 1). Local diapirism by the Arapien Shale has disturbed Green River and Crazy Hollow beds severely at Rocky Point, just west of the city of Gunnison (Area 5), but the Arapien is not in contact with either bedrock unit (Mattox, 1992).

SUPERJACENT DEPOSITS

No estimate is possible of the amount of Crazy Hollow rock that may have been stripped from sites along the western and eastern margins of Sanpete and Sevier Valleys during later Tertiary and Quaternary times. The formation—of original or lesser thickness—is buried by Quaternary alluvial and valley-fill deposits at many sites in these same areas. Different bedrock units cover the Crazy Hollow Formation in four different areas. One is of sedimentary rocks with only reworked volcanic fractions, but

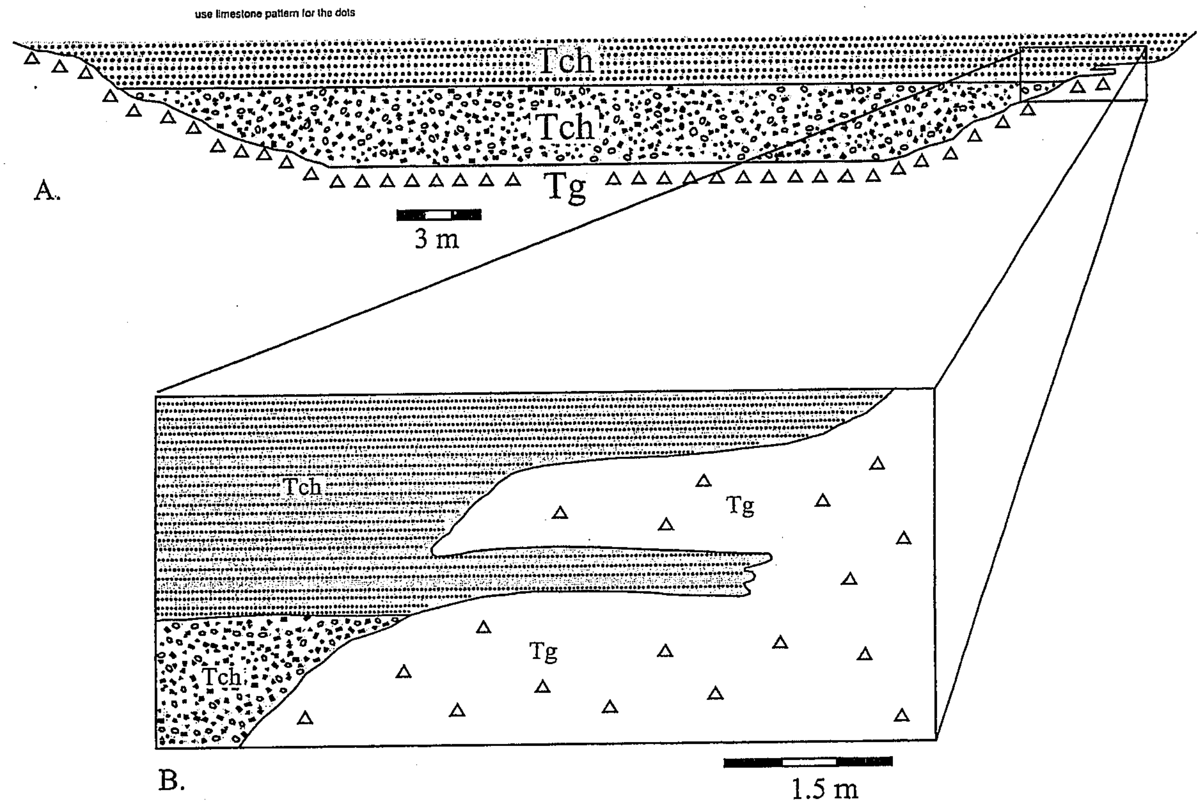


Figure 3. Diagrammatic cross section of the interfingered contact of the Green River and Crazy Hollow Formations in SE1/4SE1/4 of section 5 and NE 1/4NE 1/4 of section 8, T. 19 S., R. 1 E., near the middle of the Gunnison 7.5-minute quadrangle in Area 5 (revised by Mattox from Mattox and Weiss, 1989, and Mattox, 1992, Fig. 2). The beds of the two formations are parallel in that area.

The depression in the Green River limy mud may have been bottom topography or a shallow channel, similar to that described from Area 9. The depression was filled first by sand mixed with black chert pebbles, and then by salt-and-pepper sand that intertongued with the coincidentally deposited limy mud. Both stratigraphic units have hardened subsequently, and cherty blebs and nodules have formed in the Green River limestone.

the other three are of mixed sedimentary and pyroclastic deposits.

In the Aurora-Redmond Canyon area (Fig. 1: northern part of Area 3) the Crazy Hollow is overlain unconformably by the Sevier River Formation of mixed clastics, some limestone and reworked volcanic clasts (Willis, 1987, 1988, 1991). The Sevier River Formation in this area was formerly called the Bald Knoll Formation of presumed early Tertiary age (Gilliland, 1951). This was the type locality of the Bald Knoll, but it was demonstrated to be the Sevier River Formation of Miocene-Pliocene age (Willis, 1986, 1988). Willis (1988) showed further that the rocks that had been called Bald Knoll *elsewhere* in the Sevier Valley-Salina Canyon area were *not* equivalent to the type Bald Knoll; he named *them* "the formation of Aurora" (Willis 1987, 1988).

The superjacent beds in the Salina area (Area 1) were called Gray Gulch by Spieker (1949), but that provisional name never achieved formal usage. Gilliland (1949) had proposed the name Bald Knoll for a sequence of very light-colored claystones, siltstones, sandstones, tuffs and some limestones that lies on the Crazy Hollow 5 miles (8 km) due west of Redmond, Sevier County (Gilliland, 1951). The name Bald Knoll then had priority as a formal term, so McGookey (1960) carried it eastward across Sevier Valley (from Area 3 to Area 1) and applied it to the mixed sedimentary and bentonitic unit lying on the Crazy Hollow near and southeast of Salina. Williams and Hackman (1971) followed McGookey's usage. But these beds are *not* correlative with Gilliland's type Bald Knoll, now known to be Miocene-Pliocene in age; they are late Eocene in age (Willis, 1986, 1987, 1988). Willis substituted the formation of Aurora for them, suppressed the name Bald Knoll, and substituted Sevier River Formation for the type Bald Knoll of Gilliland (1949, 1951). Upper Eocene beds formerly mapped as Bald Knoll (Lautenschlager, 1952; McGookey, 1960; Williams and Hackman, 1971) were renamed formation of Aurora (Willis, 1987). Steven et al., (1990) also used Bald Knoll in the old sense; doubtless the interval between their work and its publication was long. The upper Eocene beds consist of mudstone, bentonitic shale, sandstone and limestone, and they—the formation of Aurora—overlie the Crazy Hollow disconformably not only in its type area (Area 1), but also in Area 2 and the southern part of Area 3 on the west side of Sevier Valley (Norton, 1986; Willis, 1986, 1988, 1991).

