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Publications and Maps of the Geology Department



Cover: Aerial photograph showing exhumed stream paleochannels in the Cedar Mountain Formation near Green River, Utah. Courtesy Daniel R. Harris.

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The Fitchville Formation: A Study of the Biostratigraphy and Depositional Environments in West Central Utah County, Utah*

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ABSTRACT.—The faunas of the Fitchville Formation, and the lithologies enclosing them, are related in two complete stratigraphic sections in the northeastern part of the Allens Ranch Quadrangle in central Utah. The carbonate strata of this formation are interpreted to represent two sequences of varying water depth. The lower, Devonian, sequence contains regressive deposits formed in progressively shallower depths. The existence of an unconformity, separating the two depth sequences, is implied by the absence of several conodont zones including the Late Famennian *Bispathodus costatus* Zone through the Middle Kinderhookian *Siphonodella sandbergi* Zone. The upper, Mississippian, sequence at first contains transgressive deposits formed in a shallow reinvading sea, and then regressive deposits which record the withdrawal of this sea from the land. Oscillations in water depth in the two sequences are thought to be related to tectonic movements associated with the Antler orogeny.

The distribution of megafossils, principally corals and brachiopods, is noted, and local range zones are delineated. These ranges appear to have been controlled by shifting environmental conditions related to water depth.

INTRODUCTION

Acknowledgments

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Previous Work

Strata investigated in this study were originally included in the Gardner Formation of Loughlin (Lindgren and Loughlin 1919). This formation included Lower Mississippian rocks of the Tintic mining district, approximately 18 km southwest of the present study area. The Gardner was divided into a lower and an upper member. The greater part of the lower member was reassigned the name Fitchville and proposed as a new formation by Morris and Lovering (1961). The Fitchville Formation was named from exposures on Fitchville Ridge in the East Tintic Mountains. The remaining part of the lower member of the Gardner Formation and all of the upper member except the uppermost carbonaceous, phosphatic, shaly unit were assigned the new name Gardison Limestone. The Gardison Limestone was named from Gardison Ridge in the East Tintic Mountains. Morris and Lovering (1961) proposed that the uppermost carbonaceous, phosphatic, shaly unit should constitute the base of the Deseret Limestone. This formational name was adopted to replace the name of the Pine Canyon Limestone for strata directly overlying the Gardison Limestone. Units of strata which

had formerly been termed Madison Limestone in the Wasatch Mountains, Oquirrh Mountains, and other mountain ranges in central Utah are now included in the Fitchville Formation and Gardison Limestone.

The marker bed chosen to separate the Fitchville Formation from the Gardison Limestone is a distinctive limestone unit which averages about 0.67 m in thickness and has a contorted laminar structure (figs. 12, 13, 14). It was first described by Crane (1912), who worked out some of the earliest detailed descriptions of sedimentary rocks in the area of the Tintic Mountains. Lovering (1949) termed this distinctive marker the "curly limestone," a name used by later workers. Several authors have made note of this extensive feature which caps the Fitchville Formation. The most definitive study was done by Proctor and Clark (1956).

Rigby (1949, 1952) and Williams (1951) studied the Paleozoic rocks in the immediate area of this study. Clark (1954) made a regional study of all the strata included in the Gardner Formation, which now are included in the Fitchville Formation and the Gardison Limestone.

Megafossils in the Fitchville and Gardison strata are limited mainly to corals and brachiopods in association with crinoidal debris. Davis (1956) did a taxonomic study of corals from both these formations. Zonation using corals was accomplished regionally by Sando and Dutro (1960) and Sando (1960, 1977). A summation of zonation and correlation, using microfossils including conodonts and foraminifera and megafossils such as corals and brachiopods, was derived from Carboniferous rocks in the northern Cordillera, including Utah, by Sando, Mamet, and Dutro (1969). W. J. Sando is currently studying the coral faunas found in the lower Fitchville Formation. J. T. Dutro, Jr., is currently preparing a monograph which includes Fitchville brachiopods.

The occurrence of conodonts in Late Devonian and Early Mississippian strata of central Utah has been increasingly studied in the last two decades. A conodont study of Devonian and Mississippian rocks, including the Fitchville Formation and the Gardison Limestone, was accomplished by Beach (1961). He studied the conodont forms present and related them to conodont zones in Nevada and elsewhere. He recognized that the conodont fauna in the lower Fitchville was Late Devonian (upper Famennian) and so was the first to realize that the Fitchville was not entirely Mississippian in age. Clark and Ethington (1967) worked out a systematic study of conodonts in the Great Basin and developed the first complete conodont zonation of the Upper Devonian in this area. Newman (1980) did a similar study of Lower Mississippian conodonts in western Utah and eastern Nevada. A zonation of the lower and middle parts of the type Fitchville was included in studies by Sandberg and Poole (1977). Other pertinent conodont work involving

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latest Devonian and earliest Mississippian rocks of the region including central Utah is included in Sandberg and Gutschick (1977, 1978). Sandberg (1979) summarized the present state of knowledge concerning Devonian and Lower Mississippian conodont zonation of the Great Basin and Rocky Mountains.

Procedures

An unfaulted, reasonably complete, and well-exposed section was sought for this study, but fossil remains were found to be partially or wholly destroyed by dolomitization or recrystallization in most locations visited which exhibited complete sections. A suitable section was found on Wanlass Hill (figs. 1, 2), located in the northeastern quarter of the Allens Ranch Quadrangle (SE $\frac{1}{4}$, SE $\frac{1}{4}$, section 34, T.8 S, R.2 W). Fossils within part of this section, especially the lower part, had been silicified prior to dolomitization and had thus escaped destruction.

The Wanlass Hill section was measured with a Jacob's staff and a hand level. The section was described, and fossils were collected for identification. There were difficulties in removing most of the fossils due to the massive nature, tenacity, and hardness of the beds, so after the initial collections of fossils were identified, further identifications were made in place. All specimens of the tabulate coral *Syringopora* were too large to be easily removed and were identified and described in place. Many brachiopod identifications were made by J. T. Dutro, Jr., and coral sample identifications by W. J. Sando.

Stratigraphic ranges and relative abundances were noted for all fossils found in the section. Abundances of corals were determined by actual count along a horizontal section of the outcrop 180 m long. These abundances were recorded only for the lower 24.7 m of the section (tables 1 and 2). Preservation from this point through the top of the section was too poor to permit any accurate estimation of abundance.

Rock samples of approximately 1 kg each were taken at intervals of 3 m throughout the section and processed for conodonts. Samples were crushed to about 1 cm by a jaw crusher. Limestone samples were digested in 10 percent acetic acid at room temperature, and dolomite samples were treated with warm 10 percent acetic acid solutions. Insoluble residues obtained were washed through a 150-mesh sieve. Samples were concentrated by heavy liquid separation in tetrabromethane. Many conodont identifications were made by Charles A. Sandberg.

Thin sections were made from all lithologies present in the measured sequence and from any horizon where special characteristics were noted. All thin sections were oriented normal to bedding directions. Twenty-two thin sections were prepared from the strata on Wanlass Hill. Descriptions of the lithologies found in thin section were placed into the carbonate classification of Folk (1959). This classification was modified in one respect. The term *pellet* is used without strict limitations as to size or genesis.

The strata equivalent to the Fitchville Formation are listed as being 330 ft thick in the legend of the Preliminary Map of the Allens Ranch Quadrangle (Proctor and others 1956). Since the section measured at Wanlass Hill for this study was considerably thinner, 68 m (223 ft), a check seemed desirable. Morris and Lovering (1961) note the Fitchville to be essentially the same thickness as reported on the map, 335 ft, on Greeley Hill which is 4.6 km to the northeast of Wanlass Hill in the northeast part of the same quadrangle (figs. 1, 3). This location was visited, and a section of Fitchville was measured in the SE $\frac{1}{4}$ of the NE $\frac{1}{4}$ of section 23, T.8 S, R.2 W. The total thickness

measured was 67 m, only 1 m less than the thickness found on Wanlass Hill. The Greeley Hill section was measured with a Jacob's staff and hand level. The lithologies present were described, and twenty-six thin sections were prepared. Fossils were mostly identified in place with the use of determinations pre-

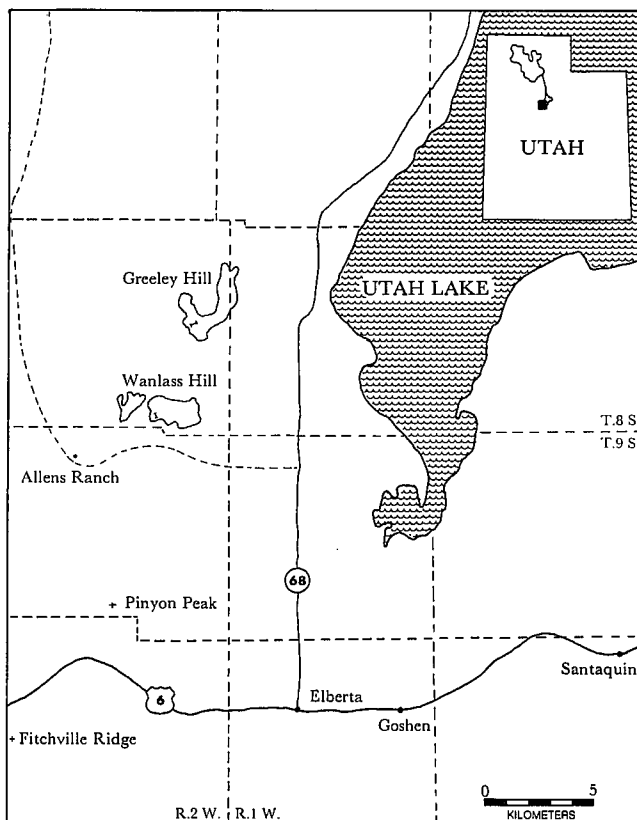


FIGURE 1.— Index map of the study area, after Stokes (1963).

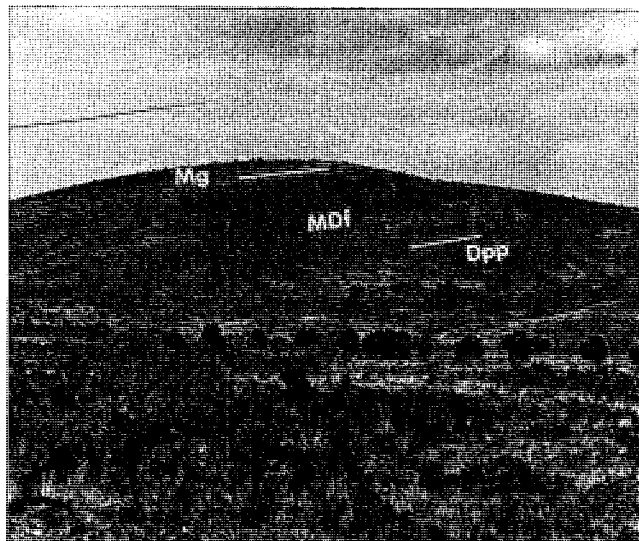


FIGURE 2.— Wanlass Hill as viewed from south. Fitchville Formation (MDf), Gardison Limestone (Mg), and Pinyon Peak Limestone (Dpp) are exposed along flanks of this part of hill.

viously made on Wanlass Hill collections. Fossil ranges were noted.

Possibly the greater thickness reported for the Fitchville on the geologic map of the Allens Ranch Quadrangle may be due to the use of a lower formational boundary than that which was later specified by Morris and Lovering (1961), or perhaps a typographical error was made on the map. The thickness reported by Morris and Lovering (1961) for the Fitchville Formation on Greeley Hill may have been taken from the map, which would have perpetuated the exaggerated figure for the thickness.

PALEOGEOGRAPHY AND PALEOTECTONIC SETTING

The Fitchville Formation and the overlying Gardison Limestone were deposited from Late Devonian (upper Famennian) time through Early Mississippian (Kinderhookian) time. The systemic boundary between the Devonian and the Mississippian is contained within the Fitchville Formation. The depositional history and paleogeography of these strata are best related to the paleotectonic setting of the region at the time in which they were deposited.

The patterns of distribution of Paleozoic rocks in the Great Basin and other areas of the western United States can be best explained by a plate-tectonic model such as that proposed by Burchfiel and Davis (1972). It includes the postulated existence of an offshore island-arc complex along the Pacific margin of the North American continent, along an eastward dipping subduction zone. This island-arc complex was separated from the continental slope and shelf areas by an inner-arc basin. In viewing this model from west to east the following would have existed: (1) An island-arc followed by a marginal, inner-arc ocean basin in what is now northern California, western Nevada, western Idaho, Oregon, and Washington; (2) a broad conti-



FIGURE 3.—Greeley Hill as viewed from southwest.

mental shelf in southeastern California, eastern Nevada, western Utah, eastern Idaho, and western Montana; and (3) a cratonic platform in Arizona, eastern Utah, Wyoming, and central and eastern Montana (Poole and others 1977).

In Late Devonian time the Antler orogeny was initiated, possibly as a result of accelerated subduction. Compressive pressures directed eastward by the underthrusting oceanic plate resulted in the partial closing of the inner-arc basin (Burchfiel and Davis 1972). Devonian and older rocks of this inner-arc basin underwent considerable deformation along the continental margin and were subsequently overthrust to the east, over what was formerly the continental shelf, as the Roberts Mountains allochthon. Uppermost Devonian rocks are discontinuous and thin compared to lower Devonian strata. Seas periodically advanced and retreated over the cratonic platform during early Famennian time through the close of the Devonian, most likely in response to pulses of the Antler orogeny to the west (Poole and others 1977). The upper Famennian part of the Fitchville Formation shows a shallowing upward, regressive sequence of sediments in the two sections examined in this study. These sediments are representative of a final retreat of the seas in latest Devonian time.

