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Sequence stratigraphic relationships and facies architecture of Turonian-Campanian strata, Kaiparowits Plateau, south-central Utah

by

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ABSTRACT

Exposures of Turonian through Campanian strata in the Kaiparowits Plateau of southern Utah present a marvelous opportunity to study variations in facies architecture relative to stratal position within depositional sequences. Coeval facies tracts of nearshore, coal-bearing, crevasse splay, and alluvial plain strata form belts that are subparallel to the present-day escarpment of the Straight Cliffs. Examination of canyons that cut the Kaiparowits Plateau permit variations in facies architecture to be studied across almost 80 km of both depositional strike and dip. Five unconformity-bounded, depositional sequences have been recognized across the plateau. In addition to the sequence boundaries, maximum flooding surfaces in marine strata and their landward equivalents provide a framework that allows a systematic study of facies architecture and suggests that depositional facies are systematically partitioned within a depositional sequence.

Sequence boundaries have been interpreted on the basis of abrupt changes in depositional facies across erosional surfaces that reflect a lowering of base level. Coarse-grained, amalgamated fluvial deposits commonly overlie fine-grained floodplain strata, carbonaceous shales, nearshore strata, or coal-bearing deposits. Fluvial strata overlying these sequence boundaries exhibit an overall fining-upward character, have an increased proportion of preserved fine-grained sedimentary rocks, become increasingly isolated, and show evidence of tidal processes near the top. This succession is typical of transgressive systems tracts and correlates with retrogradational shoreface parasequences. Tidally-influenced fluvial deposits have been recognized as much as 65 km inland of a coeval shoreline deposit and have been correlated with marine condensed sections suggesting they are of chronostratigraphic importance; tidally-influenced fluvial deposits are temporally

equivalent with marine condensed sections. Sedimentary strata comprising the transgressive systems tract are overlain by a thick succession of floodplain deposits that contain vertically isolated channel belts. These alluvial strata have been traced to the east into thick crevasse-splay deposits and thick, extensive coal-bearing deposits. The coals, in turn, have been traced into a thick succession of aggradational shoreface parasequences. This succession of facies tracts comprise the highstand systems tract.

Both the regionally persistent sequence stratigraphic framework and the detailed variations in facies architecture have been interpreted in terms of base-level change (rather than sea-level change) and changes in accommodation space. These base-level cycles can be correlated to adjacent outcrop belts in Black Mesa, the San Juan Basin, and Wasatch Plateau. Based on this comparison as well as a comparison to the Haq et al (1988) eustatic curve, it is suggested that variations in facies architecture of Turonian through Campanian strata in the foreland basin of Utah reflect eustatic variations. Expressing variations in sequence stratigraphy and facies architecture in terms of base-level change should allow the models developed in the Kaiparowits Plateau to be applied to other sedimentary basins. It also suggests that facies variations can be predicted within depositional sequences. This has significant economic implications for petroleum reservoir prediction and exploitation.

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Chapter 1

PREFACE

The goal of this dissertation is to present the results of stratigraphic and sedimentologic research performed as partial fullfillment of the requirements for the Doctor of Philosophy degree at the Colorado School of Mines, Golden, Colorado. The Department of Geology and Geological Engineering at the Colorado School of Mines recently determined that dissertations may be written as a series of scholarly papers suitable for submission to appropriate scientific journals. With the approval of my dissertation examining committee, I have elected to follow this format as it allows the information and interpretations developed during this research to be disseminated in a timely manner.

This dissertation is organized around a series of "stand alone" papers each of which deals with a different facet of sequence stratigraphy and facies architecture as expressed in the outcrops of the Kaiparowits Plateau, Utah. To supplement these "stand alone" papers are additional chapters that provide background material and a summary of the major conclusions. Because of this format, introductory material related to the physical setting of the Kaiparowits Plateau is duplicated in several papers; after-all, there are only so many ways to describe where the Kaiparowits Plateau is! Chapter 2 provides introductory and background material concerning sequence stratigraphic concepts, ideas regarding facies architecture and sedimentary basin modeling, and previous research pertinent to this project. Chapter 2 provides the necessary material that allows this research to be properly placed in terms of historical context. This chapter is not intended to be submitted for publication. Chapter 3 provides a broad overview of sequence stratigraphic relationships and large scale facies architectural patterns as seen in the Kaiparowits Plateau region. This chapter has been submitted to the Geological Society of America for publication in *Geology* and is presently in review. Chapter 4 is a discussion of the sequence stratigraphic evolution of Turonian through Campanian strata in the Kaiparowits Plateau. Following the discussion of the Kaiparowits Plateau, regional sequence stratigraphic correlations between the plateau and adjacent outcrops are presented along with a correlation to the recent work of Haq et al. (1988). Finally, this paper utilizes observations made regarding the sequence stratigraphic evolution in the Kaiparowits Plateau to develop a model for petroleum reservoir prediction in siliciclastic strata. This paper will be submitted to the American Association of Petroleum Geologists for publication in the *Bulletin*. Chapter 5 is a detailed sedimentologic and hydrodynamic analysis of fluvial architecture from Turonian through Campanian strata in the Kaiparowits Plateau. The subtle criteria that allow sequence stratigraphic concepts to be applied to fluvial strata are discussed in this chapter and are used to further develop a sequence stratigraphic model. This chapter has been submitted to the International Association of Sedimentologists for inclusion in a special publication concerned with petroleum reservoir architecture edited by Stephen Flint (University of Liverpool) and Ian Bryant (KSEPL). This special publication is an outgrowth of the recent International Association of Sedimentologists meeting held in Nottingham, England; publication is expected during 1991. Chapter 6 is a detailed sedimentologic and hydrodynamic discussion of tidally-influenced river deposits and their importance in developing a high resolution sequence stratigraphic framework. This manuscript has been submitted to the International Association of Sedimentologists for publication in *Sedimentology*. Chapter 7 summarizes the major conclusions uncovered in this research program and outlines some topics for future consideration; these are the Cliff Notes edition of this dissertation! A comprehensive list of all references cited in the various manuscripts is included as Chapter 8.

Representative measured sections from Left Hand Collet Canyon, Tibbet Canyon, and Rock House Cove are contained in an Appendix. These sections were measured from the Turonian Tropic Shale to the Campanian Drip Tank Member of the Straight Cliffs Formation and record sedimentologic variation at the centimeter scale. These sections, and others form the basis of the interpretations presented in this dissertation. Because the vast majority of this research was funded by the U.S. Geological Survey, the three measured sections contained in this Appendix and others will be submitted during 1991 for publication with the U.S. Geological Survey as part of their Miscellaneous Field Studies series.