In far northern Sanpete County, the Crazy Hollow Formation is overlain disconformably by the upper Eocene to middle Oligocene Moroni Formation, a unit of tuff, volcanic breccia and conglomerate, and waterlain sandstone (Schoff, 1951; Witkind and Marvin, 1989). The eroded edge of the Moroni Formation lies disconformably on the Crazy Hollow; at some sections only thin sheets of disaggregated Moroni cobbles crop out over the Crazy Hollow top (Fograsher, 1956). Schoff (1951) mapped the Crazy Hollow beds as part of the Green River Formation.[2] The Green River-Crazy Hollow contact is not exposed in this area, but can be closely estimated (Fograsher, 1956). Jensen (1988) denied that the Crazy Hollow exists in this area, but we believe that he was mistaken, as explained below.

THICKNESS

The thickest sections of the Crazy Hollow lie on the Green River in Area 4, on the dip slopes of the hogbacks along the east edge of Sevier Valley, between Salina and Mayfield, where Gilliland (1951) found 1,000 feet (305 m) of Crazy Hollow. Norton (1986) measured 1,307 feet (398.4 m) of the unit in this region, in sections 33 and 34 of T. 20 S., R. 1 E. Spieker (1949) cited "about 600 feet [183 m]" for the thickness of the Crazy Hollow in the type area, about 8 miles (13 km) farther south. McGookey (1960) measured a complete section not far south of the type locality as 997 feet (304 m), but Willis (1986) found no unfaulted sections in the area, and estimated the true thickness to be between 600 and 800 feet (183–244 m). Fograsher (1956) estimated that the unit is "at least 210 feet [64 m] thick" in northern Sanpete County, at the edge of the Cedar Hills.

Regionally, then, the Crazy Hollow can be said to range from 0 to 1,307 feet (0–398 m) in thickness. At many outcrops it is much closer to the minimum than the maximum thickness, being only a few scores of feet (12–50 m) thick.

[2]Although published in 1951, two years after the Crazy Hollow Formation was named, Schoff's map was completed in 1936.

AGE OF THE CRAZY HOLLOW FORMATION

Spieker suggested that the age of the Crazy Hollow "is probably Eocene, and may be late Eocene," based solely on physical criteria. Gilliland (1951) considered the issue and concluded that it is "likely late Eocene." The limited fossil suite studied by La Rocque (1956) shows that the Crazy Hollow fauna is about the same as that of the Green River Formation, but he settled on "Eocene?" for its age. Fograsher (1956) apparently took no advantage of the fossils he found, and did not hazard a suggestion of the age of the Crazy Hollow. Weiss (1982) considered evidence of the age of the Green River adduced by both vertebrate paleontologists and geochronologists, and concluded that the Crazy Hollow was Oligocene in age. Norton (1986) reviewed several works of the early 1980s and said that the Crazy Hollow is late Eocene in age. Willis (1986) showed that the Green River and Crazy Hollow Formations interfinger locally in the Salina area, as Weiss (1982) and Mattox and Weiss (1989) had shown elsewhere. Sheliga (1980) obtained ages of about 43 million years for the lower member of the Green River near Ephraim, by $^{40}Ar/^{39}Ar$ analysis. Bryant and others (1989) obtained ages of 45 to 42 million years by fission-track dating of tuffs in the Green River at the north end of the Wasatch Plateau. Based partly on such reports, workers in recent years have considered the Crazy Hollow to be late Eocene in age and only slightly younger than the top of the Green River. According to Cande and Kent (1992), however, such radiometric ages as are mentioned above are in the middle of the middle Eocene (upper Lutetian). Thus a middle Eocene age is adopted for this report.

LITHOFACIES BY AREAS

The principal rock types have been described and the high variability of lithofacies across central Utah has been emphasized. In this section the main characteristics of the Crazy Hollow Formation in each of several areas and subareas (Fig. 1) will be summarized,

1–THE SALINA-GOOSEBERRY CREEK AREA

This includes the type area (the star in Fig. 1) of the Crazy Hollow Formation and exposures southeast and northeast of the city of Salina, all in the Salina quadrangle (Spieker, 1949; Willis, 1986), and the southeastward extension of the formation up the north slope of the Fish Lake Plateau into the Rex Reservoir quadrangle and the Gooseberry country (McGookey, 1960; Williams and Hackman, 1971). A section measured by McGookey (1960) about 1.5 miles (2.4 km) up Crazy Hollow from Salina Canyon totaled 997 feet (304 m) and consisted of salt-and-pepper sandstone (6.5 percent), sandstone (15 percent), sandstone with lenses of salt-and-pepper sand (29.2 percent) and mudstone (49.3 percent). Norton (1986) measured a section about one mile (1.6 km) upstream from McGookey's; it totaled 948 feet (289 m) and included salt-and-pepper sandstone (1.4 percent), sandstone (13.6 percent), siltstone (8 percent) and mudstone (77.1 percent). The mudstones are highly varied in color, including red to orange, reddish brown, purplish red, yellow to orange, pinkish gray and green (McGookey, 1960; Norton, 1986).

Although the two sections are closely comparable in thickness, both may be somewhat too thick, for Willis (1986) found no unfaulted sections of the Crazy Hollow in that vicinity. Older published works assert a disconformity between the Green River and the Crazy Hollow, but more recent studies consider the contact generally gradational (Willis, 1986). McGookey (1960) named the superjacent beds Bald Knoll—now the formation of Aurora (Willis 1986, 1988).

2–THE RICHFIELD AREA

The southwestern-most extent of existing Crazy Hollow beds is just west and southwest of the city of Richfield, Sevier County (Steven et al., 1990). The exposures are on the southeast flank of the dip slope of the Pavant Range, in an area close to the southern limit of Lake Uinta. The Green River Formation pinches out southward in the vicinity (Lautenschlager, 1952), so that the Crazy Hollow lies on the Green River toward the north, but on the Flagstaff Limestone (the Colton Formation is also absent there) south of the pinchout (Steven et al., 1990). Schneider (1964) denied that the Green River pinches out, but his map is ambiguous on the point and he gives no evidence for his prediction that the Green River will be found in the adjacent Sevier quadrangle, next to the south. Steven et al. (1990) adopted Lautenschlager's (1952) view of the matter. Schneider (1964) and Steven et al. (1990) mapped the beds lying on the Crazy Hollow as the Bald Knoll Formation, following Gilliland (1951), but Norton (1986), following the work-in-progress of Willis (1986, 1988), used formation of Aurora. The Crazy Hollow beds continue northeast from this area into the southwest corner of the Aurora quadrangle—Area 3—(Willis, 1988).