Present distribution of uppermost Devonian rocks in central Utah suggests that they were deposited in seaways that were relatively narrow and more restricted than earlier Devonian seas had been. The present eastward extent of these rocks on the cratonic platform is further limited because of very early Mississippian erosion related to Antler orogenic movements. The upper part of the Pinyon Peak Limestone and the lower part of the Fitchville Formation were deposited in seas occupying an elongate basin which trended northeast across Utah. Deposition of these strata took place at the cratonic margin during late Famennian time (Poole and others 1977).

The strata this study is concerned with are almost entirely carbonates, either bioclastic limestones or replacement dolomites, with some thin clastic layers of sandstone or sand-streaked carbonate. The base of the Fitchville is defined by such a clastic layer (fig. 4). This contact was selected by Morris and Lovering (1961) for its convenience in mapping, for the upper limestones of the Pinyon Peak are almost indistinguishable from the lower limestones of the Fitchville Formation. Later conodont studies have indeed shown that the uppermost Pinyon Peak is depositionally continuous with the lower beds of the Fitchville as both contain the same conodont fauna. This is true not only at the type section on Fitchville Ridge but also in

TABLE 1
ABUNDANCES OF SYRINGOPORA CORALS IN A HORIZONTAL SECTION
OF OUTCROP, 180 M IN LENGTH, ON WANLASS HILL

Level (In Meters)	<i>Syringopora arculeata</i>	<i>Syringopora surcularia</i>	<i>Syringopora bisingeri</i>
0-2	6	3	0
2-4	2	7	0
4-6	4	24	2
6-8	8	30	5
8-10	7	22	3
10-12	1	12	7
12-14	11	34	51
14-16	3	5	15
16-18	14	20	15
18-20	5	13	15
20-22	3	22	20
22-24.7	3	10	10

TABLE 2
ABUNDANCES OF SOLITARY RUGOSE CORALS IN A HORIZONTAL SECTION OF
OUTCROP, 180 M IN LENGTH, ON WANLASS HILL

LEVEL (In Meters)	Caninoid corals	Clisiophyllid corals	Neo-zaphrentoid corals
0-3	28	0	0
3-6	32	0	0
6-9	150	47	8
9-12	105	25	5
12-14	40	22	6
14-18	67	65	10
18-21	25	80	4
21-24.7	760	360	80

other sections throughout the East Tintic Mountains (Sandberg and Poole 1977).

It is conceivable that the terrigenous clastics may have been derived from the cratonic platform to the east, but a more likely source was the area of the Stansbury Mountains in northwestern Utah. Here a localized uplift occurred in Late Devonian time which exposed Cambrian carbonate and quartzite rocks lying beneath Devonian strata (Rigby 1958). This uplift resulted in a north-south-trending anticline which became the source of coarse clastics now included in the Stansbury Formation (Stokes and Arnold 1958). The coarse clastics of the Stansbury Formation grade into sandstone, quartzite, and interbedded dolomites of the Victoria Formation. These clastics continue upward through time into the Late Devonian strata of the Pinyon Peak Limestone and finally into the Fitchville Formation (Armstrong 1968).

The age, lithology, and distribution of the lower part of the Fitchville suggest that it was once depositionally continuous with the lower Madison Limestone in western Wyoming. The seaway in which these equivalent beds were deposited extended northeastward in approximately the same area as the seas which were the site of the deposition of the upper member of the Pinyon Peak Limestone and its equivalents. It extended from the southwestern corner of Utah through western Wyoming to southern Montana during latest Devonian time. This marine connection may have provided the path for the first transgression of the Madison Sea onto the cratonic platform in Wyoming (Sandberg and Klapper 1967). The lower Madison, in western Wyoming, contains the same conodont fauna (Lower *Bispathodus costatus* Zone) as the lower Fitchville beds in central Utah. Evidence of a seaway connection between the two areas was largely destroyed by erosion occurring just before, or during, Mississippian time (Sandberg and Gutschick 1978).

In Early Mississippian time, according to the plate-tectonic model, the structural setting of the region from west to east was as follows: (1) an inner-arc complex and basin along the Pacific margin, (2) the Antler orogenic highland, (3) a foreland basin, and (4) the cratonic platform. What had previously been the continental shelf had by this time been modified into the Antler orogenic highland and foreland basin (Poole and Sandberg 1977). The Antler orogenic highland, which was created by deformation along the Antler orogeny, remained emergent throughout the Mississippian and was a continuing source of clastics to the foreland basin to the east. This foreland basin may have been created by compressive forces which were also responsible for the Roberts Mountains Thrust and partial closing of the inner-arc basin. Compressive stress could have warped the continental crust under the shelf and started the development of this structural trough (Poole and Sandberg 1977).

A widespread Early Mississippian (middle Kinderhookian) transgression occurred following the latest Devonian-earliest Mississippian epeirogeny on the continental shelf and cratonic platform. The first strata of Mississippian age in the area of study are in the Fitchville Formation and contain a fauna of the Lower *Sipbonodella crenulata* Zone, based on conodonts. This zone is indicative of middle Kinderhookian time.

Two depositional complexes have been postulated for the Mississippian by Rose (1976). The lower of the two includes the Madison Limestone and its equivalents. Rose stated that the lower strata of the lower complex, including the Lodgepole Limestone and equivalent strata, are transgressive in nature and also open marine. These rocks are typically dark gray, thin-bed-

ded, cherty, fossiliferous, carbonaceous, silty limestones. He said that, from comparison with modern analogs, these strata were probably deposited in a marine setting where the water was 30–100 m deep (Rose 1976).

Rose included the upper part of the Fitchville Formation and the Gardison Limestone in the lower part of the lower complex. However, the upper part of the Fitchville Formation, at least in the area of the present study, shows a shallowing-upward sequence which ends in the supratidal curly limestone, a stromatolitic unit. This sequence seems to indicate regression rather than transgression. The strata present have largely been dolomitized, which also tends to support the presence of the more restricted conditions often associated with a regressive sequence rather than the more open-marine conditions found in a transgressive sequence. It appears that the first strata to fit the typical pattern of the lower transgressive sequence postulated by Rose (1976) are those of the Gardison Limestone.

The upper part of the first depositional sequence of Rose (1976) is considered regressive and contains evidence of shallower and more restricted conditions. This regressive unit includes the Deseret Limestone.

STRATIGRAPHY

Stratigraphic Units

The stratigraphic sections measured consist mainly of limestone and dolomite units, with siliceous materials present in minor amounts. Clastic quartz grains appear in thin layers within the lower, Devonian, part of the section. These clastics are interspersed within carbonate units as calcareous sandstones. Chert is discontinuously present in the upper, Mississippian, part of the section (fig. 5).

There are four layers in which quartz grains form sandstones. The lowest of these was chosen as the lower boundary of the Fitchville Formation by Morris and Lovering (1961). It is listed as unit 1 on both Wanlass Hill and Greeley Hill. The other three layers are also distinctive and extensive enough to be traceable on both hills. The carbonate material in which they are found is the same above, below, and within the sandstone layers. Because these sands were apparently deposited in

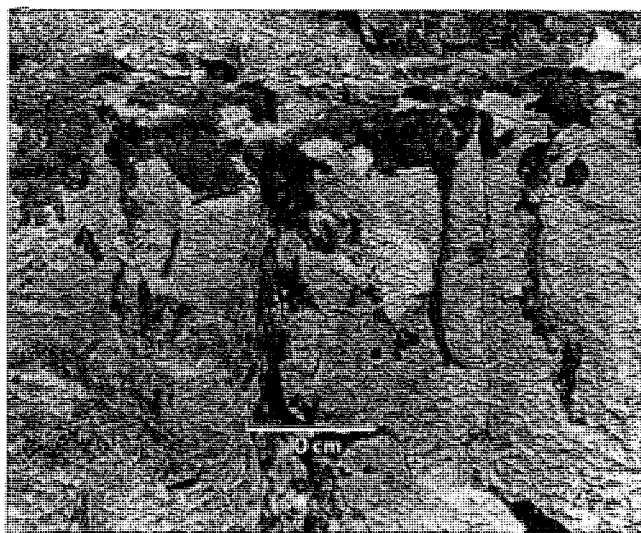


FIGURE 4.— Basal sand-grain layer (unit 1) on Wanlass Hill that forms lower boundary of Fitchville Formation.

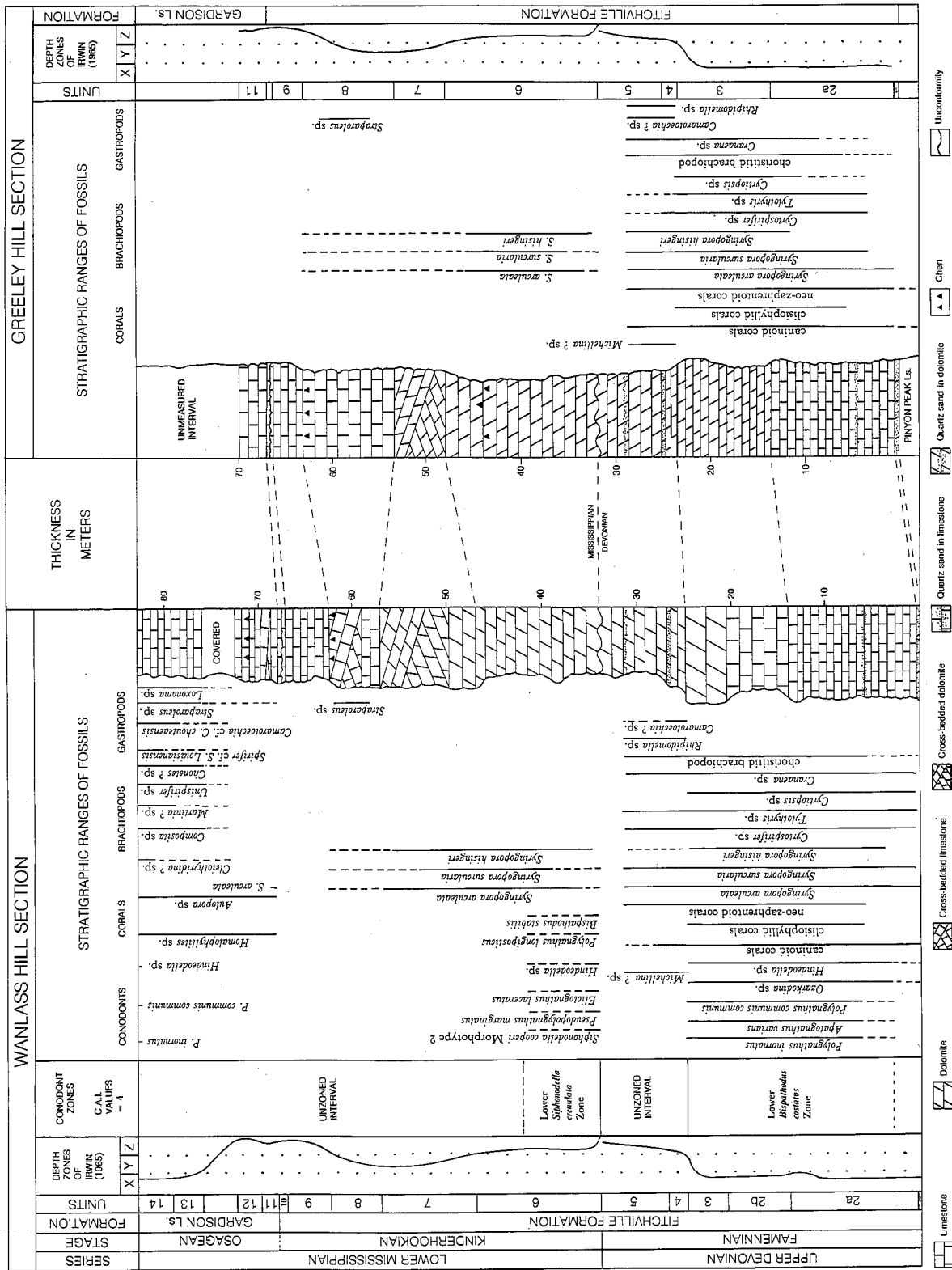


FIGURE 5. Time divisions, conodont zones, stratigraphy, and correlation of stratigraphic sections on Wanlass Hill and Greeley Hill. Proven fossil occurrences are indicated by solid lines; probable fossil occurrences are shown by dashed lines, and unfossiliferous facies are indicated by blank spaces within range zone.

the same environment as the carbonate units in which they are contained, it seems best to include them as subunits of the carbonate units.

In the Devonian part of the section on Wanlass Hill there are two limestone units, unit 2a and unit 2b. On Greeley Hill unit 2b does not appear, for the strata equivalent to it have been dolomitized. These strata are included in the first dolomite unit, unit 3, on Greeley Hill.

Fossils within the Devonian limestones are well silicified and weather out in relief on the rock surfaces. The silicification process must have been a very early diagenetic event which occurred before recrystallization of the limestones could destroy the fossils. Stylolites, shown in thin section, sometimes follow the boundaries of recrystallized grains, but in places also cut through crystals. It appears that recrystallization occurred before and during compaction and induration of the limestones.

The dolomites present can be separated into two major groups on the basis of age and character. These groups are separated by an unconformity which represents the Devonian-Mississippian boundary. Fossils are well silicified in the Devonian dolomites, units 3 through 5, but not in the Mississippian dolomites, units 6 and 7. Silicification must have occurred in the fossils of the Devonian units before dolomitization took place. Dolomitization destroyed most fossil evidence in the Mississippian units because replacement by silica had not protected them from recrystallization.