Chapter 2

SEQUENCE STRATIGRAPHIC RELATIONSHIPS AND FACIES ARCHITECTURE OF TURONIAN-CAMPANIAN STRATA, KAIPAROWITS PLATEAU, SOUTH-CENTRAL UTAH: BACKGROUND TO STUDY

INTRODUCTION

Sequence stratigraphy and facies architecture are, perhaps, the two most commonly used "buzz words" in sedimentology and stratigraphy at the present time. Geological conferences and special publications sponsored by organizations such as the American Association of Petroleum Geologists (AAPG), the Society for Sedimentary Geology (SEPM), and the International Association of Sedimentologists (IAS) have recently focused considerable attention on one or both of these topics at scales ranging from entire sedimentary basins to isolated petroleum reservoirs (e.g., Payton, 1977; Schlee, 1984; Berg and Woolverton, 1985; Wilgus et al., 1988; Crevello et al., 1989; Van Wagoner et al., 1990; Miall and Tyler, in press).

The intense interest in these topics stems primarily from the need for greatly improved stratigraphic models coupled with ever increasing demand for new petroleum reserves and more efficient drainage of existing reserves. While these models initially focused on stratigraphic variation at the scale of sedimentary basins they were soon coupled with detailed models of reservoir architecture (e.g., Galloway and Hobday, 1983). Combined with these relatively pragmatic needs has been the flourishing of quantitative models which have attempted to explain basin evolution and fill at a variety of scales (e.g., Cross, 1990). The quantitative nature of these models has required accurate, quantitative descriptions of sediment body geometry and has encouraged the integration of sequence stratigraphic concepts with those of detailed facies architecture.

While the integration of sequence stratigraphy and facies architecture may be highly desirable, there are relatively few published examples that document variations in architecture within the context of sequence stratigraphy and fewer still based on well exposed outcrops. Some notable exceptions include the work of Weimer (summarized in Weimer, 1983 and 1989), Muir et al. (1985), Goldhammer et al. (1987), Embry and Podruski (1988), Wilgus et al. (1988), Arnaud-Vanneau and Arnaud (1990), and Van Wagoner et al. (1990). The advantage to such an integration is that it begins to incorporate ideas on the rate at which accommodation space (Jervey, 1988) is created and filled with sediment and suggests that the stratigraphic record may be quite ordered at a variety of scales of observation. This in turn offers the hope that facies geometry may be accurately predicted at many differing scales in a variety of tectonic settings. These concepts are more fully developed in a subsequent section on sequence stratigraphy.

The combination of sequence stratigraphy and facies architecture suggests that sedimentary facies are carefully partitioned within the confines of a depositional sequence. Furthermore, it suggests that autocyclic processes that govern many of the characteristics of individual facies do so within the accommodation space that is governed by allocyclic controls. These concepts have direct economic application to the exploration and development of petroleum reservoirs, the exploitation of coal resources and sediment hosted ore deposits, development of ground water resources, and subsurface disposal of hazardous waste material.

Research Goals

The goals of this research were: (a) to determine the variation in stratal architecture in fluvial, coastal plain, and shoreface strata within the context of unconformity-bounded stratigraphic sequences, and (b) to test the hypotheses that the observed geometry, internal stacking patterns, and style of a depositional environment vary with respect to position within an unconformity-bounded stratigraphic sequence. The strata chosen for study to achieve these goals are the Turonian through Campanian of the Kaiparowits Plateau region of southern Utah. Outcrops in this area allow continuous examination of stratal relationships and facies variation along approximately 80 km of both depositional strike and dip. This research integrates what have largely been separate fields of research in sedimentology (facies analysis and facies models) and stratigraphy (correlation and stratal architecture).

Significance of Research

The results of this research should be of interest to stratigraphers, sedimentologists, and others interested in basin analysis and sediment architecture in both academia and industry. This research has direct economic benefits, particularily in the exploration for and development of fossil fuel resources. Recognition of a systematic variation in depositional architecture related to position within unconformity-bounded depositional sequences allows the details of reservoir shape, connectedness, and lateral and vertical extent to be inferred with somewhat limited data resources. As a result of this type of research we are able to look at newly discovered reservoirs, place them in a sequence framework, and begin to understand how reservoir geometry and connectedness are likely to develop.

Work completed thus far in the Kaiparowits Plateau has already made several new contributions to our understanding of stratigraphy and sedimentology. A new model has been proposed for coal accumulation within the John Henry Member of the Straight Cliffs Formation (McCabe and Shanley, 1988, 1990), and new models have been proposed to explain the evolution of fluvial and littoral strata within the plateau (Shanley and McCabe, 1989a,b, 1990; Hettinger, et al., 1990). Because this research program has been oriented towards elucidating controls on facies evolution and the role they occupy within a larger framework such as sequence stratigraphy, the results are applicable to other successions of strata. Theoretical consideration of accommodation space and base-level change suggest that the results of this research are not unique to this portion of the Western Interior basin, nor to this particular period of geologic time.

OVERVIEW OF SEQUENCE CONCEPTS, FACIES ARCHITECTURE, AND QUANTITATIVE STRATIGRAPHIC MODELS PERTINENT TO THIS STUDY

Sequence Stratigraphic Concepts

Sequence stratigraphic concepts suggest that the stratigraphic record is strongly ordered. This sense of order imparts a degree of predictability which is of economic appeal to those searching for petroleum reservoirs or those wishing to develop existing reservoirs. Furthermore, sequence stratigraphic concepts, and the correlations they provide, allow the construction of a chronostratigraphic framework of far greater resolution than is possible through radiometric or biostratigraphic means. When combined with the advances in geophysics and sedimentology over the last half-century, modern day sequence stratigraphic concepts suggest that sedimentary rocks in a wide variety of depositional environments and in a variety of tectonic settings are highly ordered and predictable in occurrence and geometry. Furthermore the development of sequence stratigraphic concepts has provided a conceptual framework for understanding the relationship between changes in base level and changes in sedimentary architecture. This has paved the way for detailed quantitative modeling of complex depositional systems within sedimentary basins.

