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PROTEROZOIC TO RECENT STRATIGRAPHY, TECTONICS, AND VOLCANOLOGY, UTAH, NEVADA, SOUTHERN IDAHO AND CENTRAL MEXICO

Edited by

Paul Karl Link and Bart J. Kowallis

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Editor

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Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.

Middle: Lake Bonneville shorelines west of Brigham City, Utah.

Bottom: Bryce Canyon National Park, Utah.

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Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

Sequence stratigraphy and paleoecology of the Middle Cambrian Spence Shale in northern Utah and southern Idaho

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ABSTRACT

Middle Cambrian rocks of the Great Basin have long been known for their rich and diverse fossil content. Skeletonized fossils include trilobites, eocrinoids, hyolithids and brachiopods (both articulate and inarticulate). Like the celebrated Burgess Shale, units such as the Spence Shale Member of the Langston Formation also contain soft-bodied annelids, arthropods, sponges, algae and other taxa.

The Spence Shale was deposited on a passive-margin ramp and is characterized by numerous, meter-scale, shallowing-upward sedimentary cycles or parasequences which can be grouped into systems tracts of a larger (lower-order) eustatic cycle. The occurrence and preservation of Spence Shale fossils reflects, among other factors, variation in sedimentation rates which is related to position within a cycle. For example, basal portions of lower (transgressive systems tract) parasequences often contain dense lag concentrations of poorly-preserved fossils which were deposited under conditions of sediment starvation associated with transgression. Thus, trilobite and other fossil assemblages are located in stratigraphic positions within the Spence Shale that can be predicted on the basis of sequence architecture. Recognition of higher-order cycles on the basis of paleontologic and sedimentologic criteria enables high-resolution (< .1–.5 Ma) correlation, thus contributing to both paleoenvironmental and ecological interpretations within the Spence Shale.

INTRODUCTION

In recent years, considerable attention has been focused on the lithologic expression of eustatic cycles. Far less attention has been directed to the taphonomic and biotic responses to such cycles. Although papers by Kidwell (1986a,b, 1989, 1991a,b) on the Miocene of Maryland and by Brett and Baird (1985, 1986, 1996), Brett (1995) and Batt (1996) on the Devonian of New York are notable exceptions to this generalization.

The field trip will examine the sedimentologic, faunal and taphonomic responses to higher-order eustatic oscillations expressed in Middle Cambrian rocks of the eastern Great Basin with emphasis upon the Spence Shale Member of the Langston Formation. These rocks are noted for their excellent exposures, stratigraphic completeness and exceptional trilobite faunas. In addition, work by Palmer (1960, 1971, 1974), Robison (1960, 1964a,b, 1976, 1991) and others has greatly refined the biostratigraphic and sedimentologic framework in which to examine the cycle stratigraphy.

SEQUENCE STRATIGRAPHY

General Concepts

The fundamental concepts of sequence stratigraphy have been described in a number of works (Vail and others, 1977, 1991; Loutit and others, 1988; Van Wagoner and others, 1988; Einsele and others, 1991; Haq, 1991; Emery and Myers, 1996). Vail and others (1977) outlined the orders of sedimentary cycles followed here. Sarg (1988) applied concepts originally developed for terrigenous systems to carbonate systems. Read and others (1986) modeled the effects of magnitude and rate of eustatic oscillation, lag time, subsidence rate, tidal range and sedimentation rate on resultant rock packages.

Unconformity-bounded depositional sequences are the fundamental units of sequence stratigraphy. Sequences can be subdivided into parasequences, which are higher-order, shallowing-upward packages bounded by marine flooding surfaces. Following the usage of Montañez and

Osleger (1993), we will use the terms cycle and parasequence interchangeably within this paper to denote meter-scale cyclic packages.

Parasequences can be grouped into systems tracts (e.g. transgressive, highstand and lowstand systems tracts). Lowstand systems tracts (LST) are typically represented only by unconformities in shallow shelf areas and by thick turbidite fans in deeper water. Transgressive systems tracts (TST) are relatively condensed packages commonly represented by retrogradational, carbonate-dominated parasequences. Highstand systems tracts (HST) are demarcated from TST by sharp discontinuities or surfaces of maximum sediment starvation, which occur within highly-condensed facies. In general, highstands commence with condensed deep-water deposits and display aggradational to progradational parasequence sets (i.e. they commonly show an overall upward shallowing trend).

Systems tracts and their component parasequences are recognizable due to the sedimentologic effects of base level rise, which include sediment starvation as siliciclastics are impounded on the inner shelf and carbonate "shut-down" due to increased turbidity and enhanced nutrients (Hallock and Schlager, 1986). The lithologic expressions of sequences and their component parasequences and systems tracts reflect interactions between eustasy (both rate and magnitude of change), tectonic subsidence and sedimentation rate.

Cambrian Strata in the Western U.S.

Sequence stratigraphic concepts have been applied to Cambrian ramp and platform rocks in the western U.S. by a number of authors. Lohmann (1976) was among the first to note cyclic deposition in Cambrian strata of the Great Basin and to correlate cycles with sea-level oscillations. Bond and others (1988, 1989) modeled rates of subsidence and eustatic rise for third-order packages in Middle to Upper Cambrian rocks in the Canadian Rockies and Great Basin. Osleger and Read (1991, 1993) compared Late Cambrian, cyclic packages from a number of North American localities. Montañez and Osleger (1993) documented the expression of higher-order oscillations in platform and shelf environments in Middle to Upper Cambrian rocks of Nevada.

Middle Cambrian units in northern Utah and southern Idaho exhibit several orders of sedimentary cyclicity. At the largest scale, they are all included within the Cambrian Sauk Sequence or Supersequence (Sloss, 1963). The Cambrian strata also exhibit third-order "grand cycles" (Aitken, 1966), consisting of formation-scale shallowing-upwards sequences which are broadly correlative across the western Cordillera and assumed to represent 1–10 my duration (Bond and others, 1989; Osleger and Read, 1993). In addition, smaller-scale, fourth-order, sequence-like divisions, which are thought to span some 100–500 ky duration are present. Finally, the effects of relatively short-term events are also displayed in numerous meter-scale, shallowing-upwards packages or parasequences, which are considered to represent fifth-order cycles (10–100 ky duration; Algeo and Wilkinson, 1988; Osleger and Read, 1991, 1993).

These higher-order cycles can be traced for over 100 km in the study area. Whether or not these short-term cycles reflect autocyclic control (e.g., Ginsburg, 1971; Wilkinson, 1982; Cloyd and others, 1990; Hardie and others, 1991) or allocyclic (orbitally forced?) control is beyond the scope of this study. However, the ability to correlate such cycles over relatively great distances argues against local autocyclic control (Osleger and Read, 1991, 1993).

Eustatic Oscillations and Shell Beds

Eustatic oscillations profoundly influence the nature of the rock record. Such fluctuations in sea-level also exert a control on the nature of fossil assemblages, particularly their preservation. Kidwell (1986a,b, 1989, 1991a,b) was among the first to make this connection and placed Miocene shell beds from the eastern U.S. into a sequence stratigraphic framework. She argued that shell beds in passive continental margins may be generated by a variety of mechanisms, with sediment input being the dominant factor.

Banerjee and Kidwell (1991) examined Cretaceous molluscan assemblages from western Canada. They recognized two distinctive positions of frequent shell bed development, termed base of parasequence (BOP) and top of parasequence (TOP) beds; such skeletal accumulations resulted from sediment starvation and dynamic bypass, respectively.

In a study of Devonian rocks from New York, Brett and Baird (1985) cautioned that shell concentrations may be formed by current-winnowing associated with shallowing as well as by transgression-induced sediment starvation. Brett and Baird (1993) discussed taphonomic evidence for condensation in a sequence stratigraphic framework with examples from Silurian and Devonian rocks in New York.

A Eustatic-Taphonomic Model

In order to provide a heuristic framework for this work we have taken Kidwell's (1986a) R-Sediment Model and incorporated it into a sequence stratigraphic approach. Kidwell recognized four general types of shell beds that formed in response to changes in sedimentation rate. The four shell-bed types were classified by whether they formed in response to increases or decreases in sedimentation and the nature of the surface (omission or erosion) occurring immediately above or below the shell bed. Of particular interest to this field trip are the Type I and Type III beds, which are associated with zero sedimentation (omission surfaces).

In a sequence framework one might expect to find Type III shell beds occurring at the bases of parasequences (BOP shell beds), where sedimentation slowdown occurred as a result of terrigenous sediment impoundment on the craton or due to carbonate factory shutdown during initial flooding (Fig. 1). Sepkoski and others (1991) noted a similar increase in bioturbation intensity in sediments deposited immediately after transgressions and associated with basal positions in Cambro-Ordovician sedimentary cycles. These deposits would be most commonly associated with the transgressive systems tract (TST) or early highstand systems tract (HST).

Furthermore, one might anticipate more substantial accumulations of degraded skeletal debris and spicules (Fig. 2) to occur in association with the most highly-condensed intervals of the third-order sequence as a result of thinning and stacking of component parasequences. Thus, BOP shell beds should become successively more enriched with hiatal lag debris toward the tops of the TST (i.e. in those parasequences just below the surface of maximum flooding).

Within a parasequence, densities of skeletons typically decline upwards as sedimentation rates increase. However, the proportion of well-preserved fossils should increase (Fig. 3). In the overall sequence, this type of preservation would be most commonly associated with the mid to late HST.

Finally, one might expect to find Type I shell beds associated with sediment winnowing or bypass occurring at the tops of parasequences as the rate of sea-level rise drops or progradation results in a shallowing to above fair-weather wave base (TOP shell beds). In a hierarchical sense, one would predict that the TOP shell beds of individual parasequences would become more pronounced in the late HST of the sequence.