The uppermost part of the Fitchville Formation consists of three limestone units, units 8-10. The last unit, unit 10, is the curly limestone, defined by Morris and Lovering (1961) as the upper boundary of the Fitchville Formation.

The lowermost 15 m of the Gardison Limestone were investigated and divided into four units, units 11-14.

Dolomitization

All the dolomites investigated within the Fitchville Formation are secondary in nature. The presence of organisms adapted to open-marine conditions of normal salinity within these strata supports the contention that the dolomite formed by replacement rather than by primary sedimentation. Evidence that might accompany primary dolomite, such as association with other evaporitic minerals, is not present.

The dolomites are seen in thin section as mosaics of interlocking crystals. It appears that dolomitization proceeded too rapidly for any euhedral crystals to form.

The seepage refluxion model of dolomite genesis proposed by Adams and Rhodes (1960) may be applicable here. In this model, restricted circulation of normal-marine waters promotes the formation of heavy, warm, magnesium-rich, hypersaline brines near the substrate surface. These brines would be heavy enough to move downward through the sediments by replacing connate water. As the magnesium-rich brines seep downward, replacement of calcium by magnesium causes dolomite to form at the expense of calcite or aragonite within the sediments (Adams and Rhodes 1960).

A birdseye texture is visible in a thin section from the base of the first Mississippian dolomite, unit 6. This texture is indicative of desiccation caused by subaerial exposure, which could occur only in the highest intertidal or supratidal regions along a coastline (Shinn 1968). Tidal-flat sedimentation is indicated. This is a place where magnesium-rich brines might form because of increased evaporation. "Reflux dolomitization is part of the geologic cycle inherent with tidal-flat sedimentation" (Lucia 1972).

Supratidal deposits are also found near the top of the up-

per, Mississippian, dolomites. The magnesium-rich brines responsible for dolomitization may have formed here also.

Stylolites present within dolomite units throughout the stratigraphic sections provide clues as to the time at which dolomitization took place. In some places these separate areas are of different crystal sizes, indicating that they at least partially provided a path for dolomitizing fluids. In some other places stylolites cut through dolomite crystals. Dolomitization must have occurred before, during, and after the compaction effects of diagenesis.

Adams and Rhodes (1960) found that in Permian rocks of west Texas there was a correlation between the grain size of the original limestone and the textures of the dolomites replacing it. Coarsely crystalline dolomites were limited to beds originally composed of coarse-grained limestones. Finely crystalline dolomites were found in places that fine-grained limestones had originally formed. Dolomite textures were caused more by original crystallinity than by dolomitization.

It appears that the dolomite textures found in the Fitchville Formation are due to both original crystal sizes in the replaced beds and the effects of dolomitization. Within single beds a range of dolomite crystal sizes may be seen, often separated by stylolites. This relatively small range of sizes is due to the differential effects of dolomitization. But, in general, coarsely crystalline dolomites appear to have formed in places where environmental conditions would have favored the formation of coarse limestones, and finely crystalline dolomites have formed from sediments which appear to have originally been fine muds.

PALEOECOLOGY

Fossils included within strata may be the most useful source of information available for use in paleoenvironmental studies, for they show reaction to many environmental factors. Adaptations made by modern forms in response to factors in an environment can be studied and evaluated. The same adaptations found in similar fossil forms can provide a basis for interpreting environments of the past.

The Paleocology of Fitchville Corals

Modern corals are adapted to a marine environment. They are strictly marine and cannot tolerate much variation in salinity. Owing to sessile life habits, they must feed on small nektonic or suspended organisms. For this reason good circulation of reasonably clear, nutrient-rich water is necessary for their survival (Heckel 1972).

All these environmental characteristics must be present for modern corals to survive. It is thought that corals have always required these things in their environment. Therefore, wherever corals are found in Fitchville strata, these environmental characteristics must have been present. Other than these general characteristics, little additional information about environmental characteristics can be deciphered from the specific corals found in the Fitchville Formation. In general, solitary rugose corals are thought to have inhabited relatively softer substrates than colonial tabulate forms, such as *Syringopora* (Heckel 1972). Since these types are found in association with each other within Fitchville strata, differences in the firmness of the substrate cannot readily be determined.

The Paleocology of Fitchville Brachiopods

Brachiopods are currently an exclusively marine-living group of organisms. They are generally benthonic, epifaunal suspension feeders. Unlike corals, brachiopods can tolerate more turbid conditions (Rudwick 1965).

Modern brachiopods prefer hard substances on which to attach, but there are some types, such as terebratulids, that can attach to softer material such as algal stems. Brachiopods that do not cement their shells to the substrate are confined to relatively quiet environments, not swept by strong currents. Apparently the pedicles of brachiopods are not sufficiently strong to withstand turbulent conditions. Modern forms found in agitated waters such as reefs are commonly found in protected areas which provide shelter from strong currents (Rudwick 1965).

Spiriferids, dominant in the Fitchville, may have developed long lateral extensions of their valves to spread the weight of their shell over a greater area of the substratum by acting as skilike platforms. In some other spiriferids the ventral cardinal area is modified into a broad, flat base which may have served the same function. Both these adaptations would bring the center of gravity closer to the posterior of the shell. Since the shape of the shell may have provided much of the means of support for the Fitchville brachiopods, it would appear that in general the paleoenvironments present during deposition of brachiopod-bearing strata were not typified by strong current action. Such currents would have made existence very precarious for these organisms. Fitchville brachiopods were apparently adapted to life on relatively soft and quiet bottoms.

The Paleocology of Conodonts

Conodonts are unknown in nonmarine deposits. Their distribution does not appear to be tied to any one enclosing rock type. Members of the same species may be found in lithologies as diverse as light colored limestones and black shales. Müller (1962) speculates that this independence from specific substrate types indicates that conodont animals were free-swimming on the whole. Seddon and Sweet (1971) preferred to view conodonts as planktonic. This mode of life would also account for their preservation in different lithofacies, and might better explain the fact that many species have a worldwide distribution. Their concept is one of a simple vertical stratification in which some groups are limited to near-surface waters, while others occur at lower depths. Recent planktonic organisms show just such a stratification caused by factors such as temperature, light penetration, nutrient supply, and the like. This model explains why some genera of conodonts are present in samples from various lithologies, deposited in all depths whereas others are not found in shallow-water deposits (Seddon and Sweet 1971).

The model of Seddon and Sweet (1971) was applied by Sandberg (1976) to Late Devonian conodont biofacies of the *Polygnathus styriacus* Zone in the western United States. He found that the distribution of some conodonts, such as *Bispathodus stabilis*, was ubiquitous. They probably lived in the uppermost waters and were thus included in deposits formed at all depths. Other conodonts, such as *Palmatolepis*, were found to be limited to deeper-water deposits. *Polygnathus*, however, occurred both in deep water and in very shallow water. Their peak was found in intermediate depths, indicating that *Polygnathus* reacted to environmental factors other than just depth (Sandberg 1976). The possibility that *Polygnathus styriacus* might have been adapted to deeper waters than the genus as a whole, deeper than any present in the western United States during this time, would explain the rarity of this species in the western United States at a time when it was abundant in deeper-water deposits of Germany.

As suggested by Sandberg (1976), the conclusions as to the paleoecology of the various conodonts of his study can be ex-

tended to similar forms at least through the end of the Famennian, which includes the lower part of the Fitchville Formation. On the basis of the conodonts contained within the Fitchville strata, a deep-water environment is ruled out at the time of deposition.

Orientations

In both stratigraphic sections studied many of the fossils are not found in original growth positions. One notable exception is found in the *Syringopora* corals present, most of which appear to be in the original position they occupied in life. Rugose horn corals are found in almost any attitude, with perhaps the most common orientation being one where their long axes, as measured from apex to calyx, are parallel to bedding. It would appear that many of these corals fell to their final resting places or underwent transport after death. Many of them show evidences of erosion on outer surfaces which indicates probable transportation.

Brachiopods found in the sections are also preserved in various orientations. Generally, specimens consisting of disarticulated valves are found, indicating that they underwent considerable postmortem transportation. In some places disarticulated valves are preserved with specimens where both valves are intact.

Crinoids invariably occur in a disaggregated condition throughout both stratigraphic sections.

In general, the faunal assemblages found in the two sections represent necrocoenose, or death assemblages, in which the organisms, excepting *Syringopora*, were brought together after death. The currents responsible for this probably were not vigorous, as indicated by the presence of *Syringopora* in growth position and articulated brachiopod shells.

Associations

No mutually exclusive associations can be deduced from the Fitchville fossils preserved in the two stratigraphic sections studied. The effects of transportation would tend to obscure any such associations that did exist. Generally, at any given horizon, all members of the fauna appear to have been able to coexist.

In the Gardison strata the disappearance of *Syringopora* coincides with the first appearance of *Aulopora*, another tabulate coral. Perhaps *Syringopora* was forced out by competitive pressures exerted by *Aulopora*, a form which probably occupied a similar environmental niche.

An association between *Syringopora surcularia* and *Syringopora hisingeri* is common in both stratigraphic sections. Most colonies of *Syringopora* are separated by a considerable lateral distance, but these two species often appear side by side or even close enough as to exhibit intertwining corallites (fig. 6). Perhaps one species alters the substrate in some way which makes it more suitable for colonization by the other. This may be a mutualistic relationship, or simply a commensal one.

Abundances

Unfortunately the occurrence of most fossil forms was too sparse to allow quantitative studies. Relative abundances were noted for all fossils found, but often, especially with brachiopods, only the presence or absence of a group could be determined.

Actual abundances were recorded for all coral types found in the Fitchville Formation. Because of the scarcity of preserved specimens above 25 m in the section, only data below this level were tabulated (tables 1 and 2).

Ratios of one type of coral to another are fairly constant. Generally, when the abundance of one type in a group increases, so does the abundance of others. This is true among the three species of *Syringopora* and among the three solitary rugose coral types.

Syringopora reaches a peak in abundance at the top of the limestone unit, unit 2a. Evidently environmental conditions favoring the growth of *Syringopora* were present here during deposition of the enclosing rock. Possibly this was an occurrence of better-oxygenated, more nutrient-laden waters brought in by increased current action.

Solitary rugose corals reach a peak in abundance at the top of the dolomite unit, unit 3. Perhaps more vigorous currents also brought an increased amount of nutrients and oxygen into the environment at this point.

The relative abundance of brachiopods was observed. Brachiopods were found to be more abundant in some horizons than in others. A peak was noted in the upper part of the middle of unit 2a. This peak coincides with the start of an increase in abundance of *Syringopora* within this unit. However, by the top of the unit, where the corals became most abun-

dant, the brachiopods have passed their peak. It would appear that a change in conditions favored both groups at first, but only corals later. If current action brought this change in conditions, both groups might have benefited from increased oxygen and nutrient levels to the point where the currents became swift enough to be somewhat detrimental to the brachiopods.

A similar situation is noticed at the top of unit 3. Brachiopods become more abundant at the same place that corals start to increase in abundance. The corals increase in abundance through the top of the unit whereas the brachiopod abundance levels off.

The Wanlass Hill section was sampled for conodonts, which are sparse in the lower part of the section and missing from the upper part. The peak of conodont abundance was found in the middle of the stratigraphic section, near the Devonian-Mississippian boundary.

Conodont abundance might be affected by several factors including sampling errors, differing rates of sedimentation, and limiting environmental factors. The sparse occurrence of conodonts in many of the Fitchville strata is probably due to the fact that these strata were deposited in very shallow water.



FIGURE 6.— Close association between two *Syringopora* colonies, *S. bisingeri* (A) and *S. sureularia* (B).

These waters would be shallower than the horizons occupied by many conodont genera in the vertical stratification sequence outlined by Sandberg (1976).

DEPOSITIONAL ENVIRONMENTS

Introduction

Determination of the environments present during deposition depends on an evaluation of the physical, chemical, and biological characteristics of the sediments. The lithologies, sedimentary structures, and paleoecological factors indicated by fossils provide clues that can be used to reconstruct environments of the past. These various lines of evidence all point to a shallow-water origin for the strata of the Fitchville formation.

The strata of the Fitchville Formation and of the lowermost Gardison Limestone can be related fairly well to the model proposed by Irwin (1965) to explain clear-water (non-terrigenous) carbonate sedimentation in shallow epicontinental seas. This model delineates three major energy-depth zones divided on the basis of the degree of water agitation caused by wave and current action (fig. 7).

The deepest zone, X, is below effective wave base where the energy regime allows the deposition of fine sediments such as mud. Quiet waters typify this zone.

The next zone, Y, is shallower and occurs where effective wave base intersects the surface of the bottom. Because of agitation by waves and currents, muds are not deposited to any great extent, and coarser bioclastic debris accumulates as a winnowed deposit. A more abundant, diverse fauna may exist here because of waters rich in oxygen and nutrients. Also, at this level well-sorted, cross-bedded deposits may form due, respectively, to winnowing and traction by currents.

The shallowest zone, Z, is typified again by quiet waters. Since waves and currents have dissipated most of their energy in the zone below this, muds are once more allowed to accumulate. Faunas, especially in the uppermost part of this zone, may be restricted by limiting environmental factors such as increased salinity, reduced oxygen and nutrient levels, and the like.