Subdivision of the stratigraphic record into unconformity-bounded units (sequences) enjoys a rich and colorful history in the geological literature. Much of our present understanding of sequence stratigraphic concepts was largely put forward by L. L. Sloss at Northwestern University who identified six regionally extensive, unconformity-bounded packages of strata within the Phanerozoic of the North American craton (Sloss et al., 1949; Krumbein and Sloss, 1951; Sloss, 1963, 1988). These packages of strata were termed "sequences." A contemporary of Sloss, H. E. Wheeler at the University of Washington, also recognized unconformity-bounded sequences and extended stratal correlations from the craton into "geosynclines" (Wheeler, 1958, 1959a, b, 1963). This work led Wheeler to correlate unconformity surfaces with their correlative conformities a concept that was not fully developed until the 1970s (Mitchum et al., 1977). Although previous workers had recognized the temporal significance of unconformities in stratigraphic analysis (e.g., Grabau, 1924; Moore, 1936; Wanless and Shepard, 1936; Krumbein, 1942), it was Sloss and Wheeler who recognized major unconformities throughout the Phanerozoic record that could be correlated across much of North America. Because of the extensive nature of these unconformities, both Sloss and Wheeler considered that these unconformity-bounded sets of strata had chronostratigraphic significance and were the fundamental subdivision of the North American stratigraphic record (Krumbein and Sloss, 1951). Sloss (1988, p. 1662) suggested that "...the stratigraphy of a cratonic region is divisible into rational and useful packages by reference to major regional unconformities" and that unconformity-bounded sequences were, above all else, "...operational units." Despite efforts to popularize these concepts in contemporary textbooks (Krumbein and Sloss, 1951) the concepts of unconformity-bounded sequences were slow to be utilized beyond a small circle of "...former students and close acquaintances" (Sloss, 1988, p. 1663). An attempt by Chang (1975) to re-introduce the utility of unconformity-bounded stratigraphic units was largely ignored.

During the 1960s and 1970s the ranks of seismic interpreters at Exxon Production Research Company (EPR) in Houston, Texas were infused with graduates of Northwestern University who had been exposed to Sloss' sequence stratigraphic concepts. Their charge at EPR was to improve existing mapping techniques for petroleum exploration purposes. Before improvements could be initiated, however, significant advancements in recognizing and correlating time-stratigraphic units, as opposed to the more traditional rock-stratigraphic units, were needed. The sequence stratigraphic concepts developed at Northwestern were combined with a vast subsurface and outcrop database to address this pragmatic problem. Although several abstracts were published which testify to the emerging work at EPR in sequence and seismic stratigraphy (Vail and Wilbur, 1966; Vail and Sangree, 1971; Vail, 1975, 1977, Mitchum et al., 1976), it was not until publication of AAPG Memoir 26, Seismic Stratigraphy: Applications to Hydrocarbon Exploration (Payton, 1977) that sequence stratigraphy became "...instantly and widely popular ... as an object of either praise or abuse" (Sloss 1988, p. 1663).

Vail et al. (1977a) recognized widespread, unconformity-bounded stratal units that bore many physical similarities to the cratonic sequences described by Sloss and Wheeler. In Memoir 26, Mitchum et al. (1977) identified each of these stratal units as a depositional sequence which he defined as a "...stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities" (p. 53; notice the merging of ideas developed by both Sloss and Wheeler). Significantly, the depositional sequence as defined by Mitchum et al. (1977) was of less geographical extent, and spanned substantially less geologic time than those of either Sloss or Wheeler. Whereas Sloss's sequences were between 50 and 100 m.y. duration, the depositional sequences described by Vail et al. (1977a) range from 1-10 m.y. and were referred to as "third-order cycles" (Vail et al., 1977a). Because of the difference in scale between the depositional sequences recognized by Vail et al. (1977a) and Sloss' original sequences, the latter were elevated in hierarchy and termed supersequences (Vail et al., 1977a).

Perhaps the most critical concept emphasized by Vail et al. (1977a) was the chronostratigraphic significance of sequences, seismic reflections and stratal surfaces. This concept continues to generate heated debates and is a continuing source of confusion. Vail et al. (1977b, p. 99) stated "...primary reflections on a seismic section show chronostratigraphic correlation patterns rather than the gross lithostratigraphic units" and that "...seismic reflections approximate chronostratigraphic correlations." They further stated that stratal surfaces, which are a primary source of seismic reflections, are "...geologic-time surfaces because they are former depositional bedding surfaces that were synchronous over the area of their occurrence" (Vail et al., 1977b, p. 100). Unfortunately, it seems these statements have been, and still continue to be, interpreted as suggesting that seismic reflections and stratal surfaces are geologic time lines, perhaps equivalent in concept to ash layers or bentonite surfaces. The intent of Vail et al. (1977b) was to merge outcrop concepts developed by Campbell (1967) with seismic concepts. These concepts simply emphasize, albeit cryptically, that seismic reflections are like stratal surfaces and unconformities in that they have chronostratigraphic significance; they separate younger rocks from older rocks. These surfaces need not have formed instantaneously, nor over the same period of time. Although some exceptions to these temporal relationships have been noted (Christie-Blick et al., in press), they do not invalidate the concepts advanced by Vail et al. (1977b). As a result, seismic reflections, stratal surfaces at a variety of scales, and unconformities may be used to subdivide the stratigraphic record into mappable units that have chronostratigraphic significance.

Continued research in the late 1970s and early 1980s at EPR (Van Wagoner et al., 1990) refined sequence stratigraphic models through recognition of condensed sections and clarification of the sequence boundary unconformity concept (Vail and Todd, 1981; Vail et al., 1984). Accommodation space models (Jervey, 1988) led to the recognition that depositional sequences could be subdivided into smaller scale units termed "systems tracts," a modification of a concept originally proposed by Brown and Fisher (1977). Systems tracts were defined by bounding surfaces, and position within the depositional sequence, and were found to consist of genetically related strata that formed contemporaneous depositional systems (Brown and Fisher, 1977; Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner, 1985; Van Wagoner et al., 1987, Van Wagoner et al., 1988; Van Wagoner et al., 1990). The numerical models of Jervey (1988) and the conceptual models of Posamentier et al. (1988) suggest that stratal relationships similar to depositional sequences exist at a wide variety of scales all the way down to lamina and laminasets (Campbell, 1967; Van Wagoner et al., 1990) that span only a few minutes or days. This self-similarity or fractal nature of stratigraphic units is important when integrating facies architectural studies with the concepts of sequence stratigraphy.