Schneider (1964) reported that the Crazy Hollow Formation is 260 feet (79 m) thick "just west of Richfield," and Lautenschlager (1952) gave 366 feet (112 m) in the same general area. Norton (1986) measured a section 1,030 feet (314 m) thick in Big Hollow, in the southwesternmost outcrop of the Crazy Hollow, about 8 miles (10.3 km) west-southwest of the center of Richfield. The Crazy Hollow there rests on the quartzite and black limestone cobbles of the conglomerate that lies near the top of the Flagstaff Limestone (Schneider, 1964). She reported the bulk composition of the unit as salt-and-pepper sandstone (0.8 percent), sandstone (13.1 percent), quartzite and black chert conglomerate (1.9 percent), mudstone (14.3 percent), sandy limestone (2.2 percent) and a covered interval of 60.7 percent with pebbles and chunks of limestone in the soil (Norton, 1986). The sandstone beds are reddish gray to yellow, orange and light gray. The mudstones are red and brown, and the sandy limestone beds pale red (Norton, 1986).

3–THE AURORA AREA

This area contains numerous exposures in the Aurora quadrangle (Willis, 1988) and one at the extreme southern edge of the Redmond Canyon quadrangle (Willis, 1991). The Crazy Hollow Formation here continues the trend of the Richfield area, northeastward along the lower slopes of the Pavant Range. It is sandwiched between the Green River Formation and formation of Aurora, as it was in the northern part of the Richfield area. Beds on those slopes are cut by numerous northwest-trending faults that chop them into many blocky outcrops, except close to the village of Aurora. Three tiny outcrops of Crazy Hollow beds are exposed across Sevier Valley in the southeast quadrant of the Aurora quadrangle (Willis, 1988), in the SE1/4 section 16 and the NW1/4 section 21, T. 22 S., R. 1 W. There the Crazy Hollow lies on the Green River beds but has no bedrock cover.

The beds succeeding the Crazy Hollow Formation are different in the far north of the Aurora quadrangle. The few Crazy Hollow outcrops there, both south and north of Denmark Wash, are small fault slices, plus one such slice just across the northern quadrangle boundary, in the Redmond Canyon quadrangle (Willis, 1988, 1991). Only some of those outcrops show Green River beds below the Crazy Hollow, but the succeeding beds are not the late Eocene formation of Aurora. The covering formation, disconformable on the Crazy Hollow, is the Sevier River Formation of Miocene-Pliocene age—previously called the Bald Knoll Formation and formerly thought to be late Eocene in age (Willis, 1988, 1991).

Despite the separation of outcrops to both sides of Sevier Valley, and the significant change in the rock overlying the Crazy Hollow in the northwest, the formation seems to have about the same lithology in all the areas of exposure. Hills of dark mottled orange, red and yellow sandstone and mudstone are punctuated by discontinuous ledges of resistant sandstone (Willis, 1988). Norton (1986) measured a section, about one mile (1.6 km) northwest of Aurora, of 979 feet (298 m) of Crazy Hollow beds between Green River limestone and Aurora mudstone containing volcanic glass. She found that most of the formation (71 percent) is sandstone, followed by mudstone (24.6 percent), muddy sandstone (3.5 percent), one bed of unfossiliferous sandy limestone (0.8 percent) and one bed of pebbly sandstone (0.07 percent).

Although about half of the sandstone beds are pale orange, yellowish orange, or pinkish gray, a rainbow of other colors is present: dark yellowish orange, very light gray, moderate orange pink and grayish orange to reddish brown (Norton, 1986). The sandstone beds are mostly fine or medium grained quartz. Dark-gray or black chert sand grains are not common; no salt-and-pepper sandstone is exposed at this section. Black chert pebbles are conspicuous in the one thin "pebbly sandstone" bed, and two beds of very pale orange sandstone (8 percent of the sandstone total) contain lenses of black chert pebbles (Norton, 1986). A few sandstone beds have the form of a channel fill, and several show both tabular- and trough-cross-bedding.

The colors of mudstone are almost as varied as those of the sandstone beds, but they run to darker shades: reddish orange and reddish brown, orange, yellowish brown and pale red (Norton, 1986). Many are somewhat shaly, and one reddish-brown bed contains numerous crystals of gypsum.

4–THE REDMOND EAST AREA

This area embraces a variety of outcrops low on the outer flank of the Wasatch monocline, all in the eastern part of the Redmond quadrangle (Witkind, 1981). The quadrangle is the southeast quarter of the Gunnison 15-minute quadrangle mapped much earlier by Gilliland (1951); Witkind's map is largely a compilation from Gilliland's work. This area contains the thickest accumulations of Crazy Hollow beds, with no overlying bedrock, although Witkind showed the Bald Knoll [formation of Aurora] over it in the subsurface of his cross section. Some of the outcrop patches that are very wide east-west suggest great thickness, but they are wide because of their low dip.

Norton (1986) measured a stratigraphic section in sections 33 and 34 of T. 20 S., R. 1 E., near the south end of this outcrop belt. The array of rock types there includes salt-and-pepper sandstone and pebbly sandstone (4.2 percent), sandstone (6.6 percent), and limy sandstone (3.4 percent), all in the lower part of the section; mudstone, some beds with lenses of salt-and-pepper sandstone (26.4 percent); limy mudstone (1.6 percent); silty mudstone (8.7 percent); sandy limestone (4.7 percent); muddy limestone (3.3 percent); limestone (11.9 percent) and a covered interval with red and gray mudstone soil (29.4 percent). The sandstone and limy sandstone are light gray, the mudstones are mostly reddish brown or reddish orange, and the limestones are pale red and weather to pale orange or yellowish gray. Her section is 1,307 feet (398 m) thick.

Gilliland (1951) reported the base of the Crazy Hollow as disconformable in the few places where it is exposed in this area. Norton found the formations accordant at the base of her measured section, but the basal pebbly sandstone over Green River limestone suggests a disconformity. Walking out beds to sites somewhat north of her section shows basal Crazy Hollow limestone lying on upper Green River limestone. Once again, the contact appears to be conformable in some places but disconformable in others.

5–THE GUNNISON AREA

Outcrops of the Crazy Hollow Formation are numerous at the southern end of the Gunnison Plateau, just north of where it plunges beneath the sediments of Sevier Valley. This area lies in the northwest quarter of the Gunnison 15-minute quadrangle, mapped by Gilliland (1951), and in the Gunnison 7.5-minute quadrangle, mapped by Mattox (1992). Their results are quite comparable, although Mattox was able to show more detail; Gilliland had the disadvantage of having no topographic maps. Most outcrop patches are all of rusty-weathering salt-and-pepper sandstone, pebbly sandstone and conglomerate with pebbles mostly of black chert. The Crazy Hollow lies on the Green River Formation in this area, and has no overlying bedrock cover. The thickest exposure north of Highway 28 is 65 feet (20 m), at the middle of the 7.5-minute quadrangle. The thickest exposure in the area, estimated by Mattox (1992) to be about 300 feet thick (91 m), is the badly faulted cap of Rocky Point, in the southwest corner of the 7.5-minute quadrangle, just west of the city of Gunnison.

Pale-orange and very light gray micritic limestone beds, each less than 10 feet (< 3 m) thick are rare in the whole area (Mattox, 1992). On the gentle slopes northeast and east of the city of Gunnison the beds are mostly light-gray and reddish mudstones. Gilliland (1951) reported a few unidentifiable bone fragments from the upper beds on Rocky Point. Platy fragments of silicified Green River limestone are present at the base of the Crazy Hollow Formation locally. Even so, the two formations are intimately related and of about the same age (Fig. 3; Mattox and Weiss, 1989; Mattox, 1992).