The slope of the bottom surface on which the Fitchville strata accumulated was probably greater than that of a true epicontinental sea as the concept is used by Irwin (1965). In his model the three energy depth zones may extend seaward to an extent of hundreds of kilometers. These zones probably extended only for tens of kilometers in Fitchville seas. Therefore, the model outlined above must be applied with some reservations. The three zones must have extended a smaller distance seaward, perhaps sometimes resulting in a complete loss of zone Z, due to wave and current action extending up to the shoreline. Such a loss did not occur, however, in the waters present during Fitchville deposition. Supratidal deposits at the top of the Fitchville include an algal stromatolitic bed which must have formed in a fairly extensive zone, along a shoreline of very little relief. This limestone, and the conditions under which it formed, are characteristic of zone Z. Thus, all the strata of the Fitchville Formation can be related to one of the three zones, X, Y, and Z, postulated by the model.

Lithologies, and their included faunas, are similar on both Wanlass Hill and Greeley Hill, which are separated by a distance of 4.6 km. Generally only small disparities, in thickness or stratigraphic level of rock units, exist between the two. For clarity and simplicity of discussion, the stratigraphic section on Wanlass Hill will be used to describe the paleoenvironments of the Fitchville Formation and the first few meters of the Gardi-

son Limestone. Any major differences between the two sections will be noted.

Quartz Clastic Layers

The base of Fitchville Formation was defined by Morris and Lovering (1961) to be at the bottom of a persistent bed of sandstone or sand-streaked limestone. This basal unit is a fine, calcareous sandstone in the stratigraphic sections investigated in this study. This sandstone is designated unit 1. In places it extends up to 20 cm downward into the underlying dolomite as distinct, discordant, sand-grain bodies (fig. 4). The cement within the sandstone, including the sand-grain bodies, is this same dolomite.

The clastic portion occupies 65–70 percent of the sandstone (fig. 8). The quartz clasts are bimodal in size. Most (up to 90%) are approximately 0.1 mm in diameter. The remaining 10 percent are clasts which average 1–1.5 mm, with a few ranging up to 3 mm in approximate diameter. The larger grains are usually subrounded. The smaller grains are typically subangular, with a range from subangular to subrounded. Sorting is generally good. In many areas, the smaller grains are present almost to the exclusion of the larger sizes. Many of the quartz grains have frosted surfaces.

The second sand-bearing layer appears in unit 2a, 6 m above the first one on Wanlass Hill, and 4.5 m above the first on Greeley Hill. Not so well developed as the first, it is similar in most other respects. The clasts are once again interspersed

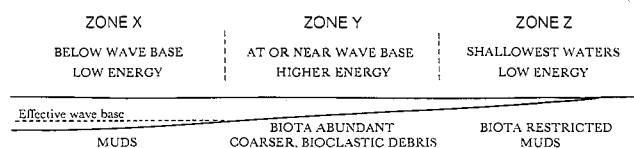


FIGURE 7.—Diagram of epicontinental, shallow, clearwater (nonterrigenous) carbonate sedimentation as postulated by Irwin (1965).

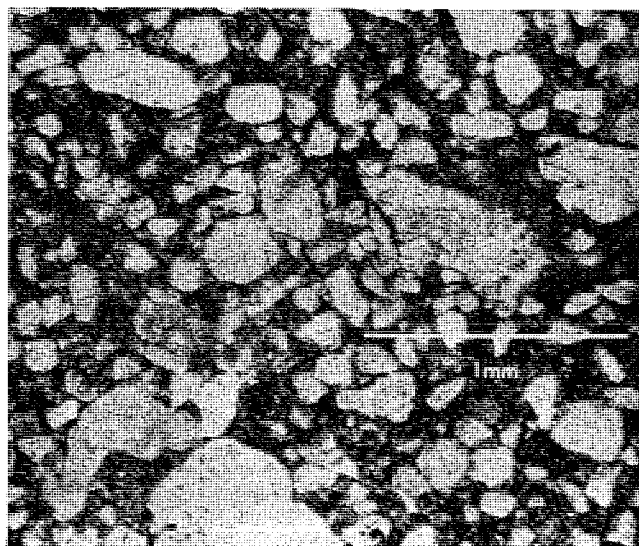


FIGURE 8.—Photomicrograph of sand-grain layer (unit 1) which forms lower boundary of Fitchville Formation. Pictured here is a thin section prepared from Wanlass Hill.

within a matrix-cement of fine crystalline carbonate, in this case the limestone of unit 2a. The areas containing the clasts sometimes form distinct sand-grain bodies. The only major difference between this layer and the first is that here the larger quartz grains range only from 0.5 to 1 mm.

The third sandstone layer occurs within dolomite in unit 4, at a stratigraphic level of 26.8 m on Wanlass Hill and 25.3 m on Greeley Hill. It occurs as a homogeneous bed 10 cm in thickness. Quartz grains extend into the underlying dolomite in sand-grain bodies as they did in the prior two sand-grain layers. These structures are up to 35 cm in depth.

The quartz clasts in this layer are subangular to rounded and are well sorted. Their size is approximately 0.1 mm. The grains are interspersed in a very finely crystalline dolomite matrix-cement and show a mud-supported arrangement.

The last quartz clastic layer in the Fitchville appears in unit 5 at 31.3 m on Wanlass Hill, and at 29 m on Greeley Hill. It is different from the prior sand-bearing layers in that the clasts are found only within distinct burrows. These burrows appear as lighter traces on the gray dolomite (figs. 9, 10). The burrows are generally horizontal, but do take on vertical orientations in places. Burrowing appears to have reached depths of 10–15 cm below the substrate surface. The burrowing organisms must have been mud-eaters which ingested nutrients as they burrowed. The trace fossils left by them would be termed "fodinichnia" by Seilacher (1964).

The color difference in the burrows is due to the inclusion of very fine quartz grains which appear only within the confines of the burrow traces. These sands are about .025 mm in size and are fairly well sorted. Their shape is subangular to sub-rounded.

The model of Irwin (1965) did not take into account processes that led to the deposition of terrigenous materials. However, it appears that the deposition of the sand-grain layers did not alter any of the conditions present during the deposition of the carbonate units in which they appear. The nature, including grain size, of the carbonate material below, within, and above each of the quartz sand layers is the same. Apparently there was little, if any, change in the energy level of the environment during the time any of the quartz clastics were deposited. The model appears to still apply to the carbonate units, but the deposition of the clastic grains is another matter.

The four sandstone layers are similar to an example given by Wilson (1975) of detrital siliceous grains in carbonate strata. He contends that two types of such grains are extensive in terms of occurrence and distribution. One type consists of silt-sized clasts of probably wind-blown origin. He cites a modern example in the Persian Gulf as being of this type. Here vast dust storms are capable of blowing silt and clay-size particles completely across the gulf, a distance of 400 km. The geologic record may contain many layers of such silts, sometimes in association with larger, rounded, and frosted quartz grains (Wilson 1975).

The interspersal of the quartz grains in a matrix of fine calcareous material creates a fabric in which there are few grain-to-grain contacts in all four layers and indicates that deposition of the clasts was contemporaneous with the muds which formed the carbonate matrix material. The energy level of currents that could transport the large quartz grains would also be great enough to winnow out the fine muds and keep them in suspension. This winnowing did not occur. It would follow that the clastics were deposited in quiet water which allowed the fine muds to settle out of suspension and be deposited. Winds might have carried the quartz clasts directly over the waters in

which they were deposited. Transport by ocean currents could then be negligible.

The frosted nature of the larger grains found in the first two sand-bearing layers supports the contention that many of the clasts may have experienced transport by wind. A majority of the clasts in the sand-bearing layers could have been delivered to the site of deposition by strong winds. However, winds of cyclonic strength would have been necessary to carry grains up to 3 mm, such as those found in the lower two layers, over water to the site of deposition. The fact that these large grains are mixed in with smaller sizes (the majority of all clasts present) could be due to fluctuations in wind velocity.

From the first sand-bearing layer to the last, a general fining-upward trend is noticeable in the size of the included



FIGURE 9.—Distinctive burrowed layer in unit 5, which appears at 29.0 m above base of Fitchville Formation on Greeley Hill.

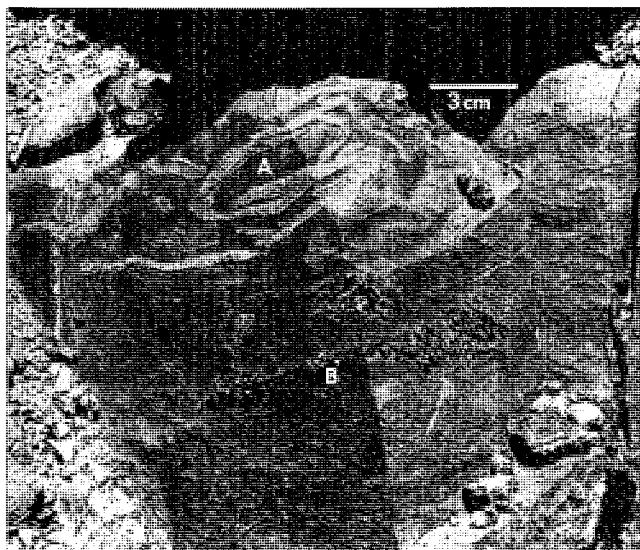


FIGURE 10.—Two distinctive features in unit 5 as they appear on Wanlass Hill. A layer of sand-filled burrows (A) is found 31.3 m above base of Fitchville Formation. A layer of distorted *Syringopora* corals (B) is found just below the burrows.

quartz clasts. This trend could be due to a decrease in the velocity of the winds carrying the sands to the site of deposition or to a decrease in the size of sands supplied to the winds at the source. In another possibility, changes in wind direction might bring sands of different sizes from different source areas. (J. R. Bushman personal communication 1980). Further study is needed to determine the cause of the fining-upward trend.

A possible explanation of the deposition of these layers includes delivery of the sands by strong winds to the shallow seas covering the site of deposition. These sands would then come to a final resting place in a shallow-marine environment.

The Stansbury Uplift, mentioned earlier, was the likely source area for all the clastic quartz grains. This area was tectonically positive at the proper time and was relatively close, within 100 km of the area of Fitchville deposition. Furthermore, this uplift exposed strata such as the Cambrian Tintic Quartzite. Most of the quartz grains from the four sandstone layers demonstrate strained, or undulatory, extinction when viewed under a polarizing petrographic microscope, and favor the possibility that the clasts were derived from the Tintic Quartzite, a unit where the action of metamorphism could produce quartz with strained extinction.

The Lower (Devonian) Limestones (Units 2a and 2b)

The lowermost strata of the Fitchville, excluding the two lower sandgrain layers, are biomicrosparticles of unit 2a. Bioclasts appear in a mud-supported fabric. The matrix is microsparite which has recrystallized from an original micrite.

The fossils present are typical of an assemblage which indicates normal-marine salinity. Brachiopods, corals, and crinoids are found in these strata. Well-circulated, oxygenated, not overly turbulent or turbid waters most likely were found in the paleoenvironment.

The energy of the environment must have been low enough to allow micritic mud to settle out of suspension, but high enough to allow well-circulated, oxygenated waters to exist. These conditions would occur just below wave base, in zone X of the model proposed by Irwin (1965).

Unit 2b is found between 14 m and 20.5 m. It differs from unit 2a in that it weathers to a lighter color on surfaces which show pockmarked pattern. As shown in thin section, almost total recrystallization has taken place, which may account for the difference in weathered appearance.

The same coral-brachiopod-crinoid fauna that is present below is also present here. Unfortunately, lithologic evidence that might be useful in environmental reconstruction has been obliterated by recrystallization. On the basis of the identical fauna, a similar environment to the one in the unit below, unit 2a, is inferred.

Both unit 2a and unit 2b show a distinctive mottled, wavy appearance on weathered surfaces. Such a mottled appearance is diagnostic of bioturbation not extensive enough to have reworked the sediments into a homogeneous fabric (Heckel 1972). These mottled areas are generally lighter in color than the surrounding rock and weather out in slight relief, probably because of localized concentrations of argillaceous material.

It seems probable that the burrowlike bodies of the sandgrain layers are structures which share a similar genesis with the wavy structures found in these limestones. The siliceous grains would be much more resistant to diagenetic changes than the surrounding carbonate and so could preserve better-defined burrowlike structures. A concentration of argillaceous material could form by being washed into burrow openings,

and sands must have filled burrows the same way, forming the sand-grain bodies.

The Lower (Devonian) Dolomites (Units 3-5)

The lower dolomites seem to represent a shallowing-upward sequence which ends in deposits formed in the shallowest zone, zone Z, of Irwin (1965).

The lowermost dolomite, unit 3, extends from 20.5 m to 24.7 m. It contains a coral-brachiopod-crinoid fauna identical to that found in the limestones below. Fossils are especially abundant in the last 1.5 m of this unit. Lithologic evidence that might be useful in reconstructing the paleoenvironment has been obliterated by pervasive dolomitization.

On the basis of increased abundance and diversity in the fauna included within this dolomite, it appears that this unit represents a transition from zone X to zone Y. The lower part of the unit was deposited in the uppermost part of zone X, as were units 2a and 2b. The upper part of the unit (the last 1.5 m) was deposited within zone Y, where increased oxygen and nutrient levels allowed a greater proliferation of life, especially corals (table 2). Perhaps the stronger currents found here favored corals more than brachiopods.

The next two dolomites, unit 4 and unit 5, are very similar in both lithologic and paleontologic characteristics. The first unit is between 24.7 and 26.8 m. The second unit extends from 26.8 m to the top of the Devonian at 34 m. The last 2.5 m of unit 5 are different in some respects and will be treated separately.

These two units are both finely laminated and exhibit cross-stratification in places; they are finely crystalline, indicating that the original material was most likely a micrite. The environment must have included quiet waters, but some current action was present.