While the principles of seismic stratigraphy were being formalized at EPR, other researchers both within and outside of Exxon were conducting extensive field and subsurface studies in an attempt to test the emerging sequence concepts. Many of these field projects were based on work whose origins can be traced back to the early part of this century and reflect continued interest in the recognition of major transgressive-regressive cycles of sedimentation. Among the most intensively studied stratigraphic intervals are the Carboniferous of Great Britain and North America (e.g., Logan 1845; Dawson, 1866; Wright et al., 1927; Weller, 1930, 1964; Moore, 1936; Wanless and Shepard, 1936; Ramsbottom, 1973, 1977; Belt, 1975), the Cretaceous of western North America (e.g., Sears et al., 1941; Weimer 1960; Hollenshead and Pritchard, 1961; McGookey, 1972; Kauffman, 1977), and the Tertiary of the Gulf Coast Basin (e.g., Frazier, 1974; Galloway et al., 1982; Galloway and Hobday, 1983). These works suggested that the duration of each cycle ranged from 1 to 8 m.y. per cycle, similar in scale to the third-order cycles of Vail et al. (1977).

Detailed study of these large scale transgressive-regressive cycles further revealed that they were composed of smaller scale, shallowing upward packages of strata. The marine flooding surfaces or transgressive surfaces that cap these shallowing upward units, although not an instantaneous geologic event, are thought to be chronostratigraphically significant (Campbell, 1967; Frazier, 1974). These smaller stratal units were arranged in regionally extensive geometric patterns (stacking patterns) and comprised the larger scale transgressive-regressive cycles. Although some differences in scale may exist, these building blocks are variously referred to as "genetic increments of strata" or "GIS" (Busch, 1959, 1971), "depositional episodes" (Frazier, 1974), "shallowing upward cycles" (Wilson, 1975), "mesothems" (Ramsbottom, 1977, 1979), "paracycles" (Vail et al., 1977), "fourth-order cycles" (Ryer, 1981b, 1984), and "punctuated aggradational cycles" or "PACs" (Goodwin and Anderson, 1985) to name but a few! In an attempt to link these smaller units of strata with the already established sequence terminology at EPR, Van Wagoner, a stratigrapher at EPR, coined the term "parasequence" to describe these fourth-order cycles (Van Wagoner, 1985; Van Wagoner et al., 1987; John Van Wagoner, personal communication, 1989). This term was selected to convey a genetic link to the larger depositional sequence defined by Mitchum et al. (1977). Van Wagoner (e.g., Van Wagoner et al., 1990, p. 1) defined a parasequence as a "... relatively conformable, genetically related succession of beds or bedsets bounded by marine-flooding surfaces or their correlative surfaces" and considered that they were a basic building block of sequences. Furthermore, the internal configuration of depositional sequences and sequence systems tracts was defined by parasequence stacking patterns (Van Wagoner, 1985; Van Wagoner et al., 1987; Van Wagoner et al., 1988; Van Wagoner et al., 1990). These stacking patterns are thought to reflect the subtle interactions between sediment supply, subsidence, and sea-level variation. Within the framework of parasequence stacking patterns and systems tracts, work by Van Wagoner (1985), Posamentier et al. (1988), Posamentier and Vail (1988), and Van Wagoner et al. (1990) suggest a predictable arrangement of depositional facies tracts. Posamentier and Vail (1988) further proposed that the internal facies architecture within each distinct depositional facies tract also reflects subtle changes in relative sea level. Jervey (1988) and Ross (1990) constructed numerical models to simulate stratigraphic architecture; changes in architecture were viewed in terms of changes in base level. These models resulted in similar predictions of stratal architecture as the conceptual models of Posamentier and Vail (1988) and Posamentier et al. (1988) that were based on changes in relative sea level. By the late 1980s, sequence stratigraphic concepts that were popularized in subsurface seismic studies were being successfully merged with detailed outcrop models and were ready to be integrated with concepts of facies architecture. Sequence stratigraphy has evolved as the detailed study of genetically related facies within a framework of chronostratigraphically significant surfaces (Van Wagoner et al., 1990). For those interested in additional background material concerning the evolution of sequence stratigraphic concepts, Busch and West (1987), Cross and Lessenger (1988), Schwans (1988), Sloss (1988), Sonnenfeld (1991), Van Wagoner et al. (1990), and Walker (1990) should be consulted.

Comment

Before continuing it is appropriate to consider the response to recent sequence stratigraphic concepts within the geological community. Concern exists that sequence stratigraphy, as presented, is simply a rehashing of old ideas with new names attached. This has been compounded by the fact that much of the data used to support these concepts has yet to be published. In particular, the lack of published data that would allow evaluation of the now popular "Vail curves" (Vail et al., 1977; Haq et al., 1987, 1988) has been the source of significant criticism of the entire sequence stratigraphy paradigm. The popularization and, perhaps cautious acceptance, of sequence stratigraphic concepts is a direct result of these concepts having been adopted, modified, tested, and now published by researchers who deal extensively in subsurface stratigraphic problems. Because of this, much of the original data that resulted in these concepts has been difficult to release to the scientific community as a whole. While it is true that many of the ideas contained within sequence stratigraphy had been previously proposed, their utility was uncertain and few comprehensive examples were offered for study. Furthermore, the state of knowledge in allied disciplines such as sedimentology and geophysics was unable to corroborate or refute sequence stratigraphic concepts. Within the confines of industrial reseach laboratories, where researchers have at their disposal a wealth of information related not only to outcrop exposures but also to the subsurface, these ideas were embraced. It was also in these same industrial research laboratories that major advances in both geophysics and sedimentology were being made. In some respects, the acceptance and development of sequence stratigraphic concepts was simply a matter of these ideas being nurtured in the appropriate environment. Whereas many of these ideas were previously of uncertain utility, within the petroleum industry they were, and continue to be, of tremendous utility.

Despite the arguments presented in support of these concepts, it is important to realize that sequence stratigraphic concepts are still largely based on subsurface observations and relationships from reflection seismic and well log data. There are few outcrop studies that provide criteria sufficient to document detailed sequence relationships and fewer still that allow the details of facies architecture to be understood in terms of sequences. This research program in the Kaiparowits Plateau adds to the growing body of outcrop based sequence stratigraphic studies.

Facies Models and Facies Architecture

While stratigraphic concepts were rapidly evolving following the 1960s, the science of sedimentology also underwent major changes. Prior to the late 1950s and 1960s, sedimentology and stratigraphy were closely allied disciplines. Sedimentology primarily focused on understanding the provenance, composition, and paleocurrents of large bodies of sedimentary rock, while stratigraphy was more concerned with the correlation and mapping of these sedimentary units (e.g., Krumbein and Sloss, 1951; Pettijohn, 1957;

Hatch and Rastall, 1965). Little attention was given to the origin of sedimentary rocks in terms of detailed depositional systems or depositional processes. Exceptions to this include the work of Kuenen and Migliorini (1950) and Fisk et al. (1954), however, these pioneer studies were not fully appreciated until much later.