6–THE MAYFIELD AREA

This is a region of broad dip slopes of cuestas of Green River Formation low on the flanks of the Wasatch monocline. Small patches of the Crazy Hollow Formation lie scattered over the Green River slopes, trapped in many cases on the downthrown (east) side of one of the antithetic faults that cut the monocline. Most of the outcrops are in the south half of the Sterling quadrangle (Weiss, 1994), but a few lie on a similar great Green River cuesta south of Mayfield, in T. 20 N., R. 2 E. of the Mayfield quadrangle (Johnson, 1949). The prevalent rock type is salt-and-pepper sandstone with numerous pebbles and small cobbles of black chert. Light-gray, pink and red sandy mudstone are interbedded with the grayish sandstone and conglomerate (Weiss, 1994). The Crazy Hollow beds are not covered, even by Quaternary deposits; the thickest outcrops in the area are 90 feet (27 m) thick, probably a mere fraction of the original thickness.

The intimate relation of the Green River and Crazy Hollow Formations is well shown in this area, for thin lenses of red mudstone and pebbly salt-and-pepper sandstone are present high in the beds of the upper, limestone member of the Green River Formation. Further, the small knoll of Crazy Hollow rock in the middle of the SE1/4 of section 22, T. 19 S., R. 2 E. is capped by 15 feet (5 m) of yellowish-brown silty limestone typical of the upper member of the Green River, although that cap is not mapped as Green River (Weiss, 1994).

7–THE TOP OF THE GUNNISON PLATEAU

Three different types of deposits of the Crazy Hollow Formation lie in three different subareas on the top of the south half of the Gunnison Plateau (Fig. 1). The three subareas are: A) the southwest quadrant of the Manti quadrangle (Weiss and Sprinkel, 2000); B) the east-central part of the Hells Kitchen Canyon SE quadrangle (Mattox, 1987); C) the southwest quadrant of the Chriss Canyon quadrangle (Weiss et al., 2001). Subareas A and B are on the crest of the Gunnison Plateau, in the Divide graben (Mattox, 1987) that dropped the upper, limestone member of the Green River Formation to form a resistant cap at the top of the plateau. Subarea C is at the upper bend of the West Gunnison monocline.

A–Manti Quadrangle: Remnants of the Crazy Hollow beds lie atop the upper, limestone member of the Green River Formation on some of the elongate fault blocks within the Divide graben (Mattox, 1987) where it swings southeastward out of the Hells Kitchen Canyon SE quadrangle into the southwest quadrant of the Manti quadrangle (Weiss and Sprinkel, 2000). The Crazy Hollow rock is all "clean" quartzose sandstone, locally cross-bedded, calcareous and weakly cemented. It is fine- to medium-grained and contains only a small population of the black chert grains that make salt-and-pepper sandstone elsewhere. The maximum thickness of Crazy Hollow in this subarea is 70 feet (21 m) (Weiss and Sprinkel, 2000). The bedding in the Green River and the Crazy Hollow is accordant, but the contact is not well exposed, so conformity or lack of it cannot be determined.

B–Hells Kitchen Canyon SE Quadrangle: Five very small patches of fine-grained red sandstone and fine- to medium-grained pebbly salt-and-pepper sandstone and conglomerate lie on top of the limestone member of the Green River Formation in the east-central part of this quadrangle (Mattox, 1987). Pebbles of black chert, white quartz arenite, and gray carbonates are present, and both grain- and matrix-supported conglomerate beds are exposed (Fig. 2). Most beds are but weakly cemented by calcite. The thickest outcrop is about 40 feet (12 m) thick (Mattox, 1987).

Thin-section petrography (T. F. Lawton, written communication, 2000) shows the framework grains are about 50 percent finely crystalline chert, much of it fossiliferous, and microcrystalline collophane. Some grains of collophane contain spherical quartz-filled microfossils that may be radiolarians derived from phosphatic Permian(?) rocks. Other mineral constituents are monocrystalline quartz (25–30 percent), potassium feldspar with both microcline and perthitic textures (5 percent), and sparry calcite (15 percent). The latter may conceal original detrital carbonate grains.

Although Mattox did not map the two members of the Green River separately, the upper, limestone member overlies the lower, shale member here as it does elsewhere in the region. The contact of the Crazy Hollow with the Green River limestone member is not well exposed, but the coarseness of the former suggests a basal conglomerate over a disconformity at these sites. The rock in each of these small patches is weakly coherent (Fig. 2), so that the weathered grains wash down the slopes from the plateau crest. They accumulate on the slumped Colton beds below the down-faulted Green River beds in the Divide graben. On the east side of the crest, particularly, black pebbles are common on soils on those slumped Colton beds in the western part of the Manti quadrangle (Weiss and Sprinkel, 2000). Their appearance there is always startling, for black chert is not present in undisturbed Colton beds.

C–Chriss Canyon Quadrangle: The West Gunnison monocline is conspicuous in the southwest quadrant of the Chriss Canyon quadrangle, and it drops the Colton, Flagstaff and Green River Formations from the top of the Gunnison Plateau down to Flat Canyon and toward Juab Valley. The monocline is cut by a number of mostly antithetic faults. In a graben between such faults in the upper bend of the monocline, near the top of the plateau, is a canoe-shaped map exposure less than two miles long (<3.2 km) of Crazy Hollow beds (Weiss et al., 2001). At its south end this body extends only 200 feet (61 m) into the Hells Kitchen Canyon SE quadrangle (Mattox, 1987).

Most of the exposure consists of bedding surfaces of a well-cemented brownish-orange calcareous silty mudstone and conglomeratic sandstone. Numerous pebbles of black chert are scattered through the mudstone, and most of the pebbles in the sandstone are also of black chert. The cross-bedding in a sandstone layer is inclined NNE, which suggests a southwesterly source (T. F. Lawton, written communication, 2000). Lawton also transmitted the report of a thin section from this outcrop: it contains 40 percent monocrystalline quartz, some of it highly spherical, 40 percent detrital calcite grains being replaced by calcite cement, 2–3 percent of chert grains with fossil ghosts, less than one percent of K-spar and 15 percent of calcite cement. Worn overgrowths are common among the quartz grains, and relict fossils show among the grains of detrital calcite.

No stratigraphic contact with the Green River Formation is exposed. The Crazy Hollow beds are faulted down against the Colton Formation on the east and down against the lower, shale member of the Green River Formation on the west. Various Quaternary mass-wasting deposits lie over parts of the Crazy Hollow preserved in the graben. Although no thickness can be measured for this exposure, the Crazy Hollow Formation is estimated to be about 400 feet (122 m) thick in this area.