A variety of factors, such as the nature of the sea-level event (rate and magnitude), subsidence rate, sedimentation rate and ramp position (proximal or distal) will strongly influence sequence architecture (Read and others, 1986). Based on the above general model, the following predictions can be made about the lithologic and taphonomic characteristics of the resulting parasequence packages:

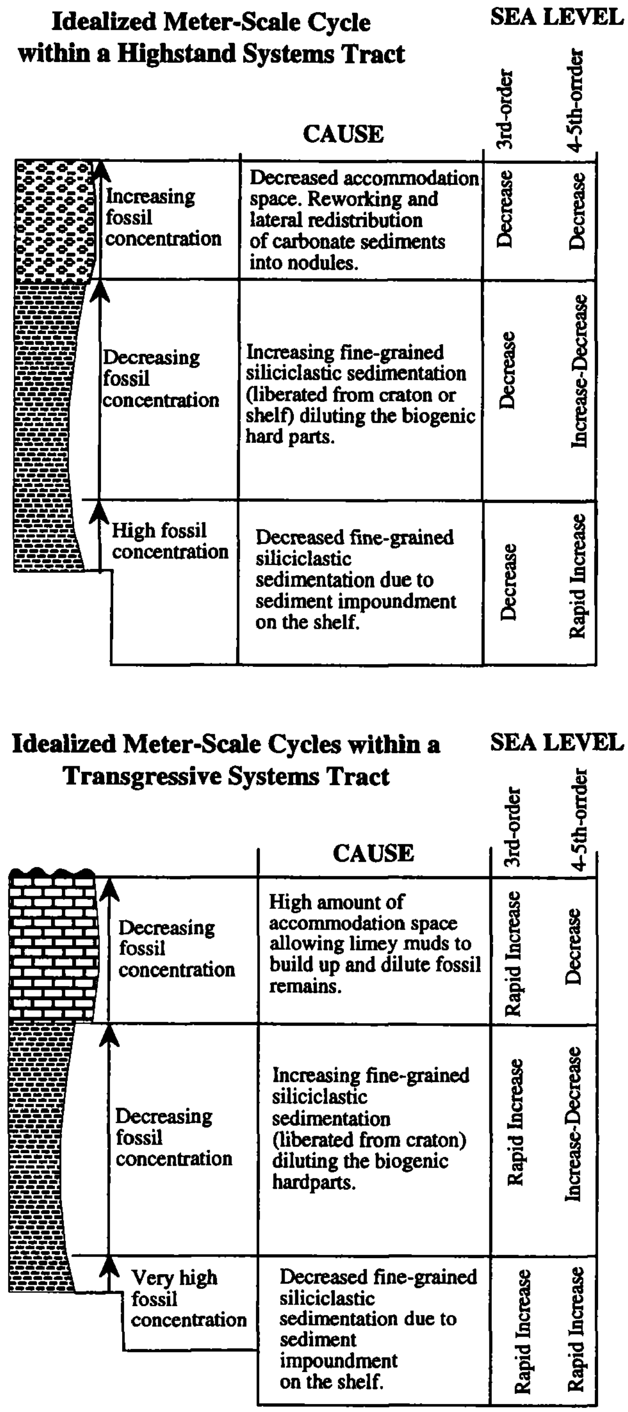


Figure 1. Eustatic-taphonomic model for Spence Shale parasequences. Key to symbols same as in Figure 7.

Predicted Sedimentologic Characteristics of Cambrian Parasequences.

1. Abrupt basal contacts;
2. Large facies shifts at base;
3. Highly condensed (time-rich) sections at base with common hardgrounds;
4. Grain size or carbonate content increases up section;
5. Expanded upper sections (time-poor), although current winnowing may occur at tops of HST parasequences;
6. Gradational internal contacts.

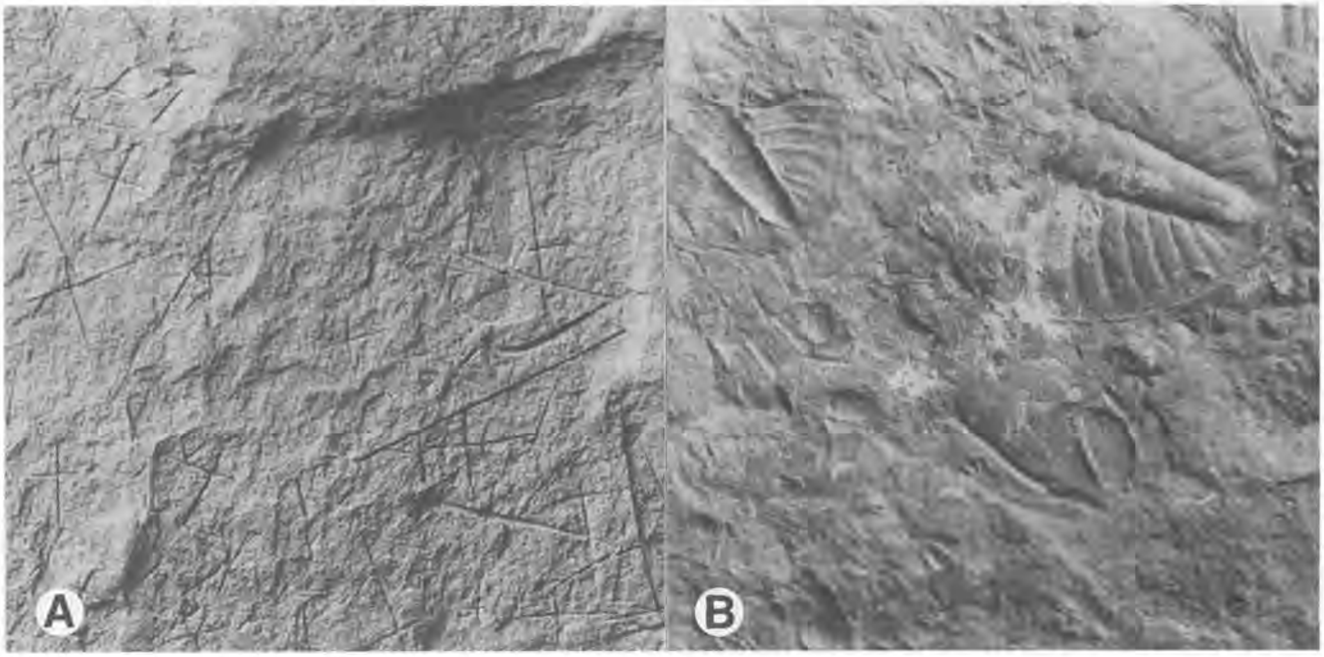


Figure 2. A. Sponge spicule accumulation occurring in BOP (base of parasequence) position at the deepest site, Cycle Two, Oneida Narrows (x 2.3). B. Dense accumulation of trilobite debris (cranidia and pygidia) occurring in BOP position, Cycle One, Miners Hollow (x 1.9).

Note that points 1–3 above and below are most applicable to transgressive systems tract parasequences.

Predicted Taphonomic Characteristics of Cambrian Parasequences.

1. Density of skeletal elements is highest in condensed beds associated with flooding surfaces at bases of cycles (BOP shell beds);
2. Quality of preservation is lowest in condensed beds at bases of cycles;
3. Frequency of intact specimens increases up-section in cycles;
4. Planktonic, deep-water elements dominate in lower to mid portions of cycles;
5. Turbulence and winnowing may affect fossil preservation and result in skeletal concentrations in upper portions of cycles (TOP shell beds).

TAPHONOMY

Trilobites

As trilobites are one of the most common fossil elements in the Spence Shale, it is worthwhile to examine their taphonomic characteristics. The trilobite exoskeleton was composed of numerous articulating elements (sclerites), which were molted periodically to accommodate changes in size and shape of the organism. They also accumulated as carcasses and disarticulated elements at the time of death (Fig. 2A). Trilobites, unlike many modern arthropods (e.g. crustaceans), apparently did not resorb the mineralized matrix of their cuticle prior to ecdysis (Miller and Clarkson, 1980; Speyer, 1985). Hence, trilobite exuviae were as readily preserved as carcasses. The fact that trilobites molted poses problems in evaluating the taphonomy of their fossil assemblages. Trilobite Lagerstätten that have not been redistributed by currents are actually a composite of the life history, recorded by molts, and the death history, represented by mortal remains, of trilobite individuals.

The possession of multielement skeletons predisposes trilobite remains to taphonomic alteration. Biological phenomena influence the source of potentially-preservable remains, sedimentological agents may disarticulate and reorient remains (biostratinomy) and chemical processes (fossil diagenesis) may enhance or impede fossil preservation (Speyer, 1987, 1991).

That trilobite sclerites are easily transported has been noted (Taylor, 1976; Westrop, 1989; Robison, 1991). Recognizing the potential for selective sorting of skeletal elements during transport, Hesselbo (1987) performed hydrodynamic experiments on models of trilobite sclerites. His findings reinforced the belief that sclerites are easily transported and indicated that cranidia and pygidia indeed behaved differently during transport. Such sorting of cranidia from pygidia is commonly observed in Spence Shale trilobite assemblages.