During the1950s and early 1960s there was a revolution in sedimentology in which researchers began to compare modern depositional processes with observations made in ancient rock sequences. This heralded a period of time, which lasted for almost 20 years, during which many sedimentologists and stratigraphers parted and went their separate ways. Furthermore, detailed hydraulic engineering studies conducted by civil and hydraulic engineers in the 1930s through 1960s were "discovered" by geologists who were able to merge the concepts of hydraulic flow regime with variations in the type and scale of bedforms. Although the concept of variations in sedimentary structures as a function of flow conditions can be traced all the way back to Sorby (1852, 1859), it was not until the work of Simons et al. (1965) and Harms and Fahnestock (1965) that the flow regime concept and its implication for the analysis of sedimentary rock sequences was fully appreciated. The development of process oriented sedimentology resulted in detailed facies descriptions and the early development of detailed facies models. Examples of these early landmark studies include Bouma (1962), Allen (1965), Coleman and Gagliano (1965), de Raaf et al. (1965), Walker (1965) and Visher (1965). Much of this work was originally supported by major petroleum company research laboratories such as Shell Development Company and EXXON Production Company that had long recognized that an understanding of depositional processes and facies could significantly aid reservoir exploration and development. By the early 1970s a sufficient amount of data existed about both sedimentray processes and a wide range of facies models that early synthesis volumes began to appear in the literature (e.g. Allen, 1970; Selley, 1970; Shelton, 1973). Research into sedimentary hydrodynamics, depositional processes, and the construction of idealized facies models continued throughout the 1970s and early 1980s. The techniques and results of much of this research are summarized in Reineck and Singh (1980), Leeder (1982), Scholle and Spearing (1982), Galloway and Hobday (1983), Allen (1984), Walker (1984b), and Reading (1986), (the references to Reineck and Singh, 1980, Walker, 1984, and Reading 1986, all refer to second editions of immensely successful publications. The first editions were published in 1975, 1979, and 1978 respectively and represent the real milestones in the advance of sedimentology).

As models for depositional systems became increasingly complex and the need to understand three-dimensional geometry increased, researchers began to study the detailed architecture of sedimentary strata in exposures where lateral variability was easily observed (e.g., Campbell, 1976; Horne and Ferm, 1978; Ferm and Horne, 1979; Allen, 1983; Miall, 1985, 1988). Those interested in further review of the evolution of sedimentological thinking are referred to Middleton (1977), Anderton (1985), and Reading (1986).

Quantitative Stratigraphic Models

Changes in facies architecture with time have long been noted and models ranging from purely conceptual to quite sophisticated, mathematical treatments have been developed to improve our understanding of these changes. Pioneer attempts to model stratigraphic architecture include Barrell (1917), Sloss (1962) and Allen (1964). An increasingly sophisticated understanding of depositional systems and sequence stratigraphy has led researchers to propose changes in depositional architecture through geologic time as a function of either (or both) allocyclic and autocyclic processes. Allocyclic processes are those that are external to a given depositional system or sedimentary basin (such as eustasy) as opposed to autocyclic processes which are intrinsic to a depositional system (such as delta lobe switching).

Numerical models have been developed at a variety of temporal and spatial scales to simulate processes and products ranging from localized depositional events such as the filling of fjords (e.g. Syvitski and Farrow, 1989) to the filling of sedimentary basins (e.g., Lawrence et al., 1990). Intrinsic to many of those models that attempt to simulate stratigraphic architecture is the concept of accommodation space. Although this term was only recently defined (Jervey,1988), it was manifested in the early conceptual/numerical models of Barrell (1917), Sloss (1962) and Allen (1964). The concept of accommodation space is quite simple. "...In order for sediments to accumulate, there must be space available below base level (the level above which erosion will occur)" (Jervey, 1988, p. 47); it is the 'receptor' concept of Sloss (1962). The creation of this accommodation space is primarily a function of both eustatic fluctuation and tectonic subsidence. The stratigraphic architecture of sediments that fill the available space is largely controlled by the rate at which accommodation space is created or destroyed, the rate of sediment influx and dispersal, and the geographic position of sediment influx relative to the position where the rate of accommodation space is the greatest. The "trick" in numerical modeling of geologic systems at any scale is determining the relative importance of the processes that control accommodation space and sediment influx/dispersal. An overview to some of the considerations necessary for numerical modeling of geologic systems are found in various papers contained in Cross (1990).

Numerical models of stratigraphic architecture can be subdivided into three broad, and often overlapping, categories. By their very nature, all these mathematical models have distilled complex sedimentary processes and their interactions to a handful of major governing processes that are treated as process variables. Despite the necessary simplifications required by modeling, these models all suggest distinct, predictible, evolutionary trends in facies architecture. The first group of models are those that attempt to describe and understand discrete depositional systems and include the alluvial models of Bridge (1975), Allen (1978, 1979) and Bridge and Leeder (1979), and the deltaic models of Komar (1973) and Kenyon and Turcotte (1985). The second group of models attempt to simulate the evolution of sedimentary basins and their stratigraphic fill but do not dwell on the facies architecture within that fill beyond a consideration of broad regional stratal relationships. These include Sloss (1962), Allen (1964), and Flemings and Jordan (1989, 1990). The final group of models consider the evolution of sedimentary basins and their fill and also attempt to describe the facies architecture within the fill. These models include Blair and Bilodeau (1988), Heller et al. (1988), Jervey (1988), Lawrence et al. (1990), Ross (1990), and Jordan and Flemings (in press). Because of the range in scales considered by this this group of models, they are of particular interest to the field research in the Kaiparowits Plateau. Blair and Bilodeau (1988), Heller et al. (1988), Jervey (1988), and Jordan and Flemings (in press) consider the broad partioning of sediment between three major facies groups, marine, nonmarine, and deep marine within basin scale stratal boundaries. Lawrence et al. (1990) and Ross (1990) deal with this level of detail but in addition they attempt to describe parasequence stacking patterns in both marine and nonmarine systems within the scale of depositional sequences by incorporating the work of Bridge and Leeder (1979) and Allen (1983). Bridge and Leeder (1979) and Allen (1983) considered the evolution of floodplain strata and suggested that fluvial architecture, channel sandstone interconnectedness, and sand-shale ratios could vary with changes in floodplain aggradation. By integrating these concepts with the ideas of accommodation space, Lawrence et al. (1990) and Ross (1990) related changes in alluvial aggradation to changes in base level. In so doing, both Lawrence et al. (1990) and Ross (1990) attempted to relate the detailed evolution of facies architecture to a larger scale such as sequence stratigraphy and predicted a well defined evolution of stratigraphic architecture of fluvial, coastal plain and shoreface strata governed by base-level changes.