The fauna is sparse but includes some rugose corals, brachiopods, and tabulate corals. The fossils are not water worn, for fine features are preserved. Most of the brachiopods are preserved with both valves intact. These fossils show less sign of current transport than those in any of the prior units, yet the first laminated and cross-stratified beds are contained within them, probably because of a lack of bioturbation. An environmental factor may have prevented burrowing organisms from existing here.

Except for the tabulate corals *Syringopora* and *Michellina*, the fossils in these horizons often appear to be unusually small. *Rhipidomella* sp. and *Camarotoechia*? sp. specimens found within this unit on Wanlass Hill are about 60-70 percent of the size of comparable specimens described by Stainbrook (1947) as holotypes from the Percha Shale of New Mexico. Some normal-sized specimens, however, were found on Greeley Hill. *Syringopora* specimens seem to have normal-sized corallites, but do not show normal growth patterns (fig. 10). Spacings between the corallites are quite reduced. The corallites grow in directions parallel to bedding instead of the usual pattern where they grow normal to bedding. In one specimen corallites were growing in an upright position and then turned sharply into a pattern parallel to bedding. Solitary rugose corals found in association with the distorted *Syringopora* colonies also show abnormal growth patterns. In them the calyx is elliptical in form rather than circular, which would be more normal. It appears that the corals grew in these patterns, for the corallites do not show signs of being mechanically crushed. An environmental factor must have affected the growth pattern of *Syringopora* and the rugose corals and limited the size of the brachiopods able to exist in these units.

One chemical factor cited in the literature as limiting the growth of marine invertebrates is the presence of abnormal amounts of iron in the water. Present within unit 4 and unit 5 are some small, dark red, rice-grain-shaped particles of an iron mineral, possibly hematite. They are primary sedimentary features and indicate that the environment was enriched with iron during deposition. Some fossils are replaced, at least in part, by hematite or a related iron mineral.

Tasch (1953) reports a connection between iron concentrations in the water and growth retardation of organisms living in it. He cites experiments in the literature which indicate that abnormally high iron concentrations cause cellular chemical reactions affecting enzyme activity related to growth in marine invertebrates. This is a probable explanation for the existence of stunted fossils found in these strata of the Fitchville Formation.

The strata of all of unit 4 and the lower part of 5 would fit into the lower part of zone Z. Here there would be enough current action to produce cross-bedding but not so much as to prevent the deposition of micritic muds.

The upper part of unit 5, comprising the top 2.5 m, is transitional in terms of environment. At 31.3 m the last good evidence of life, the burrows of the last sand-bearing layer, occurs. At 33 m most of the dark red iron particles disappear. These last 2.5 m show transition from the lower part of zone Z to the higher part of zone Z where life became limited by very shallow conditions.

The Upper (Mississippian) Dolomites (Units 6 and 7)

The first unit above the unconformity which separates the Devonian from the Mississippian is a dolomite, unit 6. It is readily distinguished from the units below the unconformity by poor preservation of fossils in it. Only a few, rare, poorly preserved *Syringopora* corals and scattered crinoidal debris are visible to the naked eye. At the very base of the unit on Greeley Hill birdseye structures are found in thin section. They are indicative of very shallow intertidal or supratidal conditions of periodic subaerial exposure (Shinn 1968) and mark the first deposits formed in a transgressive sea reinvading the land following the period of nondeposition represented by the unconformity. This transgression must have proceeded rapidly, for the lowermost meter of unit 6 contains a conodont fauna indicative of waters deeper than the intertidal zone. Some, but not most, of the conodont specimens found here have worn surfaces that show evidence of reworking. Thin sections reveal relic crinoidal structure further up in this unit.

The second unit, unit 7, begins at 47 m and extends to 57 m. Preservation of fossils is again poor, but some are recognizable. *Syringopora*, some horn corals, and crinoidal debris are present.

Fine laminations and cross-stratification are found in unit 7. They are indicative of greater current action than in unit 6 and lead to the placement of unit 7 in zone Y, closer to wave base.

The Upper (Mississippian) Limestones (Units 8 and 9)

The first Mississippian limestone, unit 8, is a dark gray unit which contains a poorly preserved fauna, among which are brachiopods (including a spiriferid), rugose horn corals, crinoids, and a gastropod (*Straparoleus*).

In thin section unit 8 is a pelsparite which contains some intraclastic material. The sparry cement appears to be primary

and is indicative of a more energetic environment than that present during the deposition of unit 7, for muds either were not originally deposited to any great extent, or they were subsequently winnowed out by current or wave action. This unit is assigned placement in the Y energy-depth zone, where effective wave base intersects the bottom. Here the waters of the environment were more agitated than during the deposition of unit 7.

The next unit, unit 9, is a micrite which demonstrates a laminated nature in places. It begins at 62.5 m and extends to 67.2 m. The laminations are especially prominent at 65 m, and in places they are contorted. This pattern is indicative of creation by algal mats. Algally produced structures, such as these laminations, are typical of deposits formed in the very shallow waters of the upper intertidal or supratidal regions along a coastline (Heckel 1972).

Intraformational breccias are present sporadically throughout unit 9. Such a breccia consistently appears in the last 0.5 m of this unit. Rip-up clasts within this breccia range up to 15 mm in size (fig. 11). These clasts are the result of the desiccation and peeling up of material already partially lithified and are indicative of supratidal environments (Lucia 1972).

Desiccation also produces birdseye textures in sediments. Such a texture is seen, in thin section, in the uppermost part of unit 9. The birdseye texture, intraclastic breccia, algal laminations, and lack of a fauna are all indicative of conditions present in a supratidal environment. This unit must have formed at the very top of zone Z.

The Curly Limestone (Unit 10)

The top boundary of the Fitchville Formation was placed at the upper surface of a laminated limestone unit called the "curly bed," or "curly limestone." These informal names are attached to a unit that several workers have discussed in the literature. The most definitive work was that published by Proctor and Clark (1956).

This feature is not always found separating the Fitchville from the overlying Gardison Limestone, but it is rather extensive and crops out in an area of at least 1,550 km². The west-

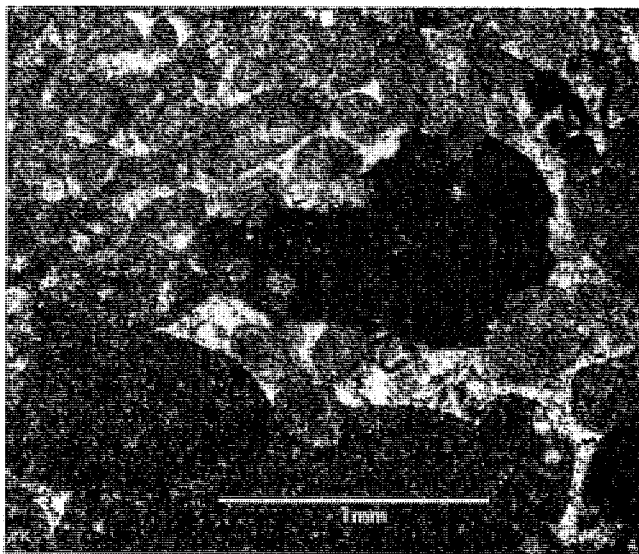


FIGURE 11.—A photomicrograph of intraclasts in unit 9, 67 m above base of Fitchville Formation on Wanlass Hill.

ernmost expression of this unit is in the Boulter Mountains of the Rush Valley area. It is found farthest south on Long Ridge, about 11 km south of Goshen, Utah, and just about as far north as Ophir, Utah, in the Oquirrh Mountains, and east to the Lake Mountains, near where the current study was done. The curly bed has not been found in the Wasatch Mountains (Proctor and Clark 1956).

For the most part this limestone bed shows noncolumnar stromatolitic features. However, one well-developed column was noted on Wanlass Hill (fig. 12). It is 20 cm in height and 10 cm in width. Except at the very base of the column, individual laminae terminate upon reaching the flanks of the column. Apparently the column was originally a feature showing 20 cm of relief between itself and the substrate, and then subsequent laminations were deposited along its flanks, filling in the lower areas until all parts of the substrate were at the same level.

The column described above is a rare exception. Generally, the curly bed is noncolumnar. Perhaps this limestone is best

termed a domed-biostrome in that it has a mode of occurrence in which laminae are linked laterally and show an undulatory or pseudocolumnar aspect in several places (Priess 1976).

In thin section the curly limestone appears as an alternation between micritic and pelletal layers (fig. 13). In a thin section prepared from this unit (on Greeley Hill) some cross-sections through algal filaments are present (fig. 14). These filaments are found in a micritic lamination. They are about 0.1 mm in diameter and are outlined by prismatic linings of calcareous crystals. The filaments are arranged so as to give the appearance of a string of beads. The structures are of a size and pattern shown by the genus *Sphaerocodium*, but a plan view of the branching pattern would be necessary to make a positive identification (J. L. Wray personal communication 1979). These algal structures will be referred to as *Sphaerocodium* ? sp.

Sphaerocodium consists of dichotomously branching, unsegmented filaments which branch in a "distinctive fan-like pattern while maintaining contact along their inner margins. Thus



FIGURE 12.—Curly bed (unit 10) on Wanlass Hill, showing a relatively rare, well-formed stromatolite dome 20 cm high and 10 cm wide. This unit is upper boundary of Fitchville Formation.

this branching habit gives a beaded appearance to groups of filaments cut transversely, which has been incorrectly interpreted as segmented filaments" (Wray 1971).

Sphaerocodium ? sp. may or may not be the major organism responsible for the creation of the laminated structure of the curly limestone. But it, or algae like it, could be responsible. It has the ability to secrete calcium carbonate within and between tissues and also to trap and bind carbonate sediments on the mucilaginous sheaths surrounding filaments. These algae may be preserved as direct skeletal remains or, as in the case of the curly bed, indirect evidence such as largely nonskeletal laminated stromatolite structures (Wray 1971).

The study of modern stromatolites has brought some understanding of the factors necessary to create and preserve stromatolite forms. First of all the environment must be suitable for the creation of mucilaginous algal mats. Principally it is blue green algae which form these mats in shallow intertidal and supratidal areas. *Sphaerocodium* is classified among the green or blue green algae (Wray 1971). The rate of growth of the algae must exceed the rate by which destruction occurs by disruption or consumption by other organisms. The sediment supply must be great enough to produce a structure but not so great as to smother the algae and prevent colonization. Finally, the accretion of stromatolite structures must exceed erosion (Hoffman 1976).

The decline in abundance and diversity of stromatolites throughout Phanerozoic time may have been due to a progressive rise in numbers and types of algae-consuming organisms. Stromatolites became more and more confined to environments where the activity of grazing and burrowing organisms was restricted or eliminated (Hoffman 1976). In modern environments these organisms are restricted to the lower portions of the intertidal zone. They do not exist above it because of limiting factors such as desiccation and temperature. In Shark Bay, Australia, hypersaline conditions limit the activity of algae-destroying organisms even in subtidal waters (Hoffman 1976).

The curly limestone contains preserved stromatolitic features but lacks a preserved fauna. Environmental conditions must have restricted marine invertebrates from the place this limestone was deposited. There is no contributory evidence to indicate that hypersaline waters were present. No evaporitic minerals are present. Desiccation might have been the primary factor in limiting the algae-destroying fauna. Algal mats are tolerant not only of great salinities, but also of long drying periods. If desiccation was the limiting factor, the curly bed must have formed in high intertidal or supratidal regions of the coastline.

In general, flat to crinkly laminae, which also may exhibit small connecting domes, are characteristic of the supratidal or very high intertidal zones (Heckel 1972). This is the general pattern shown in the curly limestone. The unit must have formed in areas where desiccation was common and restricted invertebrate animal life—as in the very uppermost part of zone Z. Birdseye structures found in thin section support this conclusion, as does a polygonal pattern, probably formed by desiccation cracking, which was noticed on the uppermost surface of the curly bed in one place on Wanlass Hill.

Two discrete columns were found on Wanlass Hill, and others have been reported from other locations (Proctor and Clark 1956). The growth of columns in present-day stromatolites is due to enhanced growth in some areas compared to others. It may be caused by selective colonization by mats and differential erosion. Substratum irregularities are believed to

initiate column growth in some instances by providing places for enhanced growth (Logan 1961).

In the curly bed some columns might have been initiated on such irregularities as are found in an area of flat-pebble conglomerate formation, like the breccia bed mentioned earlier, found directly below the curly bed on Wanlass Hill and Greeley Hill. Places where intraformational breccias form might have experienced greater current action, which would aid in the formation of columns of creating relief through differential erosion (Hoffman 1976).

In a Cambrian example in southern Australia, flat-pebble conglomerates are found in association with stromatolite columns. Columnar stromatolites that are associated with the con

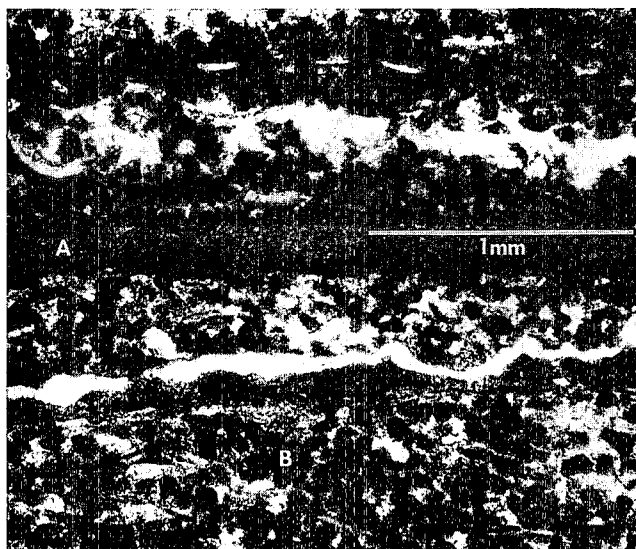


FIGURE 13.—Photomicrograph of the curly bed (unit 10) showing laminated structure. Two types of laminations can be seen, a micritic type (A), and a pelletal type (B). This thin section was prepared from a sample taken at 67.5 m above base of Fitchville Formation on Wanlass Hill.