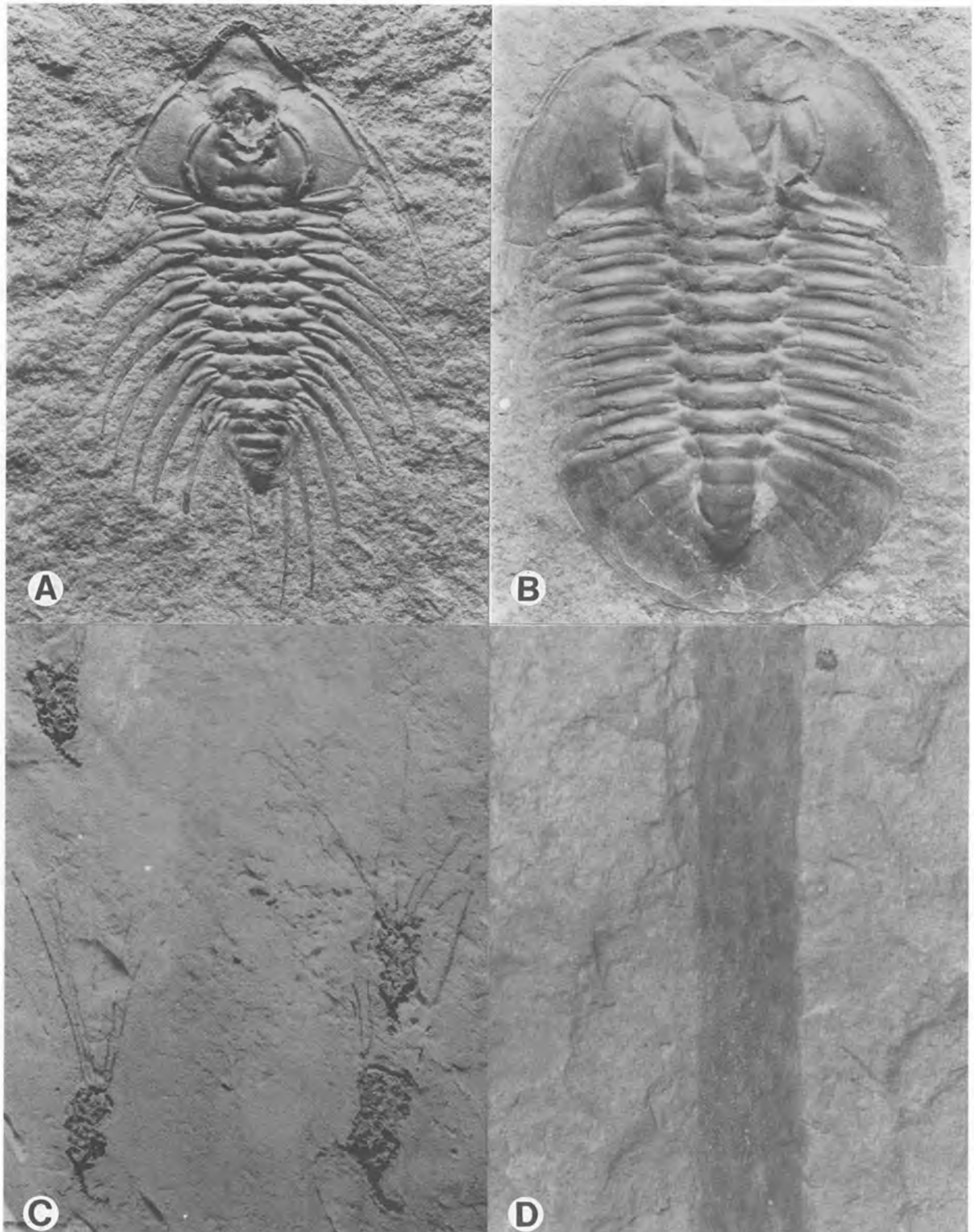


Figure 3. Well-preserved fossils from the Spence Shale. A. Polymeroid trilobite Zacanthoides grabaui, *Antimony Canyon (x 1.9). B. Trilobite* Athabaskia wasatchensis, *Antimony Canyon (x 3.5). C. Assemblage of eocrinoid* Gogia palmeri, *portion of a slab containing five individuals, all with same orientation, Immigration Canyon, Idaho (x 1.0). D. Algae, such as* Margaretia dorus, *are often preserved in deepest portions of sequence, Cataract Canyon (x 1.7). Photographs "A–C" courtesy of the Gunther family, specimen shown in "D" provided by Paul Jamison.*

Other Taxa

In addition to agnostoid and polymeroid trilobites, several other fossil groups are potentially valuable taphonomic indicators in Middle Cambrian strata. Hexactinellid sponges were evidently abundant in certain environments. These organisms may have been even more delicate than trilobites, and the rare occurrences of intact specimens (Rigby, 1980; Gunther and Gunther, 1981) indicate episodic and near-instantaneous burial. Conversely, the disarticulated megascleres of these sponges were evidently relatively insoluble under certain Cambrian geochemical conditions. In some horizons these spicules have accumulated to form lag-like concentrations (Fig. 2B). Recent work suggests that such spicule-rich siliceous limestones may provide a very useful indicator of sediment-starved condensed intervals. Concentration indices and thicknesses of spicular beds may provide a clue to relative durations of condensed intervals.

Inarticulate and orthoid brachiopods are present in some abundance at certain levels. Because the lingulides were phosphatic, they may persist through longer intervals of time-averaging. Condition of valves may provide a usable taphonomic index.

Cambrian echinoderms, dominated by weakly-articulated, multielement skeletons, are even more sensitive indices of event burial than are trilobites. The eocrinoid *Gogia* (Fig. 3C) displays a distinctive facies-related pattern of occurrence. Some bedding planes are crowded with articulated individuals, especially on undersurfaces of calcisiltites. These occurrences offer proof of the episodic accumulation of the containing beds. Additionally, disarticulated ossicles commonly have been overlooked, but actually are common in some facies. Their relative frequency may provide another condensation or time-averaging index.

Certain facies contain an abundance of carbonaceous remains of algae (Fig. 3D). These fossils are typical only of laminated, dark-gray to black shale facies, but their occurrence has yet to be quantified. A more complete understanding of the distribution of these and other soft-bodied remains may lead both to better understanding of sediment dynamics and, also, to a predictive model for the location of additional Konservat-Lagerstätten deposits.

It should also be noted that a variety of trace fossils and ichnofabrics are found within the Middle Cambrian rocks. Distribution of these traces may provide extremely useful information both on the level of oxygenation and, if normal levels of oxygenation can be inferred on the basis of body fossils, on the degree of time-richness in rocks. Traces will accumulate in sediment, as do skeletal remains, if sedimentation rates are low (e.g., at flooding surfaces; Sepkoski and others, 1991; Savrda and Bottjer, 1994).

Comparative Taphonomy and Taphofacies Models

Brett and Baird (1986) formalized the concept of comparative taphonomy, the study of differential fossil preservation, thus defining a research approach that differentiates between fossil assemblages on the basis of taphonomic criteria. The advantage of applying comparative taphonomy to facies analysis lies in the number of potential permutations afforded by any given faunal assemblage.

Speyer and Brett (1986) introduced the term "taphofacies" to describe environmental facies constrained by and identified on the basis of differences in taphonomic criteria. They generated a model that characterized environments of deposition within the Devonian Hamilton Group of New York by the degree of disarticulation and a fragmentation of trilobites. Speyer and Brett (1988, 1991) developed general taphofacies models for epeiric sea settings, using gradations in oxygen levels, sedimentation rates and turbulence to define theoretical taphofacies.

MIDDLE CAMBRIAN PALEOGEOGRAPHY

The Cambrian formations of the western Cordillera were deposited on a passive margin which formed in response to the breakup of a Late Proterozoic supercontinent (Bond and others, 1984; Link and others, 1993). During the Middle to Late Cambrian, some 2 km of post-rift sediments, largely carbonates and fine-grained terrigenous materials, were deposited in ramp to platform settings on this margin (Stewart and Poole, 1974; Levy and Christie-Blick, 1989). Palmer (1960, 1971, 1974) and Robison (1960, 1964a) presented a model of a north-south trending carbonate belt (modern orientation) which separated eastern (inner) and western (outer) detrital belts (Fig. 4). Based on this model, the Middle Cambrian units of interest to our study would fall largely within the middle carbonate or outer detrital belts. The eastern Great Basin area has been placed at approximately 10° N latitude during the Cambrian with the equator bisecting North America in a north-south orientation relative to modern directions (Scotese and others, 1979; Ziegler and others, 1979).

THE LANGSTON FORMATION

Stratigraphic relationships of the Lower and Middle Cambrian units in northern Utah and southern Idaho are discussed by Deiss (1938, 1941), Williams and Maxey (1941), Williams (1948), Maxey (1958), Crittenden and others (1971), Oriel and Armstrong (1971), Lindsey (1982) and Link and others (1985, 1993).

The Langston Formation of northern Utah is early Middle Cambrian in age. The Langston Formation is largely restricted to the hanging wall of the Willard Thrust (Critten-

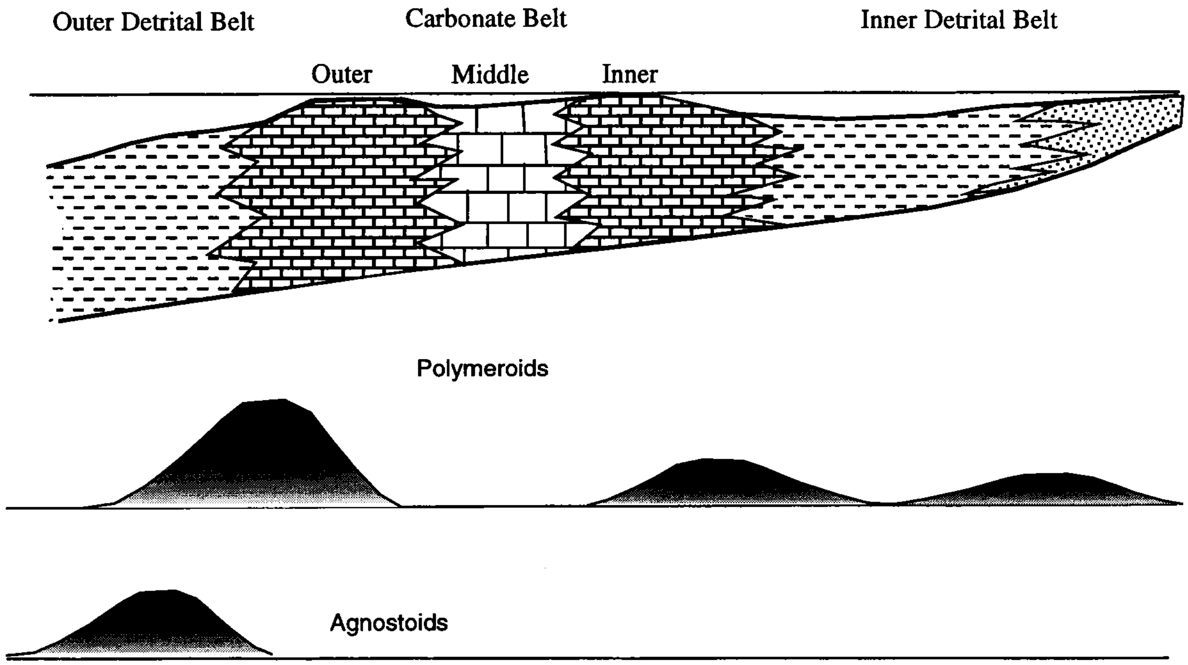


Figure 4. Inner and outer detrital and carbonate belts showing relative distribution of agnostoid and polymeroid trilobites (after Robison, 1976). Langston Formation localities represent outer carbonate belt and outer detrital belt environments.

den, 1972). These rocks are thought to have experienced some 50 km of eastward translation during the Sevier orogenic event (Levy and Christie-Blick, 1989). Outcrops are discontinuous due to the effects of Sevier compression and Tertiary extension (Miller, 1990).