Discussion

A synergistic approach that integrates different scales of observation in terms of facies architecture and stratal relationships within the framework of sequence stratigraphy results in improvements in both sedimentologic and stratigraphic concepts. When these interpretations are based on field relationships observed in well exposed outcrops, the results may be used to judge and improve numerical models.

Considerable debate has existed in the literature about the utility of sequence stratigraphic concepts in foreland basins (e.g., Swift et al., 1987; Heller et al., 1988; Jordan and Flemings, in press). The consistent argument offered to negate the concepts of sequence stratigraphy within foreland basins is that unlike passive margins and intracratonic basins (where some of the early sequence concepts were developed), foreland basins typically have maximum sediment influx near the region with maximum subsidence. Because of this relationship, some have concluded that sequence boundaries will not develop and, therefore, the concepts of sequence stratigraphy cannot be applied (e.g., Swift et al., 1987;Jordan and Flemings, in press). The ideas of accommodation space and base level that were elaborated upon by Jervey (1988) combined with the work of Ross (1990) suggest that sediment architecture is not affected by the type of basin *per se*, but rather by the interaction of the creation of accommodation space and sediment influx. Consideration of sediment architecture in terms of these parameters allows the results of outcrop based research to be applied to a variety of depositional and tectonic settings throughout the span of geologic time; they provide a unifying concept that allows us to compare and contrast architectural styles in a variety of settings.

Turonian through Campanian strata that crop out in the Kaiparowits Plateau of southern Utah provide a rare opportunity to analyze facies architecture within several depositional sequences in detail. Exposures allow a thorough examination of nonmarine and shoreface strata along some 80 km of both depositional strike and dip; within the plateau, fluvial and coal-bearing strata grade north-eastward to high energy shoreface units. Because of these field relationships, this research successfully integrates changes in facies architecture with changes in position within a depositional sequence. The resulting stratigraphic architecture is interpreted to reflect changes in the rates of base-level change.

LOCATION OF STUDY AREA

The Kaiparowits Plateau is located in the southwestern protion of the Colorado Plateau region in southern Utah in Garfield and Kane Counties, between townships 33-43 south, and ranges 2 west and 8 east (Figs 1 and 2). The Kaiparowits Plateau is considered by the Sierra Club to be among the most remote regions in the contiguous forty-eight states. Access to the plateau is by Utah Route 12 which runs from Escalante to Henrieville, by two all-weather roads that are maintained by the Bureau of Land Management (BLM), by scattered jeep trails, and finally through extensive hiking. The nearest towns to the plateau are Page, Arizona (population approximately 6500) approximately 50 km to the

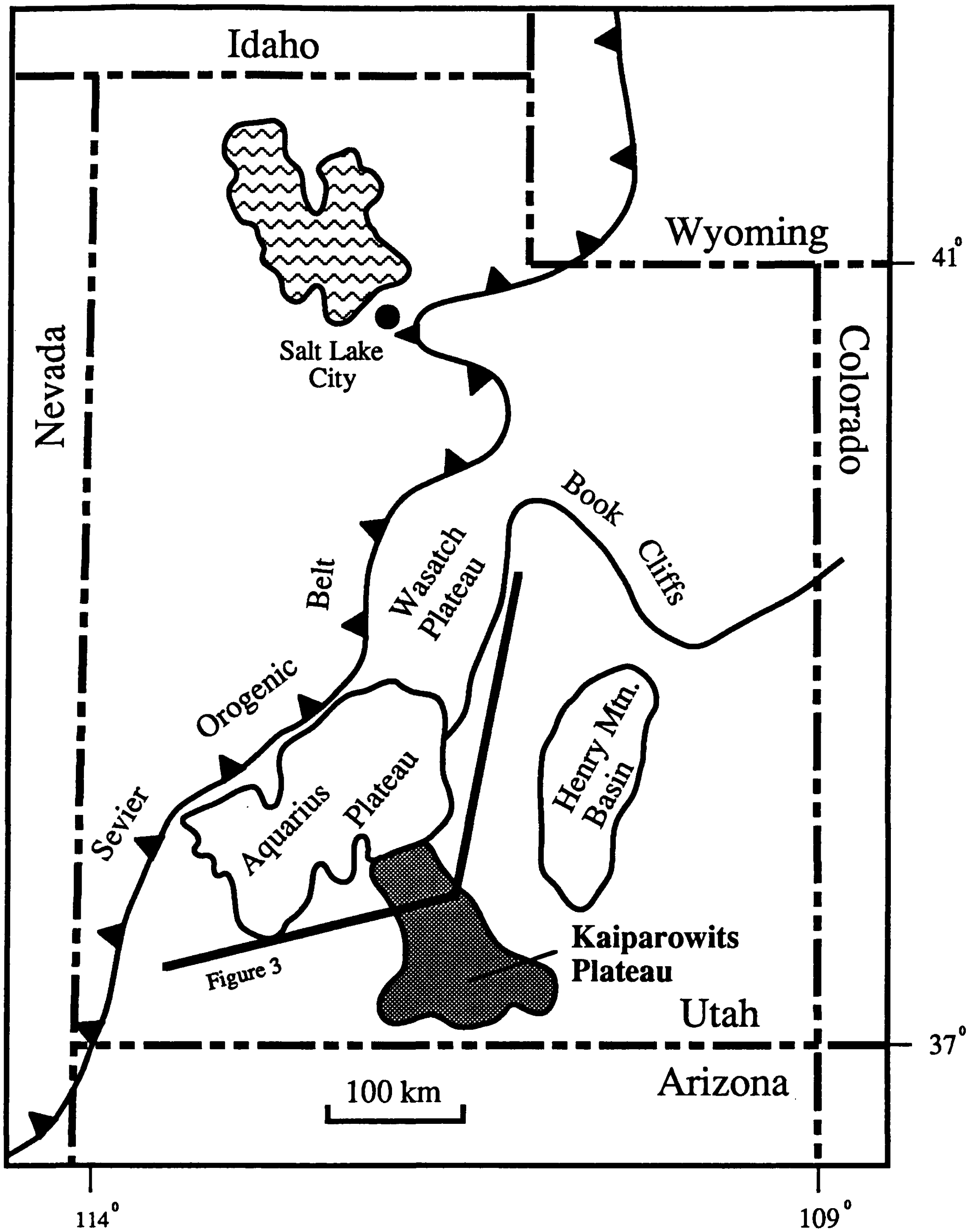


Figure 1. Regional map illustrating the location of the Kaiparowits Plateau within Utah. The line of section illustrates the position of the cross section shown in Fig. 3.