It is well known that the upper, limestone member of the Green River Formation becomes more highly clastic westward in the Gunnison Plateau, toward what once was the margin of the southwest arm of Lake Uinta. This change from open lacustrine toward lake-marginal lithofacies is well displayed in the Chriss Canyon quadrangle (Zeller, 1949; Millen, 1982; Norton, 1986; Weiss et al., 2001). In fact, the rocks and the colors of the upper member of the Green River Formation show increasing similarity westward to the rocks and colors of the Crazy Hollow Formation. Zeller was the first to consider this facies change, and concluded that the brownish-yellow muddy and somewhat pebbly limestones lying on the Arapien Shale in section 6, T. 16 S., R. 1 E., and in sections 1, 12, and 13, T. 16 S., R. 1 W., belonged in the upper part of the Green River Formation (Zeller, 1949). To distinguish them he named them the "Tawny beds," a term with a checkered history in the subsequent 50 years. Some workers have called the "Tawny beds" the Crazy Hollow Formation (e.g., Norton, 1986), and others have kept them in the upper Green River Formation (e.g., Millen, 1982). The history of the usage and assignment of the "Tawny beds" is given by Weiss et al., (2001) and need not be repeated here.

If the "Tawny beds" are called Crazy Hollow, the "normal," limy, upper member of the Green River Formation would be reduced to a small fraction of its regional thickness, and most of the resulting thicker Crazy Hollow section would become a lithofacies of the upper member of the Green River. The facies change westward in the upper member of the Green River is well exposed, so it seems better to regard the calcareous clastic beds once named "Tawny beds" as the lake-marginal lithofacies of that member of the Green River Formation, following Weiss et al. (2001). The consequence for the Crazy Hollow Formation is that it remains a deposit lying mostly on the Green River, here and in regions more central to the old lake basin than Juab Valley. It may well have once overlain the top of the Green River in Juab Valley, but no evidence of that remains.

8–THE STERLING-MANTI AREA

Two small areas of Crazy Hollow Formation crop out in southern Sanpete Valley: A) between 2 and 3.5 miles (3.2–5.6 km) north of the village of Sterling and B) on Temple Hill in the northeast corner of the city of Manti (Fig. 1). Rocks in the two subareas are quite different, and each subarea exposes special features of stratigraphy and structure.

A–Sterling: A shallow syncline that is broken by several faults strikes north in the middle of the north half of the Sterling quadrangle (Weiss, 1994). Rocks of the Colton, Green River, and Crazy Hollow Formations are folded, but the Crazy Hollow beds are confined to the western limb of the syncline. A variety of rock types is exposed in different parts of the Crazy Hollow outcrop. The east-dipping slope in the NW1/4 section 27 T. 18 S., R. 2 E. is thinly covered with sandy red mudstone and sandstone. In the adjacent SW1/4 of section 22 there is much salt-and-pepper sandstone, with reddish-brown, pale-orange, yellowish-gray and pale-red sandstone and mudstone. A great ledge of pebbly salt-and-pepper sandstone by the creek in the NW1/4SW1/4 of section 22 is 33 to 36 feet (10–11 m) thick. Norton (1986) measured a section across the SW1/4 of section 22 and got a total thickness of 659 feet (201 m). As this does not include the red beds farther south in the syncline, this may be a minimum thickness for the Crazy Hollow Formation in this subarea.

The varicolored mudstone and sandstone beds in her measured section continue on the north side of the abandoned railroad grade, into the NW1/4 of section 22, but are not well exposed there (Norton, 1986). Of special interest, however, are two (locally three) thin beds of dark-brown gray-weathering fossiliferous limestone close to the line between the SW1/4 and NW1/4 of section 22. Each bed is less than one foot (~26 cm) thick, and they are grouped in an interval less than 10 feet (3 m) thick. Whole gastropod shells, species of the genera *Goniobasis* and *Physa,* some spar-filled or with partial geopetal mud fillings, are present. Shells of the bivalve genera *Elliptio* and *Sphaerium* and abundant flakes of broken shell are stacked parallel to bedding. All are aquatic species. Charophytes appear in thin sections of the limestones (Norton, 1986).

B–Temple Hill: A low cuesta of Green River and Crazy Hollow rocks—part of the Wasatch monocline—lies across the border of the Manti and Ephraim quadrangles at the north edge of the city of Manti (Weiss and Sprinkel, 2000). Most of the volume of the hill is of the upper, limestone member of the Green River Formation, on which the Manti

Temple of The Church of Jesus Christ of Latter-day Saints stands. The Temple was built of the limestone from that hill.

Both the Green River and Crazy Hollow beds are repeated in Temple Hill, for the western part of the hill is a northwest- to north-dipping cuesta of upper Green River and Crazy Hollow beds, while the higher and more easterly part of the hill is a shallow syncline of both lower and upper members of the Green River Formation and the repeated Crazy Hollow Formation (Weiss and Sprinkel, 2000). The rocks of the syncline are in "fault contact" with the north- and northwest-dipping beds in the underlying cuesta. But the syncline is believed to be a toreva block (rather than a faulted block) that rode down the dip of the monocline and came to rest on the crest of the cuesta beneath it (Weiss and Sprinkel, 2000).

The most conspicuous elements of the Crazy Hollow beds in Temple Hill are salt-and-pepper sandstone and pebble conglomerate that form cliffs. They are present both in the cuesta and in the overlying synclinal toreva block, but the cliffs are thinner and less resistant in the synclinal block. This accords with the view that those beds came from an original site both farther east of the cuesta and farther from the source of the Crazy Hollow sediments. Yellowish-gray and orange mudstone is also present beneath the gray-weathering cliffs of sandstone and conglomerate. The thickness of the Crazy Hollow in the lower outcrop (the cuesta) is 54 feet (16 m) (C. E. Corbató, personal communication, 2000). Of that, 30 to 34 feet (9–10 m) is a mudstone weathering light orange and overlain by cliffs 20 to 24 feet (6–7 m) thick of salt-and-pepper sandstone and conglomerate.

9–THE EPHRAIM-SPRING CITY AREA

Cuestas of the Green River Formation lie at the toe of the Wasatch monocline at many latitudes, but they are most conspicuous and expose the thickest sequences of beds in a chain of cuestas that reaches from Ephraim to the latitude of Spring City. Their dip slopes lie not far east of U.S. 89 in this belt, which is well displayed on the Chester quadrangle. Just south of the junction of U.S. 89 with Utah 132, a great cuesta lies to the east of 89 and a smaller one to the west of it. That to the east is upper Green River with a thin scab of Crazy Hollow sandstone on its back. That to the west, named Sand Ridge, and lying west of the abandoned railroad grade, is entirely Crazy Hollow sandstone, about 115 feet (35 m) thick. Both of those outcrops are of "clean" sandstone, being mostly of quartz and white chert and weathering to yellow or orange. Sand grains of black chert are conspicuous in fresh rock, but not so abundant as in the salt-and-pepper sands.