The Langston Formation lies upon the Geertsen Canyon Quartzite, which is the uppermost formation of the Upper Proterozoic-Lower Cambrian Brigham Group. The Langston includes three members, the Naomi Peak Limestone, Spence Shale and High Creek Limestone (Fig. 5). The Spence Shale Member is the main unit of interest for this field trip. The dominant lithology within the Spence Shale is a calcareous shale, although limestone units also occur. The Spence Shale is 50 to 65 m thick in the Wellsville Mountains of northern Utah. Trilobite genera occurring in the Spence Shale Member belong to the *Glossopleura* Trilobite Zone of Lochman-Balk (1971) (Fig. 5). Further, Robison (1976) has placed this unit within the agnostoid-based *Peronopsis bonnerensis* Biochron.

The stratigraphic terminology for the Langston Formation and equivalent units is somewhat controversial. Although Maxey (1958) proposed a framework similar to that outlined above for the Langston Formation, Oriel and Armstrong (1971) proposed that the equivalent-age units occurring above the Brigham Group in southeastern Idaho be called the Twin Knobs Formation and Lead Bell Shale and that, in Utah, the terms Naomi Peak Tongue of the Twin Knobs Formation and Spence Tongue of the Lead Bell Shale should be used. Further, they proposed that the term Langston be restricted to dolomitic rocks occurring mainly to the east of the Spence Shale outcrop area. Palmer and Campbell (1976) employed the nomenclature of Oriel and Armstrong (1971) while Robison (1991) has proposed that the Spence Shale be elevated to formation rank. Recent maps by the Utah Geological Survey (e.g. Lowe and Galloway, 1993) retain the original terminology of Maxey (1958).

The Spence Shale contains a diverse fauna of trilobites and other invertebrates, such as merostome arthropods, articulate and inarticulate brachiopods, eocrinoids, hyolithids and sponges (Walcott, 1908a; Resser, 1939; Campbell, 1974; Rigby, 1980; Gunther and Gunther, 1981; Babcock and Robison, 1988; and Robison, 1991). In addition, instances of soft-bodied preservation also are known from the Spence Shale Member. For example, algae, annelids, arthropods and other organisms have been described (Robison 1969, 1991; Briggs and Robison, 1984; Conway Morris and Robison, 1988). Although the Spence Shale Member is well-known for its diverse and well-preserved trilobite fauna, the degree of disarticulation and fragmentation and fossil density are highly variable within the unit, both geographically and vertically.

Palmer and Campbell (1976) suggested that three distinct biofacies occur within the Langston Formation and

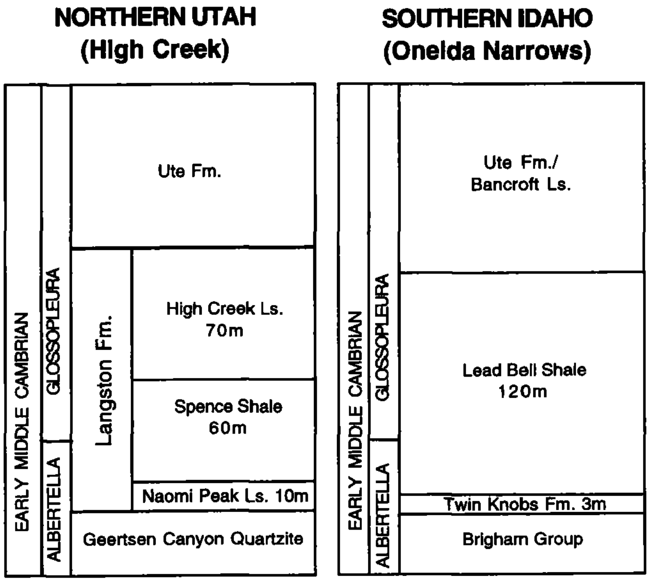


Figure 5. Stratigraphic relations of the Langston Formation and equivalents in northern Utah and southern Idaho (after Maxey, 1958; Oriel and Armstrong, 1971; Lindsey, 1982; and Link and others, 1985).

its equivalents: 1) A low-diversity, restricted-shelf biofacies, which corresponds to the inner detrital belt. This includes sandy beds in the lower Twin Knobs Formation and Naomi Peak Limestone, as well as the underlying clastics of the Brigham Group; 2) A high-diversity, platform-margin to open-shelf biofacies. This includes the majority of the carbonates and shales in the Langston Formation. 3) A deep-shelf or basinal, low-diversity biofacies characterized by agnostoid and oryctocephalid trilobites. This corresponds to the deepest units in the Spence/Lead Bell Shale such as Cycles One and Two at Oneida Narrows and Cycle 3 at Miners Hollow (OC1, OC2, MC3, Fig. 7). Robison (1991) suggested that many of the Spence Lagerstätten reflect deposition by tempestites in a distal ramp setting.

Localities

This trip will focus upon occurrences of the Spence Shale in northern Utah and southern Idaho. The analysis of the effect of higher-order sea-level oscillations on lithology and taphonomy requires excellent exposures. The following localities were chosen based upon quality of exposure and adequate coverage of depositional environments. Descriptions of localities are provided by Walcott (1908b), Maxey (1958), Oriel and Armstrong (1971), Buterbaugh (1982), Lindsey (1982) and Rogers (1987).

Sites are in the Wellsville Mountains of Utah (Fig. 6), and the Bear River Range of Utah and Idaho. The two ranges surround Cache Valley, where Logan and Utah State University are located. Detailed locations are as follows: from north to south in the Wellsville Mountains, Miners Hollow, Cataract Canyon and Antimony Canyon (Secs. 14, 13 and 36, respectively, in the Brigham City, UT 7.5′ quad.); in the Bear River Range, High Creek (NW 1/4 of the Naomi Peak, UT 7.5′ quad.), Spence Gulch (Sec. 11 in the Midnight Mountain, ID 7.5′ quad.) and Oneida Narrows (Sec. 6 in the Oneida Narrows Reservoir, ID 7.5′ quad.).

The above sites ensure sufficient north-south (100 km) and post-extensional east-west (50 km) coverage of the study area. In addition, definite lithologic and taphonomic changes occur across the study area. For example, shales in the Wellsville Mountains localities tend to be more calcareous than those in the Bear River Range. Also, the Spence Gulch site in the eastern Bear River Range appears to contain much higher densities of trilobite remains than do the more western localities. Finally, the Antimony Canyon, Miners Hollow and Oneida Narrows localities demonstrate a progression from more proximal- to more distal-ramp positions.

Sequence Stratigraphy

The Langston Formation is thought to have been deposited on a ramp (Bond and others, 1988, 1989), with the Spence Shale Member occupying a distal ramp position and the Naomi Peak and High Creek Limestone Members occupying more proximal ramp positions (Fig. 4). The presence of cryptalgal laminites and extensive dolomite attest to the shallow nature of the High Creek Limestone. Also, the absence of the Spence Shale and presence of dolomite in the eastern Bear River and Wasatch Ranges (Fig. 6) suggests the existence of extensive, relatively shallow-water conditions in that area.

The Langston Formation was deposited as part of a third-order transgressive event that encompasses parts of the Langston and overlying Ute Formations (Bond and others, 1989). Within the Spence Shale, at least seven higher-order, meter-scale, shallowing-upwards packages of parasequences are also observed (Fig. 7).

The Spence Shale parasequences are predominantly subtidal cycles (c.f. Osleger, 1991), rarely, if ever, shallowing into intertidal depths or developing exposure surfaces. The cycles begin with shales which grade upward into limestones. The limestones which cap cycles may be high-energy, cross-stratified grainstones, or laminated lime mudstones or limestone nodules containing fossil concentrations. The contact between the basal shale of one cycle and the upper limestone of the previous cycle is sharp and may represent a discontinuity or at least condensed interval as indicated by the occurrence of hardgrounds and/or

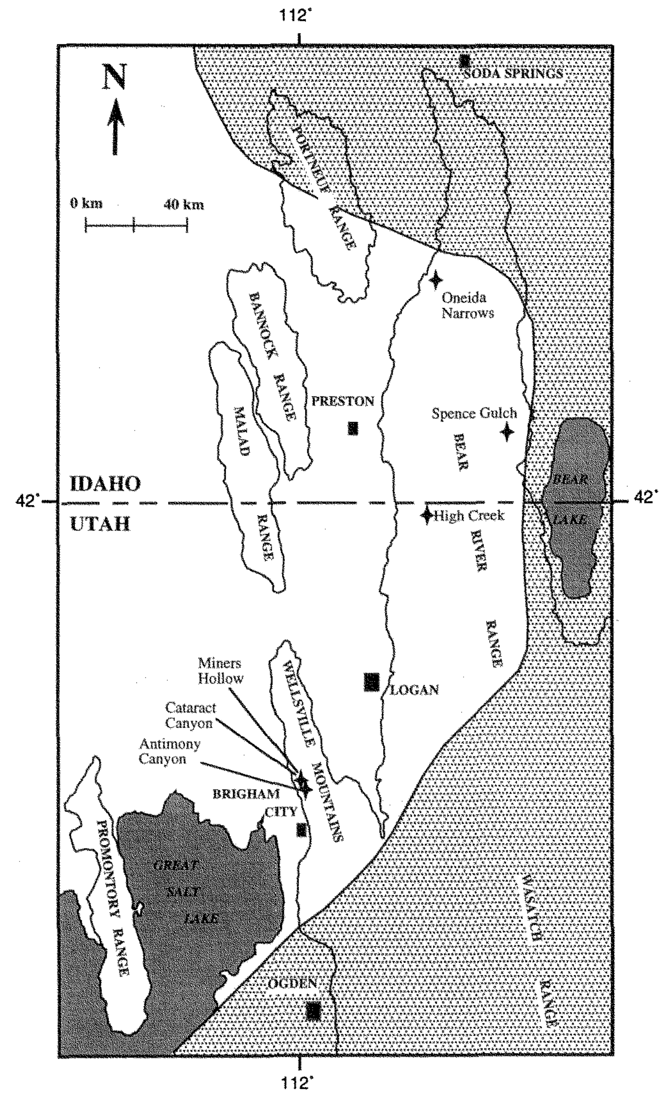


Figure 6. Spence Shale localities in Utah and Idaho. The solid line bracketing stippled pattern marks the eastern extent of the Spence Shale. Beyond this point the Spence Shale is absent and Langston Formation carbonates are typically dolostone.

skeletal concentrations at the contacts between cycles (Fig. 1). The exact development of each smaller-scale cyclic package depends strongly upon its position within the overall third-order sequence (e.g. TST or HST) and the nature of each sea-level event. Therefore, parasequence packages vary up through the formation (Fig. 7).