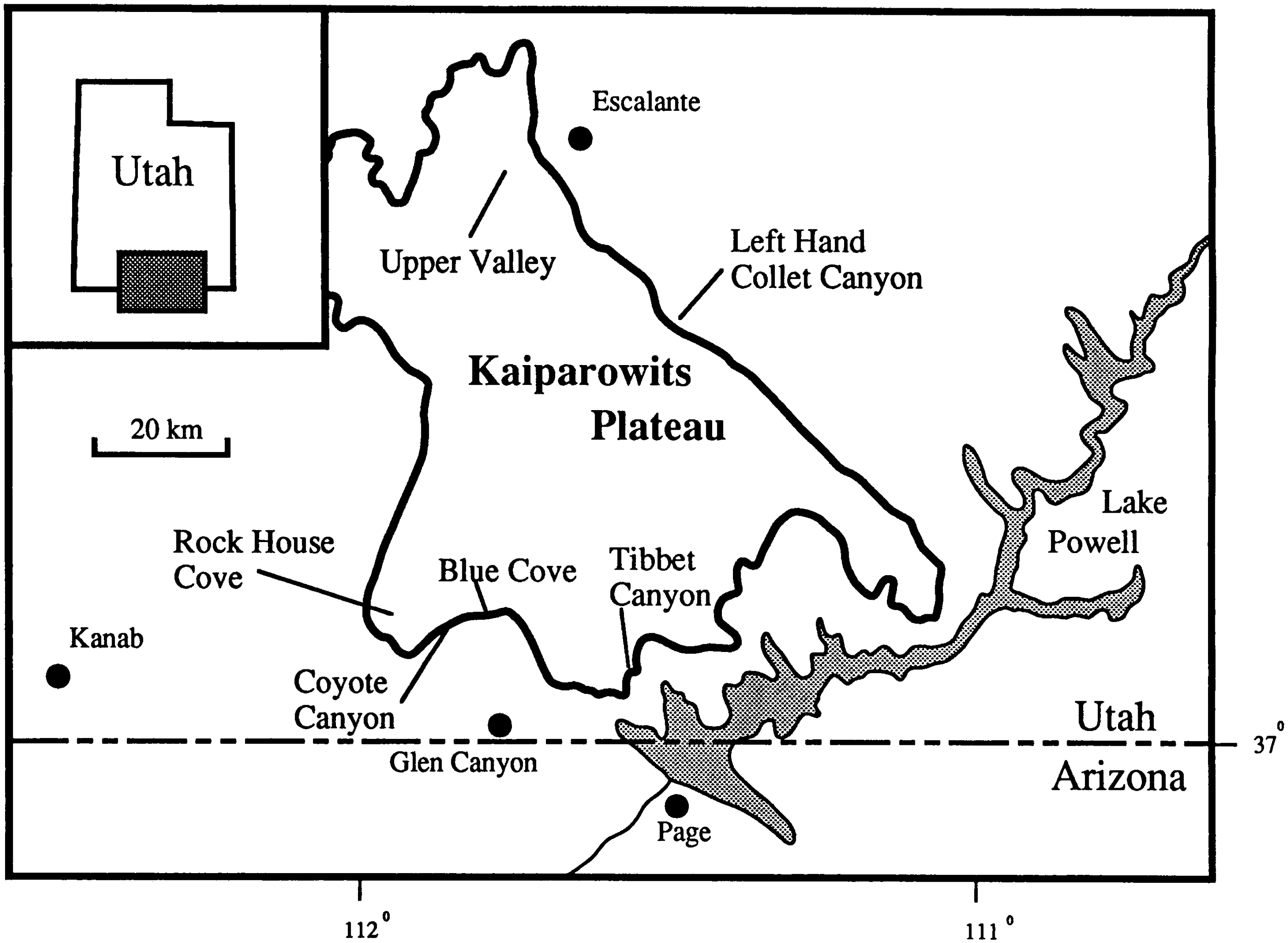


Figure 2. Detailed location map for the Kaiparowits Plateau in southern Utah. Localities referred to in the text are shown for reference purposes. In general, the northeastern part of the plateau consists of shoreface deposits which grade into coal-bearing strata in the central plateau. These in turn grade into alluvial strata towards the west and southwest.

southeast, Kanab, Utah (population approximately 2000) some 80 km to the southwest, Escalante, Utah (population approximately 400) at the confluence of the Escalante River and Alvey Wash to the north of the plateau, and Glen Canyon City, Utah (population approximately 25) on the southwest side of Wahweap Canyon on U.S. Highway 89. There are no permanent habitations within the plateau itself. The land is primarily controlled by the BLM and there are few if any restrictions regarding access. Cattle grazing is the main use of the land. To date, Escalante, Kanab, and Page have all been used a base of operations for field work.

The quality of the exposures is, in general, excellent. Sparse vegetation throughout much of the area allows for detailed correlation of strata, especially the more resistant sandstones. When the fine-grained strata are properly trenched, detailed measured sections averaging more than 95% coverage are possible. Some difficulties are encountered in the vicinity of coal-bearing strata where extensive surface burns of coal have occurred. This problem is particularily acute in the southeastern part of the Kaiparowits region where surface burns have affected many miles of outcrop.

The Straight Cliffs escarpment borders the Plateau on the northeastern margin, is approximately 300-600 m high, and is approximately parallel to depositional strike of the Turonian-Santonian paleoshoreline. Outcrops along this margin of the plateau extend for approximately 80 km. The southern margin of the plateau, Left Hand Collet Canyon in the central plateau, and Utah Route 12 to the north, provide exposures outcrops parallel to depositional dip. This combination of both strike and dip orientations allows an accurate three-dimensional reconstruction of detailed facies architecture within a depositional sequence framework.