On the east side of U.S. 89, just south of that road junction, is a low cut, made in 1957 during a realignment of the highway, in the toe of the Green River limestone cuesta. At the south end of the cut is a lens 0 to 6 feet (0–2 m) thick of yellowish-gray-weathering sandstone with some black chert sand grains. (The south half of the lens has been cut off by the topography.) It is Crazy Hollow rock, but it is enclosed in Green River limestone beds with shale partings. It is part of the succession of beds that built the upper member of the Green River Formation and another evidence of the intimate relationship between the Green River and the Crazy Hollow Formations (Weiss, 1982). The lens may have been a distributary channel on the floor of the lake or swamp in which the Green River limestones were forming—or even a sand bar in Lake Uinta. But the rock type presaged the coming of the Crazy Hollow Formation.

10–THE FAIRVIEW-MOUNT PLEASANT AREA

The Crazy Hollow Formation was identified in this region near the northern edge of Sanpete County and mapped on aerial photos by Fograsher (1956). The beds dip very gently westward here, so that the underlying Green River Formation lies to the east and the Moroni Formation lies to the west of and in patches on the Crazy Hollow beds. The Fairview quadrangle, which contains part of the area mapped by Fograsher, was mapped on a topographic base by Jensen (1988). Jensen's map is much more detailed than Fograsher's, although it has no section lines on it. Jensen, however, believed that the Crazy Hollow is not present in the Fairview quadrangle, but that it pinches out about 2 miles southwest of the city of Fairview, in the Mount Pleasant quadrangle. Consequently, Jensen included those beds mapped by Fograsher as Crazy Hollow in the upper member of his Green River Formation. Jensen was encouraged in this direction by personal communication(s) from I.J. Witkind (Jensen, 1988). Witkind himself also omitted the Crazy Hollow from this region (including the Mount Pleasant quadrangle), despite having made use of Fograsher's work (Witkind and Weiss, 1991). Jensen (1988) also noted that Schoff (1951) did not map the Crazy Hollow Formation, but although it was published in 1951, Schoff's map was made in 1932 and 1936.

Stratigraphy: Fograsher (1956) measured 10 sections of the Crazy Hollow Formation in the Mount Pleasant-Fairview area, between T. 15 S., R. 3 E. and T. 12 S., R. 4 E. Seven of them have the Moroni Formation at the top and two of the seven expose his Zone C (the uppermost) of the Green River Formation close to the base of exposed Crazy Hollow beds. In the five of his sections that lie in or close to the Fairview quadrangle the apparent full thickness of the Crazy Hollow is from 169 to 221 feet (52–67 m) thick. Fograsher (1956) estimated that the formation in the northern part of the area was at least 210 feet (64 m) thick. Jensen said the thickness of his upper member of the

Green River Formation ranges between 1,394 and 1,968 feet (425–600 m) thick within the Fairview quadrangle (Jensen, 1988). Thus, Jensen's concept of the upper member of the Green River Formation includes Fograsher's Crazy Hollow beds and a large thickness of Fograsher's Green River beds.

It is clear from Jensen's language that he had a very limited notion of the composition of the Crazy Hollow Formation; he believed it to consist substantially of sandstone. He misunderstood the original definition of the formation (Spieker, 1949), thinking that Spieker meant it as mainly sandstone. He also took as characteristic of the formation the dominantly sandstone—with minor black chert grains—lithofacies of the Ephraim-Spring City trend, citing Bonar (1948) and Faulk (1948). The beds of the Crazy Hollow that remain in that area are indeed mostly sandstone, but are by no means typical of the whole formation regionally. Jensen apparently had no knowledge of the lateral variability of the unit, and depended on old work (Bonar, 1948) from one particular area to color his view. Not having worked his way into the Fairview area from much farther south, Jensen's view of the Crazy Hollow was too narrow, too simple, and biased as to the composition of the unit. Jensen was also influenced by the fact that Schoff (1951) had mapped only Green River beds in the Fairview area, although Schoff's map was made in 1932 and 1936, long before the Crazy Hollow Formation was defined.

Inspection of the area by the senior author in 1991 convinced him that Fograsher's stratigraphy describes the Green River and Crazy Hollow Formations in this area better than does Jensen's. What remains to be described here is the relationship between the Crazy Hollow of Fograsher (1956) and the upper member of the Green River Formation, into which Jensen (1988) put all the beds that Fograsher had mapped as Crazy Hollow. Jensen was able to publish only one measured section of the Green River; it was measured on the same cliffs on which Fograsher measured his Section No. 1, in the SE1/4 [not the SW1/4 as Jensen stated] of section 14, T. 13 S., R. 4 E., about 1.5 miles (2.5 km) southwest of Milburn. The two sections are closely comparable, but neither displays the entire thickness of the Green River Formation. Fograsher's Green River Zones A (Units 1 and 2) and B (Unit 1) are recognizable in Jensen's descriptions, but Fograsher's Zones B (Unit 2) and C are absent from Jensen's section. Thus, Jensen's published section, being all Green River beds, contains none of the beds that Fograsher included in the Crazy Hollow, and does not help us with the issue of presence or absence of the Crazy Hollow Formation.

The critical defect in Jensen's argument has to do with a thick (about 40 feet [12 m]) sandstone that is conspicuous low in the Crazy Hollow Formation in section 15, T. 14 S., R. 4 E., about 2 miles (3.2 km) southwest of Fairview, in the Mount Pleasant quadrangle. Fograsher called this the "sandstone member" of the Crazy Hollow, noted that it interfingers with shale to the south, continues only a short distance north of section 15, and has at least 25 to 35 feet (7.6–10.7 m) of brown and gray shale and mudstone between it and Zone C of his Green River Formation (Fograsher, 1956). The "sandstone member" occupies less than a square mile, and was not mapped elsewhere by Fograsher; he suggested that it may be a sandbar (Fograsher, 1956). Jensen (1988) took that sandstone, which does not crop out in the Fairview quadrangle, to *be* the Crazy Hollow Formation. The trouble with his conclusion is that an additional thickness of beds (about 100 feet [30 m]) lie *above* that sandstone and beneath the volcanic Moroni Formation. Jensen mapped those 100 feet of beds, the horizon of the sandstone, and a great thickness of beds below that horizon as his upper member of the Green River Formation (Jensen, 1988). This implies that the Crazy Hollow in the Fairview-Mount Pleasant area is a lens with thick tongues of Jensen's upper member of the Green River Formation both below and above it. The reality of small-scale intertonguing of Green River and Crazy Hollow lithofacies close to the formational contact is a major point already set forth in this paper. But no evidence has been offered from anywhere in the region that the two formations intertongue units of the order of a hundred or more feet (30 m) thick. Jensen (1988) is simply wrong about the Crazy Hollow, although his map is graphically superior to Fograsher's. The qualities ascribed to the Crazy Hollow Formation in the Fairview-Mount Pleasant area are here summarized from Fograsher (1956).

Lithology: The percentages of the thicknesses of the several rock types summed from Fograsher's 10 sections are as follows: shale and mudstone (54.3 percent), sandstone (29.1 percent), conglomerate (8.7 percent) and limestone (8 percent). One third of the thickness of all of his sections is covered intervals; it is tempting to presume that they are mostly mudstone, which would make the mudstone percentage of the whole 69.3 percent. But because the exposed thick mudstone units contain a number of thin and medium sandstone and limestone beds, those rocks would not be represented accurately; the above values from exposed beds are the better basis.