FIGURE 14.—Photomicrograph of curly bed (unit 10) which shows algal structures (*Sphaerocodium*?). This thin section was prepared from a sample taken from Greeley Hill.

glomerates are best developed where the beds are thickest and occur only in association with them (Haslett 1976).

There appears to be a correlation, in Shark Bay, Australia, between the height of columnar stromatolites and the tidal amplitude. Stromatolites cannot grow above the highest water level, but given time they grow up to this level. Their height is controlled by the tidal range and the position occupied in the intertidal zone (Logan 1961).

One column found on Wanlass Hill is 20 cm in height. A minimum value for the tidal amplitude at the site at which the column formed is 20 cm.

The Lowermost Gardison Limestones (Units 11-14)

The first Gardison limestone unit, unit 11, conformably overlies the curly limestone. It extends from 68 to 70 m. It is similar in some aspects to the underlying curly bed but contains a preserved fauna of corals and brachiopods. The depositional environment of unit 11 was probably in subtidal waters. This fauna disappears in the last 0.5 m of the unit, where fine laminations are visible, perhaps indicating shallower water, with consequent restriction of life. The unit is assigned to the subtidal portion of zone Z until the last half-meter, where the upper part of zone Z is indicated.

The second limestone unit, unit 12, extends from 70 m to 72.5 m. The lower 0.5 m includes clasts of a laminated, micritic material similar to the uppermost Fitchville deposits below. These clasts are up to 15-20 mm.

Corals are present within the breccia zone at the base of the unit, and above. At 71 m, just above the breccia zone, a 10-20-cm layer of abundant rugose horn corals is present. In places this layer is made up almost entirely of corals and coral fragments. The complete corals show extensive erosion.

A thin section prepared from 71 m reveals that the rock is a intrasparudite. Rip-up clasts, up to 1 mm, appear in a sparry matrix together with bioclasts. Sorting is poor, and the texture of the rock is jumbled and has a birdseye aspect. Except for the biologic material, the characteristics of this layer indicate formation in the highest intertidal, or supratidal areas, where subaerial exposure periodically occurred.

Corals should not be present in deposits which formed in waters as shallow as those indicated by the lithologic character of the rock. These corals appear to have been vigorously washed together. If storm waves had washed them up into the shallow waters of the highest intertidal zones, the lithologic and paleontologic evidence can be reconciled. Unit 12 is placed at the top of zone Z.

An obscured zone extends from 72.5 m to 76 m.

The next identifiable unit, unit 13, extending from 76 m to 79.5 m, is a laminated limestone which appears in thin section as a biomicroparite. One of the alternating laminations is principally made up of crinoid bioclasts in a spar that appears to be secondary after an original micrite. The other laminations are pelletal. The pellets are in a mud-supported arrangement with a recrystallized spar.

Shifting patterns of currents might have supplied sediments that alternated as shown in the laminations of unit 13 and could have occurred just below wave base in zone X.

The last unit studied, unit 14, extends from 79.5 m to 83 m. It is laminated and fossiliferous. The fossils present are predominantly brachiopods, but solitary rugose corals, crinoids, gastropods, and bryozoans are present.

Thin-section study reveals that this is a biopelsparite. The

bioclasts and pellets are in a mud-supported arrangement with a spar that has most likely recrystallized from micrite.

The lithology, laminations, and fauna indicate that this unit was deposited in open-marine waters with some current action. Such waters would occur just below wave base in zone X.

BIOSTRATIGRAPHY

Of the two stratigraphic sections measured and described in this study, only the one on Wanlass Hill was sampled for conodonts. The following discussion is an attempt to integrate the data on conodonts and on megafossils. For this reason references to stratigraphic level or thickness will apply to the Wanlass section unless noted otherwise.

The Lower (Famennian) Limestones (Units 2a and 2b)

The upper part of the Pinyon Peak Limestone is depositionally continuous with the lower beds of the overlying Fitchville Formation. As reported by Sandberg and Poole (1977), the first 3 m of Fitchville strata contain the same conodont fauna as that found in the Pinyon Peak strata just below them. This fauna belongs to the Upper *Polygnathus styriacus* Zone and is found in the lowermost Fitchville strata not only on Pinyon Peak and Fitchville Ridge, but throughout the East Tintic Mountains (Sandberg and Poole 1977). The conodont sample taken from the lowermost 3 m of unit 2a on Wanlass Hill contained *Ozarkodina* sp. and *Hindeodella* sp., neither of which is useful for precise zonation.

With the possible exception of the lowest 3 m of unit 2a and the 9.3-m combined thickness of units 4 and 5, the 34 m of Devonian Fitchville strata investigated contains a conodont fauna of the Lower *Bispathodus costatus* Zone. This fauna includes *Polygnathus inornatus* Branson, *Apatognathus varians* Branson and Mehl, *Polygnathus communis communis* Branson and Mehl, *Ozarkodina* sp., and *Hindeodella* sp. C. A. Sandberg (personal communication 1979) reports that a specimen of *Polygnathus inornatus* in this fauna is a morphotype indigenous to the lower *Bispathodus costatus* Zone.

The coral fauna of units 2a and 2b contains commonly occurring clisiophyllid, caninoid, and neo-zaphrentoid rugose corals. This fauna has as yet not been critically described. W. J. Sando is currently undertaking this task. Similar advanced clisiophyllid and caninoid corals occur in the Etroeung Limestone in Belgium (Sandberg and Poole 1977). This unit occurs across the Devonian-Carboniferous boundary (Duncan, in Morris and Lovering 1961).

Tabulate *Syringopora* corals are also common in unit 2a and unit 2b. Unfortunately they have little if any biostratigraphic value. They are described by W. J. Sando (personal communication 1979) in terms of "morphotypes" since species have little value in correlations. Three of these morphotypes are present. These, described as species, are *Syringopora surcularia* Girty, *S. arculeata* Girty, and *S. hisingeri* Billings. *Syringopora surcularia* and *S. arculeata* are typically found in rocks of the Madison Group. *Syringopora hisingeri* has been identified from Devonian strata of the Eureka district, Nevada. *Syringopora arculeata* has also been identified in the Late Devonian Percha Shale of Arizona and New Mexico (Duncan, in Morris and Lovering 1961).

The brachiopods found in units 2a and 2b are similar to those found in the Percha Shale. The Percha brachiopod faunas have been described by Kindle (1909), Stainbrook (1947), Cooper (1954), and Meader (1976). In units 2a and 2b, this fauna is represented by *Cryptospirifer* sp. (some possibly being

Crytopirifer utahensis), *Tylothyris* sp., *Crytiopsis* sp., an early terebratulid that has sometimes been described as *Cranaena*, but actually is not, and a large spirifer which may possibly be an early choristid brachiopod of which the "generic assignment is questionable" (J. T. Dutro, Jr., personal communication 1980). One large punctate brachiopod was found just above the base of the Fitchville Formation on Wanlass Hill. J. T. Dutro, Jr., reports that it is similar to specimens found in the Museum of Natural History, in Washington, D.C., which were collected from the Upper Dyer of western Colorado. Dr. G. A. Cooper "tentatively identified these as *Rhynchospirina*, a retzioid genus, but they are probably new" (J. T. Dutro, Jr., personal communication 1980).

The Lower (Famennian) Dolomites
(Units 3-5)

As stated earlier, the conodont fauna found in unit 3 belongs to the Lower *Bispathodus costatus* Zone. The coral-brachiopod fauna found below, in units 2a and 2b, continues into unit 3 unchanged. No new forms have been added, and none have disappeared.

A change in lithology and an accompanying faunal change exist at the start of unit 4. Unit 5 is of a similar lithologic makeup and contains the same fauna. These two units, totaling 9.3 m in thickness, will be discussed as one unit.

The faunal changes which occur in this 9.3-m interval are thought to be due to environmental factors. Some forms disappear whereas others make a first appearance. Clisiophyllid corals and *Crytiopsis* sp. either disappear or become very rare in this interval, for none of them were found. *Tylothyris* sp., *Crytopirifer* sp., caninoid, and neo-zaphrentoid corals all range into this interval, but not past it. All species of *Syringopora* range through and past this interval. The tabulate coral *Michellina* sp. makes a first and last appearance here, as does the brachiopod *Rhipidomella* sp. *Camartoechia* ? sp. makes a first appearance here. These strata failed to yield conodonts in either of two separate series of samplings, and so apparently these strata are barren of conodonts.

Most of the fossils within this interval appear to be stunted or, as in the case of *Syringopora*, show distorted growing patterns. Perhaps the same environmental factor responsible for the stunting of the fossils also caused the appearances and disappearances.

The brachiopod faunas through the end of this last interval, the top of unit 5, were dated as Late Devonian (upper Famennian) by J. T. Dutro, Jr. (personal communication 1979). The top of unit 5 is 34 m above the base of the formation.

The Upper (Kinderhookian) Dolomites
(Units 6 and 7)

Fossil preservation in the upper dolomites is very poor, probably because silicification did not precede dolomitization as it did below these strata. The only megafossils appearing in unit 6 are the three species of *Syringopora*. They are only rarely present and then as poorly preserved specimens.

The first Mississippian conodont fauna was found at the base of unit 6. This fauna includes *Siphonodella cooperi* Hass Morphotype 2, *Pseudopolygnathus marginatus* Branson and Mehl, *Elictognathus laceratus* Branson and Mehl, *Polygnathus longiposticus* Branson and Mehl, *Apatognathus varians* ? Branson and Mehl, *Bispathodus stabilis* Branson and Mehl, and *Hindeodella* sp. The one specimen of *Apatognathus varians* ? present in this fauna appears to have been reworked from earlier strata, for it

shows signs of abrasion, and its known biostratigraphic range does not coincide with the known ranges of other members of this fauna. In North America *Apatognathus varians* is apparently confined to the upper Famennian *Bispathodus costatus* Zone (Klapper 1966). Some specimens of other genera also show abrasion.

The rest of this fauna indicates assignment of a Kinderhookian age to unit 6.

This fauna may be placed in either the Lower *Siphonodella crenulata* Zone, or the lower part of the *Siphonodella isosticha*-Upper *Siphonodella crenulata* Zone as defined by Sandberg, Ziegler and others (1978). Assignment to a zone at least as high as the lower *S. crenulata* Zone is indicated by the presence of *Pseudopolygnathus marginatus*, which appears for the first time in this zone. This and the other members of the fauna found in this horizon may range up into the *S. isosticha*-Upper *S. crenulata* Zone. *Siphonodella cooperi* Morphotype 2 and *P. marginatus* become extinct somewhere within the *S. isosticha*-Upper *S. crenulata* Zone, so the fauna in question cannot belong to a zone higher than this (Sandberg 1979).

Even though this fauna can be assigned to either of the two zones, assignment to the Lower *Siphonodella crenulata* Zone is favored, for the *S. isosticha*-Upper *S. crenulata* Zone is usually "represented by faunas that are dominated by *S. isosticha*, *Gnathodus punctatus*, and *G. delicatus* and that contain few specimens of other species" (Sandberg 1979). On Wanlass Hill not only do these species not dominate, but they are not even present.

The Devonian-Mississippian boundary appears at the boundary between unit 5 and unit 6. Unit 5 contains an upper Famennian brachiopod fauna, and unit 6 contains a middle Kinderhookian conodont fauna of the Lower *Siphonodella crenulata* Zone.

Several conodont zones are unrepresented in the stratigraphic section on Wanlass Hill. They include the upper Famennian Middle and Upper *Bispathodus costatus* Zone, and the lower Kinderhookian *Siphonodella praesulcata* Zone, *S. sulcata* Zone, Lower and Upper *S. duplicata* zones, and the *S. sandbergi* Zone. An unconformity must be present at the Devonian-Mississippian boundary.

With an average figure of .05 million years for the duration of each Late Devonian conodont zone (as determined by Sandberg and Poole 1977), and an average of 1.3 million years for the duration of each Lower Mississippian conodont zone (as proposed by Sando 1977), it follows that the unconformity accounts for a 7.5-million-year gap in the rock record on Wanlass Hill.

The unconformity is easily identified on Greeley Hill even though data from conodonts were not obtained. This location is manifested by the disappearance of preserved Famennian brachiopods and two distinctive marker features present on both Wanlass Hill and Greeley Hill. These features consist of a layer of sand-filled burrows and a distinct layer of abundant, distorted *Syringopora*. Both these layers occur within 3 m of the unconformity, in unit 5.

At the base of unit 6 on Greeley Hill, just above the unconformity, a thin section revealed a birdseye texture, which is indicative only of formation in the highest intertidal or supratidal conditions of subaerial exposure. Subaerial exposure might well occur as transgressive seas reinvaded an emergent area.

This unconformity has been recognized elsewhere, as noted by Newman (1980) and Sandberg and Poole (1977). Sandberg and Poole (1977) discovered an unconformity 32.5 m above the base of the Fitchville in its type section on Fitchville Ridge. It separates the Lower *Bispathodus costatus* Zone from the over-

lying *Siphonodella sulcata* Zone. The strata missing on Wanlass Hill, in the unconformity, account for a greater interval than that lost in Fitchville Ridge. This fact may account for a lot of the disparity in thickness between the two sections. The type section measures 82.4 m on Fitchville Ridge (Morris and Lovering 1961). The measured thickness on Wanlass Hill is 68 m. The difference of 14.4 m is just about the same as the thickness of the strata assigned in the type section to conodont zones missing on Wanlass Hill. They are the *Siphonodella sulcata* Zone through the *S. sandbergi* Zone as delineated by Sandberg and Poole (1977).