Organic carbon content varies within parasequences and, also, up through the Spence Shale, reaching a maximum value in the lower portion of Cycle 3 (MC3, Fig. 8, top). This, along with other information—abundant preserved algal debris (Fig. 3D), the presence of agnostoid and oryctocephalid trilobites and increasing shale sedimentation above this point—suggests that this corresponds closely to the maximum flooding surface, marking the boundary between the transgressive and highstand systems tracts. Variation in organic carbon within parasequences suggests possible higher-frequency cyclicity (Fig. 8, bottom).

Ramp positions (e.g. closer to the carbonate belt or more basinward) at the time of a flooding event also will result in variably-developed parasequence architectures; therefore, considerable lateral variation may occur. For example, the Antimony Canyon, Miner's Hollow and Oneida Narrows localities show progression from a proximal ramp to more distal ramp to deep ramp or basin. The tops of upper (HST) parasequences consist of variably-developed, fossiliferous limestone nodules at Miner's Hollow, while at Antimony Canyon they are represented by cross-stratified, grainy limestone beds (AC3–AC8, Fig. 7). At the Oneida Narrows locality, limestone beds are absent from the tops of some of the lower (TST) parasequences (OC1, Fig. 7). Further, the bases of the initial (TST) parasequences at the deep Oneida Narrows site consist of black, spiculitic shales (Fig. 2B; OC1, OC2, Fig. 7), which contrast with the lighter shales, generally lacking sponge spicules, found at the other sites.

Taphonomic Characteristics of Spence Shale Parasequences

The fossil assemblages of the Spence Shale appear to occupy predictable positions within third- and fourth- or fifth-order cycles. As noted above for lithology, vertical and lateral variability in taphonomic attributes also occurs between parasequences. Specific examples follow.

Density. Analysis of total density of trilobite sclerites reveals two locations within parasequences where highs occur—one in terrigenous deposits at the bases of parasequences and slightly above an omission surface (BOP shell bed; e.g. bottom of Cycle 1 at Miners Hollow, MC1, Fig. 9), the other in carbonate deposits near the tops of parasequences (TOP shell bed; e.g. top of Cycle 4 at Miners Hollow, MC4, Fig. 9). While the former is due to sediment starvation, typically in TST parasequences, the latter is due to dynamic bypassing/winnowing of sediment associated with shallowing in HST parasequences. In the overall, third-order sequence, highest densities are observed in the lower parasequences, suggesting maximum sedimentation slowdown associated with the transgressive systems tract.

The location of the boundary between Cycles 2 and 3 at Miners Hollow is uncertain as the highest density of skeletal elements occurs below the shales of Cycle 3 and within the upper few centimeters of the limestone compris-

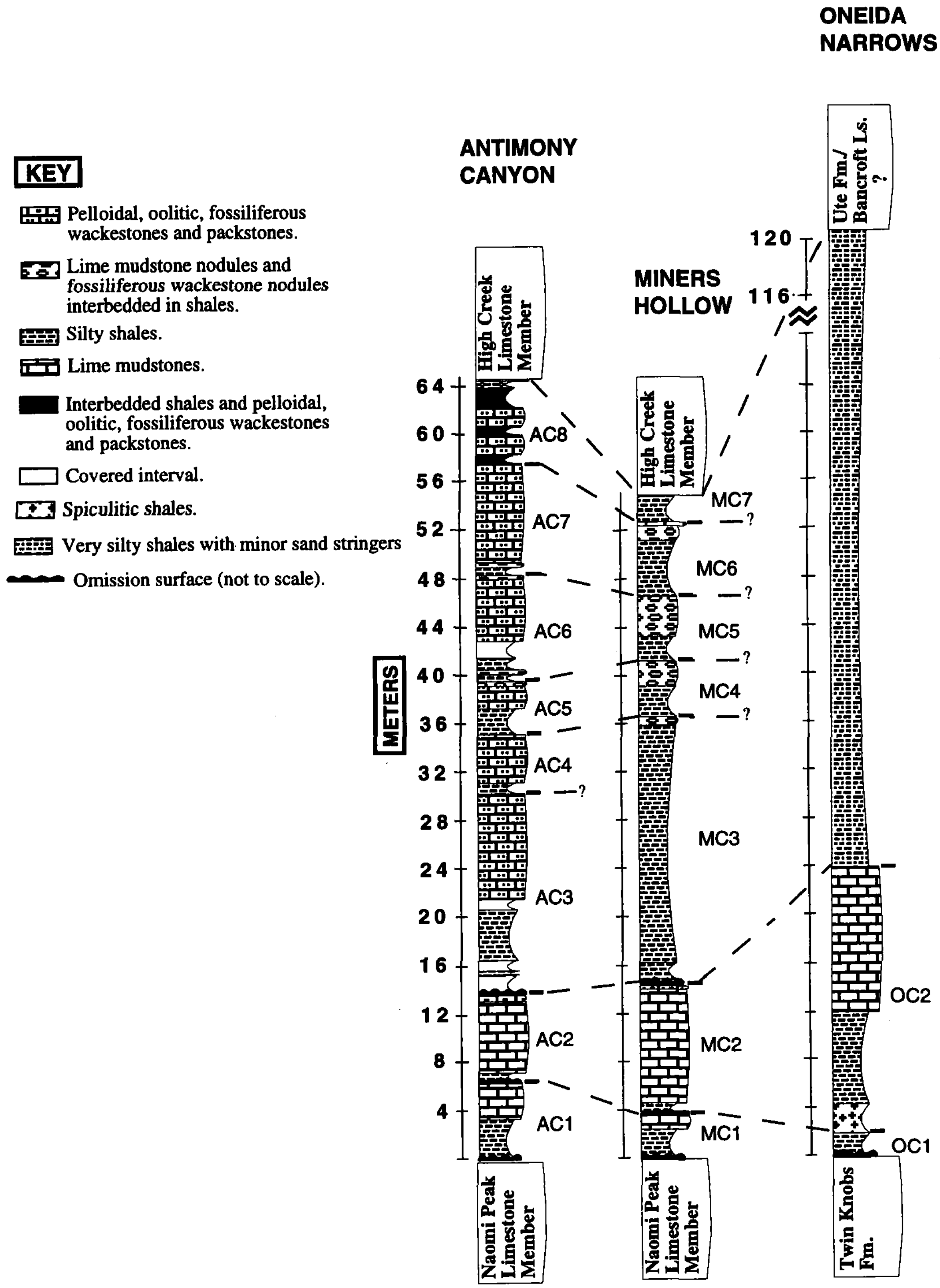


Figure 7. Stratigraphic columns of the Spence Shale at Miners Hollow and Antimony Canyon, Wellsville Mountains, Utah and at Oneida Narrows, Idaho. Note stacked parasequences (e.g. AC1, AC2). Also, increasing amounts of grainy limestone in the Antimony Canyon section.

ing the top of Cycle 2 (MC2–MC3, Fig. 9). This, coupled with discontinuities visible within the upper portion of the limestone, suggests that the cycle boundary should perhaps be placed within the upper part of the limestone.

Overall Preservation. Taphonomic grade (Brandt, 1989) increases up-cycle. Intact polymeroid trilobites are rare in the bottoms of parasequences. Infrequently, isolated intact specimens occur throughout the middle and upper portions of the cycles.

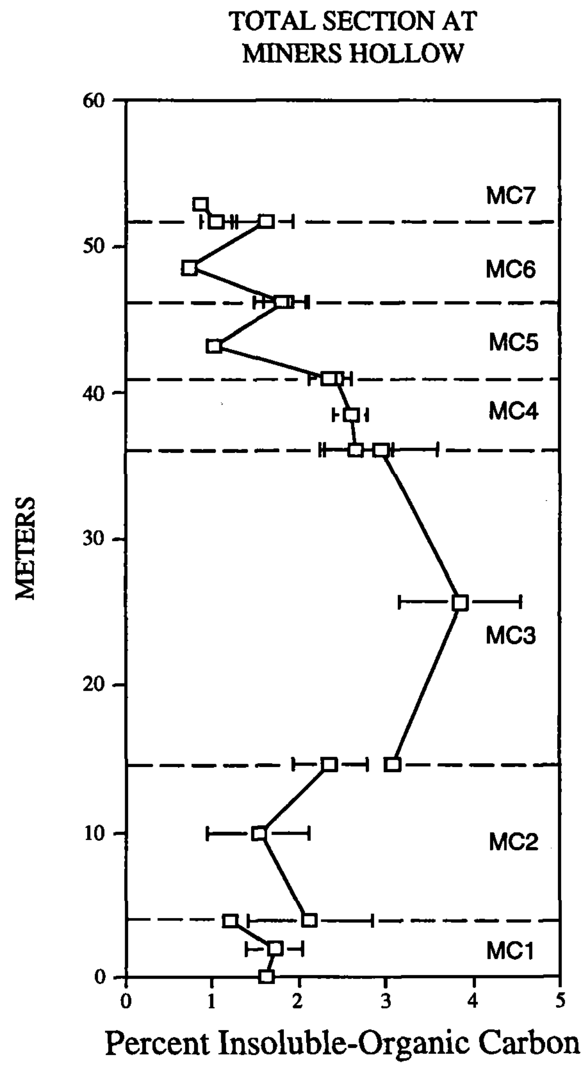
Agnostoids vs. Polymeroids. The agnostoid trilobites occur most frequently in the basal portions of the parasequences. Further, they are most abundant in the lower (TST) parasequences (e.g. MC1–MC3, Fig. 10).