Mudrocks: The mudstone and shale beds are colored brown, yellow, green, gray, red or purple; red and purple are in the minority. Many are "blocky," as Fograsher (1956) called them; such are taken to be mudstone rather than true shale. Nearly every mudstone or shale unit is greater than a few feet (1 m) thick, a few are 10 to 20 feet (3–6 m) thick, and the thickest fully exposed is 55 feet (17 m) thick. Fograsher (1956) pointed out that shale and mudstone beds are more abundant (82 percent of the thickness exposed in his measured sections) south of Fairview than in the northern sections (39 percent) near the north edge of the Fairview quadrangle, where conglomerate is a significant fraction of the Crazy Hollow Formation. Though the entire formation is calcareous, Fograsher (1956) reported no fossils in the mudstones and shales.

Sandstone: The sandstone beds are red, gray, buff and tan, and most are medium to coarse grained. Most are medium to thick bedded—3 to 15 feet (1–4.5 m) thick—except for the "sandstone member" of Fograsher (1956). That body has a maximum thickness of 43 feet (13 m) in the cliffs along the San Pitch River just southwest of Fairview. It is light-yellowish-gray brown-weathering medium- and coarse-grained quartz and lithic sandstone moderately well cemented with calcite, and contains traces of biotite and pyroxene. It contains a very few percent of black chert grains as well. The unit is cross-bedded, grades into mudstone southward, and terminates abruptly on the north, outside of the Fairview quadrangle (Fograsher (1956). It is probable that the same sandstone body extends northwest about 3 miles (5 km) to Fograsher's measured section No. 17 (NW1/4 section 8, T. 14 S., R. 4 E.), but that is also outside of the Fairview quadrangle, so that Jensen (1988) was accurate in stating that the "sandstone member" (i.e., the Crazy Hollow Formation to Jensen) did not crop out in the Fairview quadrangle.

Though he makes no mention of salt-and-pepper sandstone, Fograsher (1956) cites one occurrence of black chert pebbles, low in the "sandstone member." They average one inch (2.6 cm) in diameter, and are associated with small slabs of upper Green River cherty limestone. He knew that they resembled similar pebbles from much farther south, but postulated that they had been eroded from one thin (0.1 foot [3 cm]) bed of black chert in the upper member of the Green River a mile or so north of the pebbles. This is hard to credit—to erode chert from high in one formation, round it into pebbles, and deliver them into the lower part of the next younger formation a mile away. Those pebbles are more probably the same black chert brought to other regions of Crazy Hollow outcrop. Why so little black chert was delivered to the Fairview-Mount Pleasant area is not known. It may have been because a high point on the upper plate of the Sevier orogenic belt—the Charleston-Nebo thrust sheet—impeded delivery of pebbles of Paleozoic chert eastward at this latitude.

Conglomerate: The Crazy Hollow Formation contains several beds, 3 to 20 feet (1–6 m) thick, of coarse quartzite conglomerate in the districts 5 to 6 miles (8–9.5 km) north and northwest of Fairview (Fograsher, 1956). The average size of the mainly "buff to gray" clasts is 4 inches (10 cm), and the sandstone matrix is of similar color. No clasts of igneous rock are present, so these conglomerates are unrelated to the Moroni Formation. The conglomerate is 42 percent of the thickness exposed in measured sections in these areas, whereas mudrocks are only 39 percent (Fograsher, 1956). The sandstone that is interbedded with the conglomerate is more varied in color, being red, gray, or tan, and is medium to coarse grained. Jensen (1988) mapped the principal conglomerate ledges as thinning southward from the northwest corner of the Fairview quadrangle, but ignored those in the highlands 7 miles (11 km) due north of Fairview.

These conglomerate beds are a special case for the Crazy Hollow Formation, for its conglomerates elsewhere are all of the black-chert-pebble variety. Just 8 miles (13 km) northwest and 11 miles (18 km) west of this patch of conglomeratic Crazy Hollow, and beyond the volcanics of the Moroni Formation, is Hop Creek Ridge, on the northwest side of the Cedar Hills. On the ridge and to both sides are great thicknesses of Upper Cretaceous conglomerate in the Indianola Group and Price River Formation (Schoff, 1951). Banks (1991) revised the stratigraphy and mapped only units of the Indianola Group there. Regardless of the names, that area is loaded with quartzite cobbles and boulders derived from later Precambrian formations in the Basin and Range province, once the hinterland of the Sevier orogenic belt. Those quartzite clasts in the Crazy Hollow Formation in northern Sanpete Valley are merely reworked from the vicinity of Hop Creek Ridge.

Limestone: Numerous beds of white, light-gray or brownish limestone are present in the Crazy Hollow Formation, and they are more abundant and constitute a greater volume southwest of Fairview than in the north (Fograsher, 1956). Many are platy or thin bedded, and most are fossiliferous—in marked contrast to the Crazy Hollow limestones of southern Sanpete County and points south. Most of these fossils are gastropods and bivalves; ostracodes are common, plant remains uncommon, and fish remains rare (Fograsher, 1956; Jensen, 1988). Most beds of limestone (Fograsher made no attempt to determine the presence of dolomite) are thin, a few are of medium thickness, and one that is 14 feet (4 m) thick lies at the top of the Crazy Hollow, directly under the Moroni Formation, west-southwest of Fairview (Fograsher, 1956).

ENVIRONMENT OF DEPOSITION

Late in the history of the Green River Formation the sediments were mostly thin-bedded limy mud, lenses of oolitic or ostracodal sand, and some stromatolite layers. Thin tuffs, fine ash layers now altered to bentonite, and lenses of quartzose sand are interspersed with the carbonate beds in the highest 10–20 meters of the formation. Locally abundant black chert near the top of the formation presaged the coming of the Crazy Hollow sediments.

The varied mass of different kinds of sedimentary rock in the Crazy Hollow Formation can only be of subaerial and freshwater origin. The variety of colors of the beds results from different states of oxidation—mostly of iron. The different textures reflect mostly the nature of the rocks and weathered products exposed in the source areas on the highlands surrounding the former southwestern arm of Lake Uinta. The bedding of the sandy and pebbly deposits and the lensing shapes of many suggest stream deposition in channels and on floodplains, with various parts of stream systems—such as point bars, riffles, and overbank deposits—imaginable at many sites. The abundant mudstone deposits are the distal parts of alluvial fans and the finer-grained blankets of mud that locally covered the floor of the old lake basin. All of the deposits are limy, doubtless because of the abundance of carbonates in the bedrocks of the source areas. The limestone beds accumulated in ponds and small lakes on the floodplains and the valley floor. The larger sheets of limestone may represent temporary re-expansions of Lake Uinta as it waxed and waned (in the short term) during its last stages. The strange thing about them is the relative paucity of carbonate deposits in Sevier Valley, as compared to Sanpete Valley, especially in its northern part. Perhaps this is true because Lake Uinta retreated northward, and the lacustrine and paludal environments persisted somewhat longer in northern Sanpete County than farther south in Sevier County. Finally, Basin-and-Range extension tectonics have tipped, bent, and raised the remnants of the Crazy Hollow deposits into a variety of present-day topographic sites.