Above the lowermost part of unit 6, through the top of the formation, the strata yielded no identifiable conodonts.

Unit 7 contains some fossil evidence, including *Syringopora* colonies which continue from the unit below. They are joined by poorly preserved horn corals and crinoid debris at a stratigraphic level of 48 m above the base of the formation.

The Upper (Kinderhookian) Limestones (Units 8-10)

Unit 8 contains poorly preserved horn corals, possibly caninoid and zaphrentoid, and brachiopods, including a spirifer. A gastropod, *Straparoleus* sp., appears for the first time in the section.

This fauna is quite different from the late Famennian fauna found below the unconformity, but the caninoid and zaphrentoid corals possibly have phyletic affinities with similar forms below the unconformity. After the time of nonmarine, emergent conditions, as indicated by the unconformity, all three species of *Syringopora* followed the shallow-water environment back into the area. The brachiopod fauna returning with this environment had changed. Those found in strata deposited before the unconformity had reached extinction and had been replaced by a later fauna.

It is unfortunate that better preservation of this uppermost Fitchville fauna does not allow more precise comparison with the lower, Devonian, fauna.

Units 9 and 10 were deposited in the highest intertidal or supratidal areas along a coastline. The conditions here restricted megafaunal life, and so no fossils other than algae are found here. Evidence of the algal genus *Sphaerocodium* is thought to be present in the stromatolitic unit 10, the curly limestone, the upper boundary of the Fitchville Formation.

The Lowermost (Osagean) Gardison Limestones (Units 11-14)

Overlying the uppermost supratidal deposits of the Fitchville curly bed are the fossiliferous beds of the Gardison Limestone. Once more a shallow, normal-marine environment proved conducive to inhabitation by a coral-brachiopod fauna.

The organisms following this environment back into the area, after the shallow-water environments present during the last part of Fitchville time, had changed. Forms that evolved later than those below were available to exploit this shallow-marine environment. *Straparoleus* sp. returned, but was accompanied by many new forms not seen below. The high-spined gastropod, *Loxonoma* sp., appears here for the first time. Brachiopods present include *Unispirifer* sp., *Composita* sp. (some possibly being *Composita humilis* Girty), *Chonetes* ? sp., *Spirifer* cf. *S. Louisianensis* Rowley, *Camarotoechia* cf. *C. choutequensis* (Well-er), *Cleiothyridina* ? sp., and *Martinia* ? sp. The rugose coral *Homalophyllites* sp. is quite common, as in Lower Mississippian rocks of the Madison Group (Duncan, in Morris and Lovering

1961). *Springopora* is found only in the very lowermost part of the Gardison Limestone. This is shown by a single specimen of *S. arculeata* just above the curly limestone on Wanlass Hill. Its disappearance coincides with the first appearance of *Aulopora* sp., a tabulate coral.

The corals in the Gardison have been assigned by W. J. Sando to his C₁ coral zone. This coral zonation was formulated from studies of the corals of the Madison Group (Sando and others 1969). The Gardison Limestone is considered to be entirely early Osagean in age. The C₁ coral zone may range from Kinderhookian into the Osagean elsewhere, but the Gardison has yet to yield conodont faunas containing *Siphonodella*. The lack of this Kinderhookian index fossil denotes an Osagean age for the Gardison (Sandberg and Gutschick 1978). A conodont fauna was found at 15 m above the curly-bed boundary. *Polygnathus inornatus*, *P. communis communis*, and *Hindeodella* sp. were found here. None of these are definitive enough to be used in precise zonation.

A Gardison brachiopod assemblage, identified for this study by J. T. Dutro, Jr., was reported by him to be a "typical Early Mississippian one (probably upper Kinderhookian)" (J. T. Dutro, Jr., personal communication 1980). The basal Gardison beds in the area of study could possibly be Kinderhookian.

CONCLUSIONS

All the Fitchville strata studied exhibit characteristics typical of a shallow-water origin. Two sequences of dynamically changing water depths are indicated from the study of thin sections prepared throughout the formation. The first sequence is regressive and represents a shallowing-upward situation which ends in an unconformity. Above the unconformity there are at first deposits that indicate the increasingly deeper waters of a marine transgression, which was rapid and was soon followed by another shallowing-upward, regressive sequence. The oscillations in water depth are thought to be due to orogenic movements related to the Antler orogeny occurring far to the west of the study area.

Both sequences outlined above are topped by supratidal deposits which formed in the shallowest of water depths. Such very shallow conditions were conducive to the formation of magnesium-rich fluids which brought about extensive secondary dolomitization in both sequences.

The presence of an unconformity is indicated by the absence of several conodont zones. The lower sequence appears in strata below the unconformity. They contain a late Famennian fauna including corals, brachiopods, and conodonts. The upper sequence of variable depth, which appears above the unconformity, contains few identifiable fossils, but does contain a Kinderhookian conodont fauna just above the unconformity.

The distribution of the fossils included in Fitchville strata, as shown by the range zones determined in this study, appears to have been controlled by shifting environmental conditions related to water depth. Direct phyletic evolutionary changes cannot be perceived in the fossils found in the section. However, evolutionary changes are implied to have taken place. Faunas migrating with, or following, a particular set of environmental conditions were seen to have changed with time in the sections studied.

APPENDIX A Measured Sections

WANLASS HILL STRATIGRAPHIC SECTION—All measurements are given in meters. Colors listed are from a rock color chart (Goddard and others 1970).

Unit	Description	Thickness of unit	Cumulative Thickness			
Gardison Limestone						
14	Limestone; coarsely crystalline; medium dark gray (N4); weathers medium gray (N5); laminated; upper half-meter fossiliferous, some laminations almost a coquina of brachiopods and <i>Autopora</i> corals	3.5	83	4	Dolomite; fine crystalline; grayish black (N2), weathers light gray (N6.5) or pale yellowish brown (10 YR 6/2); top is sandstone bed which weathers brown, homogeneous for top 10 cm, continues downward in burrowlike bodies up to 30 cm; bedding in approx. 30-cm beds; laminations, cross-stratification in places; dark red particles (10 R 3/4), iron mineral, stain surrounding rock	2.1 26.8
13	Limestone; medium crystalline; medium dark gray (N4.5); finely laminated in upper part; veined with spar; fossiliferous; in trachylasts at 77 m	3.5	79.5	3	Dolomite; medium crystalline; medium gray (N5); weathers pale orange (10 YR 7/2) or light bluish gray (5B 6/1); forms prominent ledgy cliff; common fractures; fossiliferous, especially upper 2 m, brachiopods and corals	4.2 24.7
	Covered interval	3.5	76			
12	Limestone; medium crystalline; dark gray (N3); veined; fossiliferous, corals and crinoid debris; at 71 m. a 10-20 cm zone of abundant rugose coral material in assoc. with chert; lower 40 cm include angular clasts of laminated micrite limestone, averaging 15-20 mm in size	2.5	72.5	2b	Limestone; coarsely crystalline; light gray (N7); light olive gray (5Y 7/1) to yellowish gray (5Y 8/1) weathering; sucroselike weathering surfaces; wavy, mottled, bioturbated ? surfaces	6.5 20.5
11	Limestone; medium crystalline; medium dark gray (N4); upper half lighter, finer crystalline, fine laminated, and cross-bedded; lower part of unit contains corals, brachiopods; upper part barren of life, less resistant to weathering	2	70	2a	Limestone; medium crystalline; medium gray (N4.5); weathers dark gray (N3); in .5-meter steps; wavy, mottled weathering pattern with wispy areas in slight relief; veins of tan to red spar; sand-bearing layer at 6.0 m, with frosted grains in pluglike bodies up to 20 cm long; fossiliferous	13.7 14
				1	Sandstone; fine grained, with coarse grains up to 4 mm; larger grains show frosting; continuous layer of variable thickness overlies plug structures in which sand extends to 20 cm downward into underlying dolomite30 .30

Fitchville Formation

10	Limestone; generally fine crystalline; medium dark gray (N4), weathers to medium gray (N5.5); stromatolitic, contorted laminations, some weather out in relief; some dome structures80	68
9	Limestone; cryptocrystalline; generally light bluish-gray (5B 6/2), tan in places; upper 80 cm contains angular, polygonal fragments up to 15 mm; weathered appearance of exposed bedding surfaces smooth and waxy; red-weathering veins break unit into half-meter beds, veins generally concordant; laminations, rip-up clasts throughout	4.7	67.2
8	Limestone; medium crystalline; dark gray (N2-N3); medium gray weathering at base (N5.5), but (N3) at top; chert interbeds at top, beds up to 50 cm thick (10 YR 7/5) in color; prominent laminations from 59 m, cross-stratified; fossils at top	5.5	62.5
7	Dolomite; coarsely crystalline; medium gray (N4); weathers medium light gray (N6); laminated, cross-bedded; especially fine laminations at 50 m; crinoid debris common; horn corals at 48 m, otherwise unfossiliferous; weathered surfaces sucroselike; many spar-filled vugs	10	57
6	Dolomite; fine crystalline; medium dark gray (N4.5); weathers (N4); shaly, brittle, tendency to break into tabular pieces; sucroselike weathering surfaces ..	13	47
5	Dolomite; fine crystalline; dark gray (N3); weathers medium gray (N5); finely laminated in places; all but last meter contains hematite or similar mineral in ricelike grains, reddish cast; crinoids, brachiopods, and corals; at 31.3 m distinctive layer of sand-filled burrows, with distinctive layer of distorted <i>Syringopora</i> just below	7.2	34

GREELEY HILL STRATIGRAPHIC SECTION—All figures for thickness are in meters. Colors listed are from a rock color chart (Goddard and others 1970).

Unit	Description	Thickness of unit	Cumulative Thickness
Gardison Limestone			
11	Limestone; medium crystalline; dark gray (N3); massive; angular clasts, up to 4 mm, in lowest part; corals and brachiopods	3	70
Fitchville Formation			
10	Limestone; fine crystalline; medium dark gray (N4); weathers medium gray (N5); wavy, contorted laminations; grades imperceptibly into units above and below50	67
9	Limestone; cryptocrystalline; medium gray (N5.5); weathers light bluish gray (N6.5); conchoidal fracturing; top few centimeters contain angular intraclastic fragments	3	66.5
8	Limestone; fine to medium crystalline; dark gray (N4); weathers same color; chert interbedded with limestone at 63.0 m; chert 20-30 cm in average thickness; veined with white spar10	63.5
7	Dolomite; medium to coarse crystalline; medium gray (N5); laminated, cross-bedding; sucroselike weathering surfaces	5.5	53.5
6	Dolomite; fine crystalline; dark gray (N4); chert nodules in definite horizons from 43 m to 45 m, up to 10 cm thick, 40 cm long; chert nodules oriented lengthwise to bedding	16	48

5	Dolomite; fine crystalline; dark gray (N4); at 29.0 m fine quartz sand grains in burrows; distinctive layer of distorted <i>Syringopora</i> corals just below burrows; some small brachiopods and horn corals; dark red-brown (10 R 3/4) particles of hematite or similar mineral stain surrounding rock	6.7	32
4	Dolomite; fine crystalline; dark gray (N4); weathers light gray (N6.5); red particles, as above; top of unit brown-weathering sandstone up to 30 cm thick	1.8	25.3
3	Dolomite; fine to coarse crystalline; light gray (N7); weathers (N8); in half-meter ledges; at 23-23.5 m zone of very abundant crinoidal debris; fossiliferous, especially last 1.5 m	10	23.5
2a	Limestone; medium crystalline; dark gray (N4); weathers dark gray (N4); in 30-50 cm steps; veined with white or reddish spar; quartz sand-bearing layer at 4.5 m, clasts contained in burrowlike structures up to 20 cm deep; wavy, mottled areas on weathered surfaces	13.2	13.5
1	Sandstone; fine-grained; brown weathering; some quartz grains up to 5 mm; top 10 cm homogeneous; below to a depth of about 20 cm into underlying dolomite, grains present in burrowlike structures	30	30

APPENDIX B

Thin Section Descriptions

WANLASS HILL THIN SECTION DESCRIPTIONS—Stratigraphic positions are listed in meters above the base of the Fitchville Formation.