Agnostoids are also more abundant at the Oneida Narrows section (presumably the deepest-water locality) than at the Antimony section (presumably the shallowest-water locality). Oryctocephalid trilobites, which are assumed to be deep-water indicators (Palmer and Campbell, 1976), are found mainly in the lower cycles at the Oneida Narrows locality, although they also occur in the base of Cycle 3 at Miners Hollow.

Size. Size differences occur between the Antimony Canyon–Miners Hollow localities and Oneida Narrows, with the latter possessing overall smaller sclerites and individuals, perhaps reflecting greater transport distances/depths for the Oneida Narrows site or ecologic differences.

Orientation. The trilobite elements show compass orientations which shift upwards through each parasequence, generally indicating a shift from easterly to more westerly current directions. Further, in the third-order sequence, there is a shift from dominance by easterly flow in the basal parasequences to dominance by westerly flow in the upper parasequences.

Diversity. The highest faunal diversities are noted in the lower parasequences. This may be due to nutrient enhancement of productivity associated with initial sequence flooding (Burrett and Richardson, 1972). Alternatively, time-averaging of assemblages may have played a role. These trends are substantiated by extensive collections made by Campbell (1974).



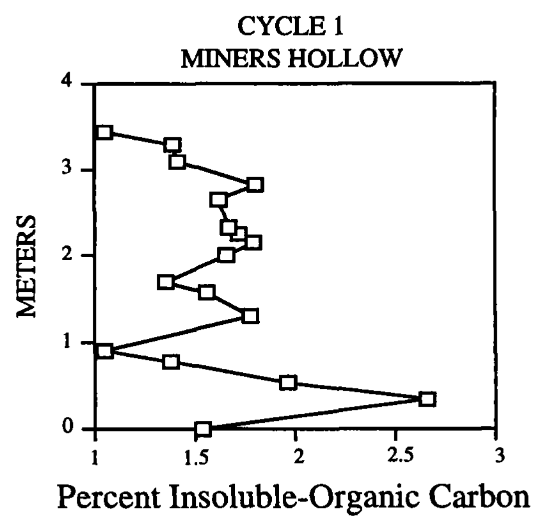


Figure 8. Vertical distribution of organic carbon in Spence Shale parasequences at Miners Hollow. For total section, note carbon high in low to mid portion of parasequence three (MC3), which, presumably, corresponds to the maximum flooding horizon. Also, decimeter-scale sampling of Cycle One reveals high-frequency cyclicity.

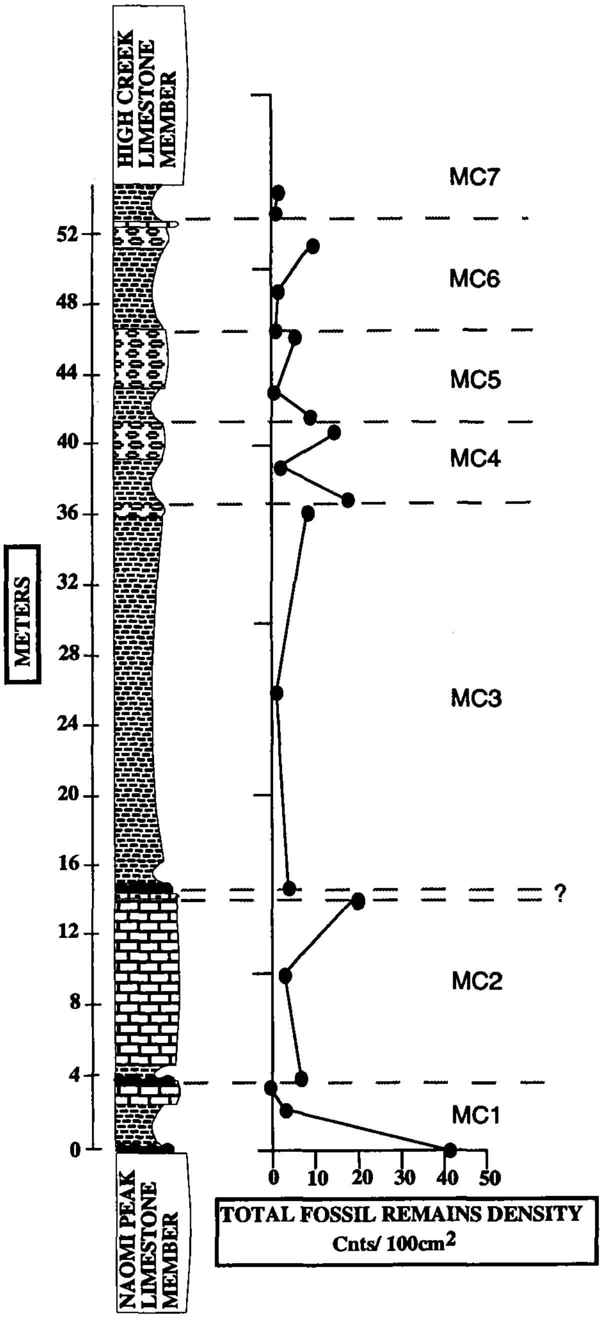


Figure 9. Trilobite density data (total remains) for Spence shale at Miners Hollow. Note highest values occurring in BOP (e.g. MC1) or TOP (e.g. MC4) positions.

SUMMARY AND CONCLUSIONS

Trilobite and other fossil assemblages occur in stratigraphic positions within the Spence Shale that can be defined on the basis of sequence architecture. The sequence stratigraphic model presented herein is a powerful predictive tool, capable of explaining distribution patterns of organisms and their preservation. This is due to the dependence of fossil preservation on sedimentation rates and environmental energy, which are, in turn, related to sea-level oscillations. Conversely, paleontologic evidence (both taphonomic and ecologic) can be employed in the recognition of sequence boundaries and condensed stratigraphic intervals. Further, recognition of higher-order cycles in units such as the Spence Shale enables high-resolution (< .1–.5 Ma) correlation, thus contributing to both paleoenvironmental and ecological interpretations.

ROAD LOG

Trip directions are from Salt Lake City, UT. Leave Salt Lake City and proceed north on Interstate Hwy. I-15. It is approximately 60 miles from Salt Lake City to Brigham City. All distances are in miles, with cumulative and interval mileage given. Although this field trip will visit only the Miners Hollow and Oneida Narrows localities, descriptions of the other sites are included to provide lateral facies perspectives within the Spence Shale. These sites provide fair (High Creek) to excellent (Miners Hollow and Cataract Canyon) exposures of the Spence Shale (Fig. 6).

Miners Hollow

Located on the west flank of the Wellsville Mountains, north of Brigham City, UT (T. 10 N., R. 2 W., Sec. 14, Brigham City, UT 7.5′ quad.). This site requires a moderately strenuous hike to reach it.

0.0/0.0 Take the first Brigham City exit (exit # 364, 1100 S St., U.S. Hwy. 91 to 89, to Brigham City and Logan). Proceed east on U.S. Hwy. 91.

2.0/2.0 Stop light. Intersection U.S. Hwys. 89 and 91, UT Hwy 13. Go left (north) on Main Street/UT Hwy. 13 and drive through Brigham City.

3.0/1.0 Y Intersection of UT Hwys. 13 and 38 at north end of Brigham City. Bear right (north) on UT Hwy. 38.

8.1/5.1 Turn right (east) on paved road. Go up hill.

8.2/0.2 Bear left (north).

8.5/0.2 Stop and park at turn-around adjacent to corral. Be careful to not block gates or vehicles. Obtain permission to cross corral from the Hawker family in the house immediately east of corral.

From this location looking east at the Wellsville Mountains, a series of canyons are visible (Fig. 11). The large canyon located to the southeast is Cataract Canyon. Looking to the north (0.5 mi.) the next small canyon encountered is Miners Hollow. Just north (0.3 mi.) of this is Donation Canyon. The last canyon visible to the north (an additional 0.6 mi.) is the very large Calls Fort Canyon.