PALEOGEOGRAPHY

LAKE UINTA AND THE GREEN RIVER FORMATION

The paleogeography of Lake Uinta during the late stages of the deposition of the Green River Formation is relevant to the history of the Crazy Hollow Formation. Green River lakes in Colorado, Utah, and Wyoming accumulated great thicknesses of lacustrine, paludal and lake-margin sediments that make up the Green River Formation. The Green River beds in Utah and Colorado were deposited in Lake Uinta, which occupied a large area south of the Uinta Mountains uplift, but also extended west and southwest around the north end of the Wasatch Plateau and into central Utah, about as far as Richfield (Hintze, 1988, Fig. 76). The "footprint" of this southwest arm—Sanpete Bay—of Lake Uinta was a little larger than that of the present extent of the Green River Formation in central Utah. The perimeter of the Green river outcrop in the region is somewhat greater than that of the Crazy Hollow Formation (Fig. 1).

In central Utah the Green River Formation shows lithofacies changes toward the western margin of Sanpete Bay, an increase of clastic grains and decrease of aquatic carbonate beds. Pinch-outs are present locally. These features that suggest nearness to the shore of Sanpete Bay are present in eastern Juab Valley, the Valley Mountains, and the Pavant Range, but are absent from the northwest flank of the Fish Lake Plateau and the west flank of the Wasatch Plateau. Although the outcrop of the Green River Formation lies across central Utah like a fat sausage, from Thistle to Richfield, Sanpete Bay probably had a somewhat different shape and extended somewhat farther to the east—much farther east than the present eastern limit of the Green River outcrop. Although no one knows how much farther east, it seems probable that Sanpete Bay and the main body of Lake Uinta did not join across the entire area of the Wasatch Plateau and the north half of the San Rafael Swell (Hintze, 1988, Fig. 76).

SOURCE AREAS AND MATERIALS

We know that the Sevier orogenic belt lay west of Sanpete Bay. Remnants of that highland are represented today in the Pavant Range, the Valley Mountains, the Canyon Range, the East Tintic Mountains, and part of Long Ridge. Reasonable sources of the distinctive particles in the Crazy Hollow Formation may be located in one or more of those uplands. But nothing of the sort can be said for the east shore of Sanpete Bay. It is reasonable, therefore, to suggest that the bulk of Crazy Hollow sediments came from the west and southwest.

The abundant black chert in the Crazy Hollow Formation can have come from Mississippian or Permian formations, exposures of which still crop out in the highlands west of the area of Sanpete Bay. The black chert also may prove to be phosphatic generally, as suggested by one sample from Subarea 7C. Black chert may have come from cherty members of the Mississippian Deseret Limestone or the Permian Park City Formation. Highly spherical quartz grains probably came from Jurassic eolianites. Mono-crystalline quartz and the sparse grains of other basement-rock minerals may have been reworked from Paleozioc or Mesozoic sandstone units. The same is true of the feldspars, but some may also have been reworked from exposed edges of the Colton Formation, which lies under the Green River Formation. The concept of feldspar grains having come from far to the southeast of the region (Stanley and Collinson, 1979; Dickinson et al., 1986) was used to explain the significant feldspar content of the Colton Formation (Weiss, 1994; Weiss and Sprinkel, 2000; Weiss et al., 2001). This seems unnecessary for the Crazy Hollow Formation, for occasional grains of feldspar from the Sevier orogenic belt and, especially, from exposed edges of the Colton Formation could have provided the small feldspar fractions in the Crazy Hollow Formation.

DRAINING OF SANPETE BAY

Lake Uinta probably disappeared as a consequence of more rapid drainage and a dryer climate. The greater abundance of carbonate beds in the Crazy Hollow Formation in the northern districts argues that water withdrew northward from Sanpete Bay. The local occurrence of carbonate beds in the Crazy Hollow shows that the water did not sweep out of the bay in a single northward flood. The lake floor was uneven, so that ponds and lakes remained locally on the old lake floor—for years in the cases of the thicker and more extensive bodies of carbonate rocks.

As the lake lowered and the margins of its basin were exposed, clastic sediments spilled into the basin and across the newly exposed lake floor. One set of cross-beds in Subarea 7C (Fig. 1) suggests delivery from the southwest. Regrettably, cross-bedding is not common in the Crazy Hollow Formation, and most is poorly developed. The regional differences seen in the ten different areas of outcrop described earlier arose from differences in the regolith and bedrock upstream from a variety of delivery points.

T. F. Lawton writes (personal communication, 2000) ". . . the source for these rocks consisted of nearby Paleozoic and Mesozoic strata and more distant basement rocks lying generally to the south. I envision a post-Sevier thrust belt, but perhaps pre-Basin and Range, world that ramped gradually toward Phoenix, Arizona and San Bernardino, California. There was no Grand Canyon in the way to intercept basement grains coming from the Mogollon Rim of central Arizona, which had not yet collapsed during extension. I would also judge that much of the salt-and-pepper appearance is the consequence of detrital collophane . . . from phosphatic strata."

No quality of the Crazy Hollow Formation suggests the elevation of the region during Crazy Hollow time. The present wide range of elevations of outcrops of the Crazy Hollow is a result of Laramide movements and Basin-and-Range extension. The failure of the system to accumulate the great thicknesses of post-Green River sediment that lie in the Uinta basin argues that the highlands west (and south?) of Sanpete Bay were lower, had a lesser gradient, and trapped less moisture than did the south flank of the Uinta Mountains.

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[3]Corbató and Moore are Profs. Emeritus of The Ohio State University, and Moore was thesis advisor to A. C. Fograsher.

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Maps

Preliminary geologic map of the Cricket Mountains, Millard County, Utah, by L. F. Hintze, 1959, scale 1″ equals 4,000 ft., ozalid print 36″ × 48″.

Preliminary geologic camp of the Burbank Hills and Northern Needle Range, Millard County, Utah, by L. F. Hintze, 1960, scale 1″ equals 4,000 ft., ozalid print.

Geology of the southern Wasatch Mountains and vicinity, by L. F. Hintze (from vol. 9, pt. 1), two colors, 20″ × 32″.

Preliminary geologic map of the Y mountain area, east of Provo, Utah, by L. F. Hintze, 1969, scale 1″ equals 2,000 ft.

Special Publication 1

Hamblin, W. K., and Murphy, R., Grand Canyon perspectives: A guide to the canyon scenery by means of interpretive panoramas.

Special Publication 3

Utah geological highway map, scale 1″ equals 15 miles. Full color with seven stratigraphic sections, seven cross-sections, ERTS photomosaic of Utah and a summary of Utah's geologic history.

Special Publication 5

Geologic map of the Y Mountain area east of Provo, Utah, 1978.

Special Publication 6

Physiographic map of the earth, compiled by W. L. Chesser and W. K. Hamblin, drawn by W. L. Chesser.

Special Publication 7

Hintze, L. F., Geologic history of Utah (new and revised), 1988.