WH-1 0	<i>Fine calcareous quartz sandstone</i> ; size of quartz clasts is bi-modal, 90% are sub-angular to sub-rounded grains approx. 0.1 mm in size, and 10% are sub-rounded grains averaging 1-1.5 mm in size, ranging up to 3 mm. Quartz grains occupy 65-75% of total slide area, with remaining portion consisting of a matrix of fine crystalline dolomite. Matrix is free of clasts in places, with sharply defined boundary between clastic and nonclastic areas. An iron mineral, which stains surrounding matrix, is common in sand-bearing areas. Quartz grains are mud-supported within matrix, for few grain-to-grain contacts are present. Most quartz grains show strained extinction under polarized light. Some places contain only clasts of the smaller size range; sorting is good in these areas. Elsewhere sorting is only fair.	WH-5 11	<i>Coarsely crystalline recrystallized limestone</i> ; slide is a mosaic of interlocking crystals ranging up to 2 mm in size, but averaging 1 mm. Some finer crystalline spar is present in fractures.
WH-2 6	<i>Biomicroparite</i> ; slide area is approx. 30% bioclastic grains, mostly crinoidal. They are poorly sorted as to shape or size, but there is some possible parallelism to bedding directions. Surrounding matrix is microspar and shows a mud-supported relationship to grains. About 90% of the bioclasts are approx. 0.25 mm, and the remaining 10% range up to 1 mm. In places up to 10% of the slide is sub-rounded quartz ranging up to 1 mm. Some poorly sorted sands appear to be current oriented. Quartz grains exhibit strained extinction.	WH-6 14	<i>Intraclastic biomicroparite</i> ; approx. 10% of slide area consists of bioclastic grains, mainly crinoidal fragments. Sorting appears poor, with mud-supported fabric. Boundaries of grains are indistinct because of diagenesis. Intraclasts have ragged edges and range from 0.25 mm to 1 mm. A stylolite filled with a finely divided iron mineral is present. In places it cuts across crystal boundaries.
WH-3 6	<i>Biomicroparite</i> ; approx. 25% of the slide contains bioclastic grains with a mean size of 0.5 mm, ranging up to 4 mm. The remaining 75% is microspar matrix, which surrounds the bioclasts in a mud-supported relationship. Outlines of bioclasts are indistinct from recrystallization. A sharply bounded area contains 20-60% quartz grains about equally sub-angular or sub-rounded. About 90% are 0.1 mm, and about 10% are 0.5-1 mm. Sorting is fairly good, with few grain-to-grain contacts. Quartz grains exhibit strained extinction. The spar in quartz grain areas is slightly greater in crystal size than in other areas.	WH-7 17	<i>Coarsely crystalline recrystallized limestone</i> ; Size of crystals is 0.5 mm to 1 mm. No sharp boundaries, but some relic structure suggests a pelletal nature in the original sediments.
WH-4 8	<i>Biomicroparite</i> ; approx. 20% of the total slide area is comprised of bioclasts, mainly crinoidal in nature. The mean size is about 0.75 mm. The remaining 80% is microspar. Bioclasts appear to have originally been mud-supported. Very little primary structure remains because of extensive recrystallization. Some relic bioclasts are up to 2 mm.	WH-8 23	<i>Medium crystalline dolomite</i> ; a mosaic of interlocking crystals averaging 0.1 mm, with some smaller crystals, 0.05 mm. Some stylolites separate areas of different crystal sizes. Small areas of silica crystals are rare, but present. A brownish iron mineral is present in some stylolites. An overall brownish color is indicative of widespread dolomitization.
		WH-9 26.5	<i>Finely crystalline dolomite</i> ; average crystal size is 0.02 mm, with a few patchy areas of coarser crystals. Slide is an overall uniform mosaic. Some opaque iron mineral grains are possibly pyritic.
		WH-10 26.8	<i>Very fine calcareous quartz sandstone</i> ; an average of 50% of the slide is subangular to rounded quartz grains, very well sorted, approx. 0.1 mm in size. In some places they are packed into close grain-to-grain contact but in most areas are interspersed in a very finely crystalline dolomite matrix and show a mud-supported relationship. Staining by a brownish iron mineral is common. Strained extinction is seen in most quartz grains.
		WH-11 31.3	<i>Very finely crystalline dolomite</i> ; this must have been a pure micritic mud originally. Some areas of the slide are lighter in reflected light because of the inclusion of fairly well-sorted, sub-angular to subrounded quartz grains about 0.025 mm. The grains occupy up to 30% of these areas and were originally mud supported. Extinction of the grains is strained. An iron stain follows the boundaries of clast-bearing areas. Some opaque mineral grains are found with the quartz.
		WH-12 33.5	<i>Finely crystalline dolomite</i> ; a fine mosaic of crystals averaging 0.03 mm to 0.05 mm. Some splorchy areas of coarser crystals are present. Some veins, about 0.5 mm across, are filled with spar.
		WH-13 41	<i>Finely crystalline dolomite</i> ; a fine mosaic of crystals averaging about 0.05 mm. Some areas of medium-sized crystals show a circular arrangement of about 1-1.5 mm diameter, might be crinoid sections. Many veins are filled with coarser spar. Stylolites separating areas of different crystal size contain an iron mineral.
		WH-14 53	<i>Coarsely crystalline dolomite</i> ; a mosaic of 0.25 mm to 0.5 mm crystals. Complete recrystallization has taken place. An occasional pore is filled with fine spar.
		WH-15 60.7	<i>Peltparite</i> ; approx. 70% of the slide area is made up of well-rounded pellets 0.25 to 0.5 mm across, in places in a grain-supported arrangement with the coarse spar cement. Sorting is good as to their size and shape. A sparite overgrowth is present on some pellets, and some are altered so as to be indistinguishable from the sparry cement. Twinning laminae of the cement go right through the pellets indicating more than just syntaxial overgrowth. Some intraclasts and bioclasts are present.
		WH-16 62.5	<i>Chert in microparite</i> ; fine crystalline quartz in a graphic texture with microsparite carbonate areas.
		WH-17 65	<i>Micrite</i> ; uniform cryptocrystalline micrite, veined with very linear, very thin, veins of microspar. Two sets of veins, about 0.25 mm wide, occur at about 30° to each other.
		WH-18 67	<i>Pelletal intrasparudite</i> ; rip-up clasts constitute 70% of the slide area, are approx. 1.5 mm in average size. Pellets make up approx. 25% of the slide area. A grain-supported fabric indicates that the spar cement is probably primary. Iron mineral matter outlines the clasts, one of which is 15 mm in size. Some linear veins of spar and a birdseye fabric are present. Clasts are not well sorted, have ragged edges. Signs of bioturbation are present. Stylolites around rip-up clasts must have formed very soon after deposition and before burial.

WH-19 67.5	<i>Algal biolithite</i> ; alternating structure containing two types of laminations; (1) approx. 0.05 mm pellets in a spar cement, averaging 4–5 mm in thickness, occupying about 70% of the slide area; (2) micritic laminations 1–2 mm in thickness. Planar birdseye structures parallel these laminations. Pellets are well sorted as to shape and size. Some micro-faulting occurs in micritic laminations, with displacements up to 0.2 mm, not continuous into the next lamination. Faulting must have occurred before overlying laminations were added, most likely because of desiccation.	GH-10 24	<i>Very finely crystalline dolomite</i> ; average size of crystals is 0.01 mm, but an area near a fracture is coarser grained. A gradational size decrease occurs away from the fracture. Iron stain is common.
WH-20 71	<i>Intrasparite</i> ; approx. 30% of the slide area consists of angular rip-up clasts up to 1 mm, in a spar cement with some bioclasts. The fabric is disordered, sorting is poor, and birdseye structures are present.	GH-11 25	<i>Medium calcareous sandstone</i> ; 60% of the slide area is well-sorted, subangular to sub-rounded quartz sand clasts, approx. 0.1 mm, that show strained extinction. The matrix is dolomitic microspar in which the grains are interspersed in a mud-supported arrangement. Much brown iron material is dispersed in the matrix. Stylolites are present.
WH-21 79.5	<i>Biopelsparite</i> ; a laminated structure consisting of two types of laminations: one consists of bioclasts (60%), crinoidal and others, in a spar cement. The fabric is at least in part grain-supported. Most bioclasts are 0.1–0.5 mm in size and are not well sorted. Alternating laminations are fine, about 0.1 mm, well-sorted pellets within a spar cement. Pellet-to-pellet contacts are rare.	GH-12 29	<i>Very finely crystalline dolomite</i> ; essentially dolomitic microspar, but some areas are coarser, up to 0.2 mm. Siliceous grains make up 2% of the slide and are approx. 0.05 mm. Stylolites follow crystal boundaries.
WH-22 83	<i>Biopelsparite</i> ; pellets, 0.1 mm to 0.2 mm, and bioclasts, averaging 0.5 mm, occupy 40% of the slide. Spar cement is recrystallized, a mud-supported arrangement was originally present. Angular to rounded crinoid debris is common. Sorting is poor with no visible preferred orientations as to shape.	GH-13 29.3	<i>Very finely crystalline dolomite</i> ; a dolomitic microspar, which contains a few areas of subrounded and fairly well-sorted quartz grains, approx. 0.1 mm. They show strained extinction. The grains form a mud-supported fabric with the matrix. An iron mineral commonly stains the slide. Stylolites are present.
GREELEY HILL THIN SECTION DESCRIPTIONS—Stratigraphic positions are listed in meters above the base of the Fitchville Formation.			
GH-1 0	<i>Fine calcareous quartz sandstone</i> ; a majority of the quartz clasts are approx. .25 mm and make up 40% of the slide area. Clasts of about 0.75–2 mm constitute about 10% of the slide. Remaining area is microspar matrix stained brown by an oxidized iron mineral. The clasts are subangular to subrounded. Sorting is poor in a mud-supported fabric. Some grains show preferred shape orientation, and most show strained extinction.	GH-14 32	<i>Very finely crystalline dolomite</i> ; a dolomitic microsparite, with a few coarser areas 0.1–0.2 mm. A birdseye texture is present, with planar structures up to 2 mm in width. Some circular structures are filled with coarser spar.
GH-2 3	<i>Biomicrosparite</i> ; bioclasts are only ghost structures, as the slide is almost completely recrystallized to microsparite. Bioclasts are almost in optical continuity with the matrix. Crinoids are recognizable, up to 1 mm.	GH-15 36	<i>Finely crystalline dolomite</i> ; crystal size is 0.05–0.5 mm and varies from one area to another. Some rare crystals are up to 1 mm.
GH-3 4.5	<i>Biomicrosparite</i> ; bioclasts, predominantly crinoidal, in a matrix of microspar. Mud-supported bioclasts, 1–1.5 mm, make up 50% of the slide area. Stylolites generally form around the borders of bioclasts. A fairly sharp boundary separates an area containing well-sorted quartz clasts approx. 0.1 mm. These grains are subangular to subrounded, and constitute about 50% of the areas in which they are found. The quartz clasts are in a mud-supported relationship within the microspar, as they are dispersed through it. Most grains exhibit strained extinction.	GH-16 39	<i>Finely crystalline dolomite</i> ; generally crystal size is 0.05 mm or less, but some rare crystals are up to 2 mm. Stylolites separate areas of different crystal size. Some stylolites cut across crystals or other stylolites.
GH-4 7.5	<i>Packed biomicrosparite</i> ; bioclasts are mainly crinoidal; sorting to size or shape is poor. Stylolites sometimes cut through bioclast grains. Some multiple, horse-tail stylolites are present.	GH-17 45	<i>Interbedded chert and very fine crystalline dolomite</i> ; chert is extensively fractured with most of the fractures continuing into the surrounding dolomitic microspar. Some coarser spar occurs in porelike structures.
GH-5 10.5	<i>Packed biomicrosparite</i> ; bioclasts are recrystallized, in optical continuity with the microspar matrix. Some spots have recrystallized to coarser spar. Stylolites are common, some cutting across bioclasts, others following bioclast boundaries.	GH-18 48	<i>Medium crystalline dolomite</i> ; a uniform mosaic of interlocking crystals approx. 0.2 mm across. Structure had some porous areas, now infilled with spar. Laminations are visible megascopically.
GH-6 13.5	<i>Finely crystalline dolomite</i> ; a mosaic of interlocking crystals, approx. 0.05 mm. Some roughly circular areas show coarser crystallization.	GH-19 53	<i>Coarsely crystalline dolomite</i> ; a very coarse mosaic of interlocking crystals which average 1 mm in size. Originally appears to have been porous, voids now filled with spar. One iron-mineral-filled stylolite zig-zags around crystal boundaries.
GH-7 16.5	<i>Coarsely crystalline dolomite</i> ; a mosaic of interlocking crystals approx. 0.35 mm in size. Some splotchy areas show coarser crystals up to 1 mm in size.	GH-20 56	<i>Pelsparite</i> ; pelloids of approx. 0.5 mm size are in grain-supported fabric surrounded by spar cement. A crinoidal bioclast or two are present. Some flattened pelloids appear possibly current oriented.
GH-8 19.5	<i>Coarsely crystalline dolomite</i> ; a mosaic of interlocking crystals in a size range from 0.25–0.5 mm. A few areas show larger, twinned, more euhedral crystals. In association with the larger crystals are some siliceous areas, up to 1 mm, which show a fine intergrowth of crystals. Oxidized iron-mineral particles, up to 1 mm, are present. Many fine stylolites follow around grain boundaries, a few cut through grains.	GH-21 60	<i>Micrite</i> ; generally a homogeneous micrite. Many round and planar birdseye structures are present.
GH-9 23.5	<i>Medium crystalline dolomite</i> ; a mosaic of interlocking crystals (av. 0.2 mm), with some areas more coarsely crystalline than others. Coarser areas are 0.5–1 mm. Some silica crystals.	GH-22 63	<i>Microcrystalline quartz</i> ; most likely chalcedony which has recrystallized from opaline chert. Microspar is now present in many fractures.
		GH-23 64	<i>Micrite</i> ; almost totally micrite, with only a few irregular spots or veins of coarser spar.
		GH-24 66.8	<i>Micrite</i> ; stylolites are filled with an iron mineral. In some places calcispheres are present.
		GH-25 67	<i>Algal biolithite</i> ; a laminated structure composed of two alternating types of laminations. One type is micritic, and the other is pelletal. In one micritic lamination are visible some sections through algal structures with a beaded aspect similar to the algal genus <i>Sphaerocodium</i> . In alternate laminations pelloids of about 0.75 mm size occur in a sparry matrix.
		GH-26 68	<i>Intrasparite</i> ; intraclasts are unsorted and range up to 4 mm. A couple of microcrystalline quartz grains are present. Two sections through brachiopod shells are visible within the slide area. A birdseye fabric is present.

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