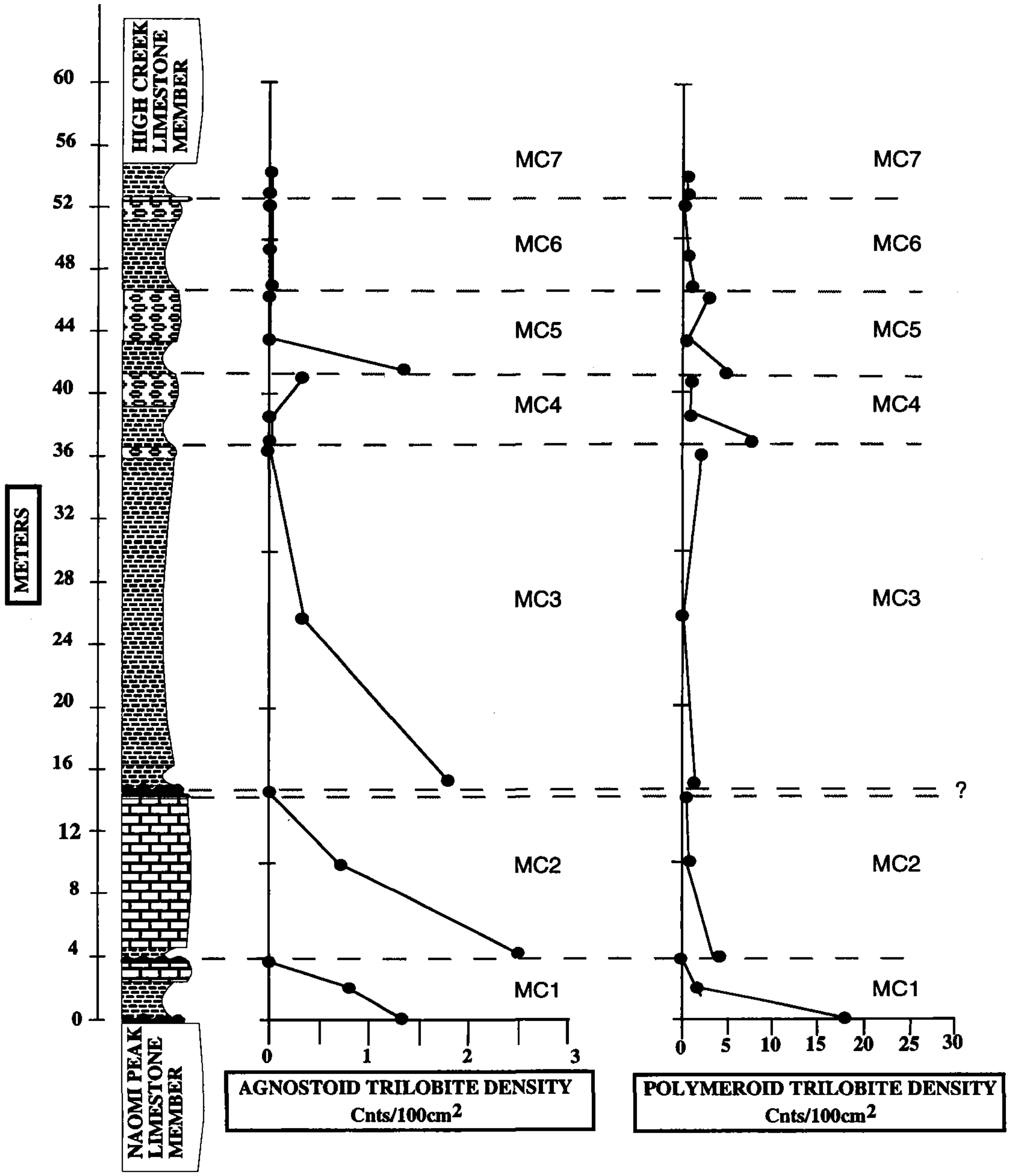


Figure 10. Vertical distribution of agnostoid and polymeroid trilobites in the Spence Shale at Miners Hollow. Note highest agnostoid abundances associated with deepest locations (bases of lower cycles, e.g. MC1, MC2, MC3) within vertical sequence.

The rocks exposed on the west flank of the Wellsville Mountains are part of a homocline and dip to the northeast. A northward-plunging anticline occurs at the northern end of the range (Oviatt, 1985). The Middle Cambrian rocks of interest occur progressively higher on the mountain front to the south towards Brigham City and to the north are covered beneath the alluvial fan in the vicinity of Calls Fort Canyon.

The rocks record the Middle Cambrian transgression onto the craton with siliciclastic units (Brigham Group quartzites) at the base, which pass upwards into carbonates (Fig. 5). The buff to white cliff-forming unit on the base of the slope is the Geertsen Canyon Quartzite, which consists of fine to coarse, relatively clean quartz sandstone. Only the upper portion of this very thick (600–1500 m) formation is exposed here. In its upper portions thin (10–20 cm) silty-shaley interbeds become increasingly common.

Overlying the Geertsen Canyon Quartzite is the Langston Formation. This has a basal carbonate member, the Naomi Peak Limestone, which is conformable with the

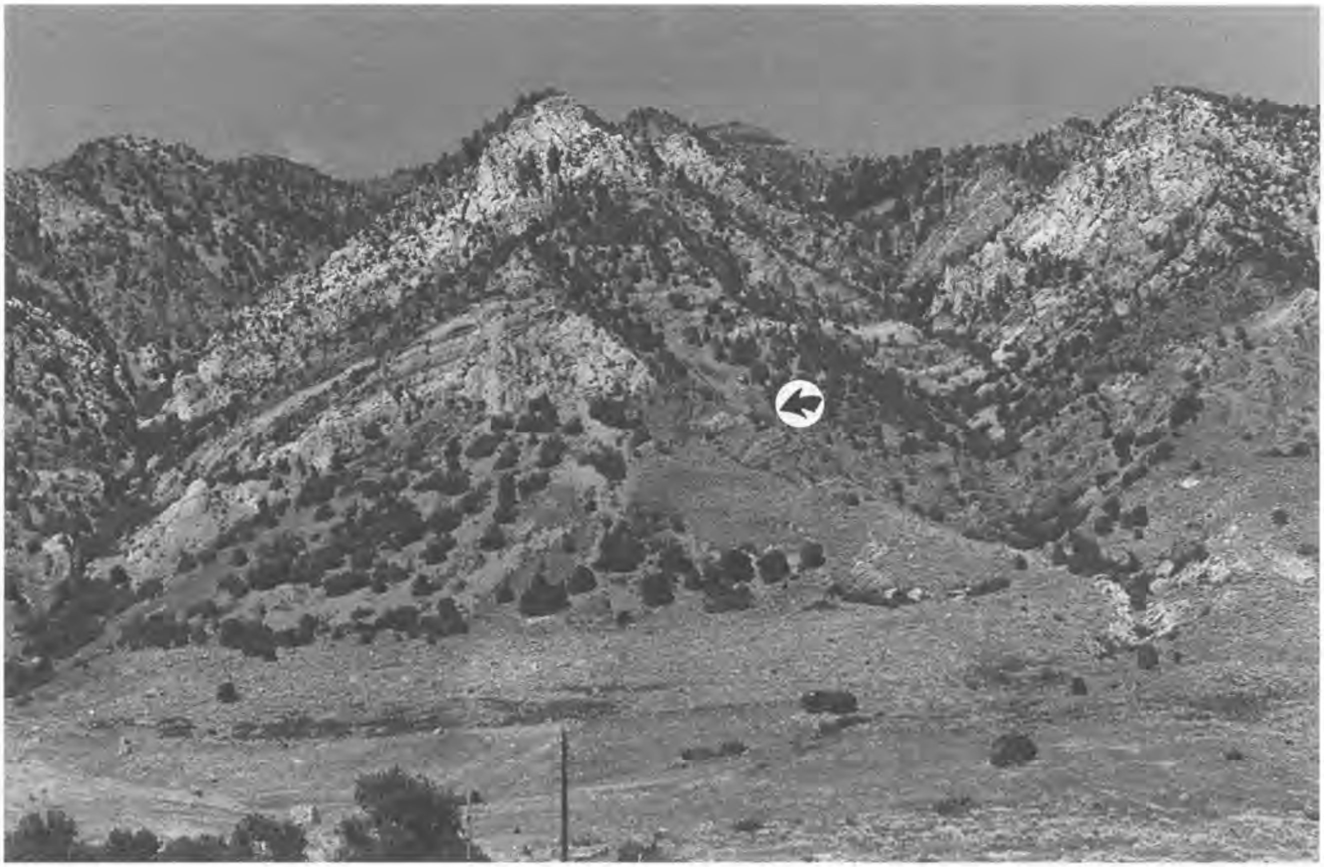


Figure 11. View of the west flank of the Wellsville Mountains, near Calls Fort Monument, south of Honeyville, Utah. Donation Canyon located to the left (north) and Miners Hollow to the right in the photograph. Geertsen Canyon Quartzite is exposed at base of mountain front and is followed upward by Langston Formation shales and carbonates. Contact between the two units indicated by arrow.

Geertsen Canyon Quartzite at this locality and often contains quartz sand in its base. This is observable as a 10-m-thick grey band occurring above the sandstone cliffs. The top of the Naomi Peak Limestone is a hardground, exhibiting considerable relief and pyrite or limonite staining.

The middle member of the Langston Formation is the Spence Shale which sharply overlies the grainy carbonates of the Naomi Peak Limestone. The Spence Shale consists of calcareous silty shales and limestones (mudstones to packstones), with the shales predominating. These shales are very dark when fresh, but weather brown as seen from the parking area. At this site the shales form a fairly steep slope.

The upper member of the Langston Formation is the High Creek Limestone. This varies from limestone to dolostone and often contains cryptalgal laminae. This forms a massive white cliff easily visible from the parking area.

Brownish units overlying the High Creek Limestone comprise the shales and limestones of the Ute Formation. The contact between these two units is sharp, with basal Ute Formation shales directly overlying High Creek Limestone carbonates.

On foot, from the corral follow a faint track north and then east and hike up the alluvial fan to the base of the sandstone cliffs on the north side of Miners Hollow. Although the slope is steep, actual climbing is never required. Exercise caution to avoid a slip and also to avoid dislodging rocks that may strike someone below you. At the sandstone cliffs bear right (northeast) and ascend to the Naomi Peak Limestone–Spence Shale contact.

Six to seven cyclic packages are observed within the Spence Shale at this locality (Fig. 7). This section of the Spence Shale is described in detail within the body of this article.

Cataract Canyon

Located on the west flank of the Wellsville Mountains, north of Brigham City, UT (T. 10 N., R. 2 W., Sec. 13, Brigham City, UT 7.5′ quad.). This site requires a moderately strenuous hike to reach it.

0.0/0.0 Take the first Brigham City exit (exit # 364, 1100 S St., U.S. Hwy. 91 to 89, to Brigham City and Logan). Proceed east on U.S. Hwy. 91.

2.0/2.0 Stop light. Intersection U.S. Hwys. 89 and 91, UT Hwy 13. Go left (north) on Main Street/UT Hwy. 13 and drive through Brigham City.

3.0/1.0 Y Intersection of UT Hwys. 13 and 38 at north end of Brigham City. Bear right (north) on UT Hwy. 38.

8.0/5.0 Turn right (east) on gravel road (approx. 4544 N Hwy. 38). Ask permission to drive to mouth of Cataract Canyon from Warren family in house at corner. Note that it might be better to walk up this road rather than drive, depending upon the clearance afforded by your vehicle.

8.8/0.8 Mouth of Cataract Canyon. Exposures of Geertsen Canyon Quartzite on north side. If driving, park and continue eastward up the bottom of canyon on foot.

The section here is very similar to that described for Miners Hollow (located 0.5 mi. north). The section begins much lower in the Geertsen Canyon Quartzite, however, and the generally-deepening trend within the Geertsen Canyon Quartzite is evident. Eventually, the Naomi Peak Limestone Member of the Langston Formation intersects the bottom of the canyon. The gradual transition between the Geertsen Canyon Quartzite and the Naomi Peak Limestone is very well exposed at this spot. Continue up the canyon to the Naomi Peak–Spence Shale contact. At this point turn north and work up the slippery Spence Shale talus to the ridge line where Spence parasequences are well exposed and easy to spot due to changes in topography associated with each cycle.

The upper Spence Shale parasequences at this locality differ from those to the north (Miners Hollow) and south (Antimony Canyon), although they are more like the Miners Hollow cycles. The tops of the upper parasequences at Miners Hollow consist of scattered limestone nodules with abundant trilobite remains. At Cataract Canyon, the nodules are much denser, almost forming limestone bands. At Antimony Canyon the tops of the upper cycles are true limestone beds and are often grainy and even cross-stratified.

Antimony Canyon

Located on the west flank of the Wellsville Mountains, north of Brigham City, UT (T. 10 N., R. 2 W., Sec. 36, Brigham City, UT 7.5′ quad.). This site requires a very strenuous hike to reach it.

0.0/0.0 Take the first Brigham City exit (exit # 364, 1100 S St., U.S. Hwy. 91 to 89, to Brigham City and Logan). Proceed east on U.S. Hwy. 91.

2.0/2.0 Stop light. Intersection U.S. Hwys. 89 and 91, UT Hwy 13. Go left (north) on Main Street/UT Hwy. 13 and drive through Brigham City.

3.0/1.0 Y Intersection of UT Hwys. 13 and 38 at north end of Brigham City. Bear right (north) on UT Hwy. 38.

6.3/3.3 Pull into private drive on right (east) (3410 N Hwy. 38). Request permission from the Beecher family to drive on private road to Antimony Canyon. Travel northeast on gravel road and up alluvial fan. Be sure to close gates after passing.

7.0/0.7 Road eventually turns south and passes community water tanks.

7.4/0.4 Stop and park at mouth of Baker Canyon. Driving beyond this point is not recommended, as the road becomes narrow, steep and talus-choked. Continue south on foot along the road for one mile.

Road passes through Pleistocene terrace deposits and the Cambrian Ute Formation. Pass Dry Canyon. An incomplete section of the Spence Shale occurs below the road past Dry Canyon. The foundation of an old mine building occurs at the mouth of Antimony Canyon. Faulting in the canyon juxtaposes Cambrian Ute Formation on the left (north) side of the canyon against the older Cambrian Geertsen Canyon Quartzite on the right (south) side.

The road turns east and travels 0.2 mi. along the north side of the canyon, eventually reaching an old mine shaft (Copper Blossom Mine). Visible above this opening are large, columnar stromatolites in the Ute Formation (Eagan and Liddell, 1997). At or near this point turn south and cross the canyon bottom and work up the south side of the canyon to the ridge line and the contact between the Naomi Peak Limestone and the Spence Shale. This 0.25 mi. hike to the ridge is very strenuous and caution must be exercised in attaining the south ridge of the canyon.

The Spence Shale at this locality differs form the other Wellsville Mountains sites in being much more calcareous with limestones dominating over shales (Fig. 7). Although the lower parasequences are not well exposed at this site, the upper ones and the contact with the High Creek Limestone are beautifully exposed. The contrast between the upper parasequences here and at Miners Hollow is striking with grainy, cross-stratified limestones at Antimony Canyon occupying equivalent positions to limey nodules occurring in the tops of cycles at Miners Hollow.

High Creek Canyon

Located in the western portion of the Bear River Range, north of Smithfield, UT (T. 14 N., R. 40 E., NW 1/4 of the Naomi Peak, UT 7.5′ quad.). This site requires a moderately strenuous hike to reach it.

0.0/0.0 Take the first Brigham City exit (exit # 364, 1100 S St., U.S. Hwy. 91 to 89, to Brigham City and Logan). Proceed east on U.S. Hwy. 91.

2.0/2.0 Stop light. Intersection US Hwys. 89 and 91, UT Hwy 13. Continue east on U.S. Hwy. 89-91 into Cache

Valley. Hwy. will cross the Wellsville Mountains, which consist of Cambrian through Mississippian rocks. Refer to Morgan (1992) for road log.

3.5/1.5 Hwy. passes through Lake Bonneville delta deposits.

25.9/22.4 U.S. Hwys. 89 and 91 diverge in Logan. Continue north on U.S. Hwy. 91. Pass through Logan, Smithfield and Richmond.

37.9/12.0 Richmond.

41.3/3.4 Forest service sign for High Creek. Turn right (east) on 12100 N.

45.3/4.0 Forest service boundary.

49.3/4.0 Road ends at parking area. Geertsen Canyon Quartzite is visible on hillside to east.

Follow the trail leading northeastward from parking area (not the major trail heading southeast and following the South Fork of High Creek). After 100 m, cut right (east) and ascend ridge. Work upwards through Geertsen Canyon Quartzite to contact with the Naomi Peak Limestone.

Unlike the Miners Hollow and Cataract Canyon sites on the Wellsville Mountains, the contact between the Geertsen Canyon Quartzite and the Naomi Peak Limestone appears sharp at this locality. The lower portion of the Spence Shale is marked by a well-vegetated saddle. Upper portions of the Spence Shale are a bit better exposed or can be excavated with some digging. At this locality the Spence Shale is less calcareous and less silty than at the Wellsville Mountains sites.

Spence Gulch

Located in the eastern portion of the Bear River Range, northwest of Paris, ID (T. 13 S., R. 42 E., Sec. 11, Midnight Mountain, ID 7.5' quad.). This is the type locality for the Spence Shale (Walcott, 1908b). Although this site is inaccessible during parts of the year and requires a long drive on unimproved roads, the actual hiking involved to reach the site is minimal.

0.0/0.0 Take the first Brigham City exit (exit # 364, 1100 S St., U.S. Hwy. 91 to 89, to Brigham City and Logan). Proceed east on U.S. Hwy. 91.

2.0/2.0 Stop light. Intersection U.S. Hwys. 89 and 91, UT Hwy 13. Continue east on U.S. Hwys. 89-91 into Cache Valley. Highway will cross the Wellsville Mountains, which consist of Cambrian through Mississippian rocks. Refer to Morgan (1992) for road log.

3.5/1.5 Hwy. passes through Lake Bonneville delta.

25.9/22.4 U.S. Hwys. 89 and 91 diverge in Logan. Turn right (east) on U.S. Hwy. 89 and travel up Logan Canyon to Bear Lake. Logan Canyon consists of folded Paleozoic rocks ranging in age from Cambrian to Mississippian. Refer to Crook and others (1985) and Morgan (1992) for road logs.

28.5/2.6 Mouth of Logan Canyon.

63.7/35.2 Bear Lake. Intersection of U.S. Hwy. 89 and UT Hwy. 30 in Garden City, UT. Turn left (north) on U.S. Hwy. 89 and travel through Garden City, UT and Fish Haven, St. Charles, Bloomington and Paris, ID.

67.5/3.8 Utah-Idaho border.

86.9/19.4 Paris, ID.

89.2/2.3 Lanark Road—turn left (west). Travel northwest.

91.6/2.4 Turn left (west) off Lanark Road toward Miles Canyon.

92.0/0.4 Fork—bear left.

92.7/0.7 Fork—bear left.

93.4/0.7 Fork—bear right.

94.5/1.1 National Forest boundary and cattle guard.

95.7/1.2 Danish Flat—road intersection. Go right (north) on poor dirt road, parallel to creek and eventually enter woods.

96.6/0.9 Road widens somewhat. Stop and park. Hike 0.1 mi. downhill through trees to east and ephemeral tributary to Mill Creek.

The basal portion of the Spence/Lead Bell Shale is well-exposed in a stream cut at this locality. The lower limestone unit (Naomi Peak Limestone Member or Twin Knobs Formation) is very thin or absent. The shale is not silty and only slightly calcareous. Unlike the other Spence Shale localities discussed herein, it contains a very high density of large, articulated trilobites. The polymeroid *Zacanthoides* is particularly abundant.

The entire formation is exposed further north along Liberty Creek (NW 1/4 Sec. 2). This can be reached by hiking north along Mill Creek to its intersection with Liberty Creek. Exposures of the Spence/Lead Bell Shale are not good at this site, due to its noncalcareous nature, but the meter-scale cyclicity is still evident and upper parasequences can be exposed by excavation.

Oneida Narrows

Located in the western portion of the Bear River Range, northeast of Preston, ID (T. 13 S., R. 41 E., Sec. 6, Oneida Narrows Reservoir, ID 7.5' quad.). This site can be accessed directly from vehicles.

0.0/0.0 Take the first Brigham City exit (exit # 364, 1100 S St., U.S. Hwy. 91 to 89, to Brigham City and Logan). Proceed east on U.S. Hwy. 91.

2.0/2.0 Stop light. Intersection U.S. Hwys. 89 and 91, UT Hwy 13. Continue east on U.S. Hwy. 89-91 into Cache Valley. Highway will cross the Wellsville Mountains which consists of Cambrian through Mississippian rocks. Refer to Morgan (1992) for a road log.

3.5/1.5 Highway passes through Lake Bonneville delta.

25.9/22.4 U.S. Hwys. 89 and 91 diverge in Logan. Continue north on U.S. Hwy. 91. Pass through Logan, Smithfield and Richmond.

44.7/18.8 Utah-Idaho border.

52.2/7.5 Preston, ID

54.2/2.0 Fork at north end of Preston. U.S. Hwy. 91 and ID Hwy. 34 diverge, take right (east) fork (ID Hwy. 34).

59.6/5.4 Cross Bear River at Riverdale. ID Hwys. 34 and 36 diverge—stay on ID Hwy. 34 (left fork).

72.9/13.3 Road cut through Upper Proterozoic–Lower Cambrian Brigham Group quartzites.

76.2/3.3 Cross Bear River.

76.4/0.2 Turn right on gravel road (Maple Grove/Oneida Narrows Reservoir). Immediately, turn south toward Oneida Narrows Reservoir and parallel Bear River.

77.5/1.1 Cattle guard.

78.3/0.8 Small road cut in lower Spence/Lead Bell Shale. Park on right (west).

At this locality the Spence/Lead Bell Shale differs greatly from all other sites described herein. The basal portions are very dark and generally lack limestone. These beds contain abundant sponge spicules and agnostoid trilobites as well as a diminutive fauna of oryctocephalid trilobites, suggesting that this is the deepest environment represented by the basal Spence Shale.

Some 100 m further south along the road hike up ridge to east. Contacts between quartzites of the Brigham Group, Naomi Peak Limestone Member/Twin Knobs Formation and the Spence/Lead Bell Shale are exposed. Although the Spence/Lead Bell Shale is not well exposed on this ridge, meter-scale cyclicity is evident. Also, the upper Spence/Lead Bell Shale includes stringers of quartz sand which is in contrast to the other sites.

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