STRUCTURAL SETTING AND LATE CRETACEOUS STRATIGRAPHY

Structural Setting (Late Cretaceous and present structure)

The purpose of this section is to briefly describe the structural setting of the Kaiparowits Plateau region as it pertains to this research. The Kaiparowits Plateau is located in the southwestern part of the Colorado Plateau region in southern Utah (Fig. 1). The Colorado Plateau region consists of broad anticlines and synclines that were uplifted and intruded beginning in the Miocene (Lucchitta, 1979, 1989; Thompson and Zoback, 1979; Hunt, 1980; Cross, 1986). The present outcrop configuration in the Kaiparowits Plateau region was largely established by the late Miocene-early Pliocene (Lucchitta, 1979; F. E. Peterson, personal communication) as the Colorado River assumed its present course and began controlling headward erosion into the broad plateaus of the Colorado Plateau. The structural configuration of the Kaiparowits Plateau (Vaninetti, 1978; Sargent and Hansen, 1982) is one of gentle, north to northwest trending asymmetrical anticlines and synclines that plunge slightly to the northwest. Average structural dips within the plateau are generally less than 3°. The plateau is locally cut by several high-angle normal faults, however, displacement across these faults is minimal and does not hamper detailed stratigraphic and sedimentological investigations.

During much of the Cretaceous a north-northeast trending highland region, known as the Sevier Orogenic Belt (Armstrong, 1968), extended from southern Idaho into southern Nevada (e.g., Burchfiel and Davis, 1975). This structural feature is part of an extensive Cordilleran orogenic fold and thrust belt that extended from northern Canada and Alaska into southern Mexico. A foreland basin developed parallel to this orogenic belt whose subsidence was controlled by flexural loading of the lithosphere by successive thrust plates and synorogenic sediment (e.g., Armstrong, 1968; Price, 1973; Royse et al., 1975, Jordan, 1981; Cross, 1986). This foreland basin was periodically flooded with an epicontinental sea that extended from Arctic Canada to the Gulf of Mexico, a distance of some 5000 km, and from western Utah to Iowa, a distance of some 1500 km (Williams and Stelck, 1975; Kauffman, 1977, 1984) during maximum Cretaceous eustatic highstand. The region now known as the Kaiparowits Plateau occupied a position along the western margin of this Interior Cretaceous Seaway, approximately 120 km to the east of the leading edge of the Sevier Orogenic Belt.

Timing of structural deformation within the Sevier Orogenic Belt and the associated response within the foreland basin has been a topic of considerable controversy. The controversy is significant not only for studies of the Sevier, but also for its implications for sedimentation within the foreland basin. Several researchers (e.g., Armstrong, 1968; Wiltschko and Dorr, 1983; Lawton, 1985; Villien and Kligfield, 1986; Burbank et al., 1988) have suggested that the timing of thrust faults can be interpreted on the basis of the ages of synorogenic conglomerates. These interpretations place the onset of thrusting within the Sevier in central Utah at the mid-late Albian and suggest that thrusting was episodic through the Maastrichtian and Paleocene. While this technique has long been used in the study of foreland basins, problems may exist concerning the timing of erosion and sediment transport relative to thrusting and isostatic adjustment. These concerns are reflected in Jordan et al. (1988), and Steidtmann and Schmitt (1988) and have resulted in models suggesting tectonic subsidence and erosion and transport of synorogenic sediments to be out of phase with each other (Blair and Bilodeau, 1988; Heller et al., 1988; Flemings and Jordan, 1990).

An alternate technique to date the onset of thrusting has been the use of geohistory or backstripping analysis. This technique (Cross, 1986; Heller et al., 1988) suggests that increased rates of tectonic subsidence reflect the onset of thrusting within the orogenic front. This interpretation places the onset of thrusting in central Utah during the Albian-Aptian. Jordan et al. (1988) and Flemings and Jordan (1989, 1990) both suggest that the backstripping technique more likely reflects proximity to the foredeep and may not yield accurate results when used to interpret the onset of thrusting.

Comment

Examination of the literature surrounding the timing of deformation within the Sevier and its possible effect on stratal patterns reveals an *a priori* assumption by many authors that stratal patterns are dominated by a tectonic signature and that eustatic effects are minimal or insignificant. While many primary sources clearly state a working assumption that eustatic changes are negligible (e.g., Wiltschko and Dorr, 1983) subsequent workers who have relied on these primary sources have often overlooked this critical assumption in presenting arguments that favor a tectonic control to stratal architecture. The emphasis should not be on whether the stratal patterns are tectonically or eustatically controlled. They are the product of changes in accommodation space which reflects both eustatic and tectonic components. If we regard base level much as Sloss (1962) did as an imaginary "...equilibrium surface ... above which a particle can not come to rest and below which deposition and burial are possible" (p. 1051) and that changes in base level control accommodation space, we can then relate changes in stratal architecture to depositional sequences in a variety of tectonic settings. At the scale of supersequences (Vail et al., 1977; Vail et al., 1990) or composite sequences (Van Wagoner and Mitchum, 1989) accommodation space is certainly controlled by large scale tectonic subsidence patterns reflecting lithospheric loading. However, at the scale of individual depositional sequences the stratal effects due to eustasy cannot be ignored (Devlin et al., 1990; Devlin and Shaw, 1990).

Lithostratigraphy

Figure 3, from Ryer (1981b), illustrates general stratigraphic relationships and correlations for Cenomanian through Campanian strata in south-central Utah. Stratigraphic nomenclature in the Kaiparowits Plateau was initially established by Gregory and Moore (1931) and subsequently modified by Peterson (1969b).

Middle Turonian strata in the Kaiparowits Plateau include marine shales of the Tropic Shale and shoreface sandstones of the Tibbet Canyon Member of the Straight Cliffs Formation. These strata interfinger with one another and are overlain by nonmarine strata of the Smoky Hollow Member of the Straight Cliffs Formation which is interpreted (Peterson, 1969a,b) as late Turonian. The nonmarine rocks of the Smoky Hollow Member are overlain by shoreface sandstones, nonmarine strata of fluvial origin, and coal-bearing strata of the John Henry Member of the Straight Cliffs Formation. The John Henry Member spans the Coniacian and Santonian and is overlain by the Drip Tank Member of the Straight Cliffs Formation which is of Campanian age and of fluvial origin. Conventional interpretations of these strata (Peterson, 1969a; Ryer, 1984) have generally regarded them as broadly coeval with a single unconformity of somewhat uncertain origin and undetermined lateral extent separating the Smoky Hollow and John Henry Members (Fig. 3). Although these correlations are consistent with existing biostratigraphic data and describe the broad temporal relationships present within the plateau, they do not account for facies tract dislocations or changes in facies architecture.

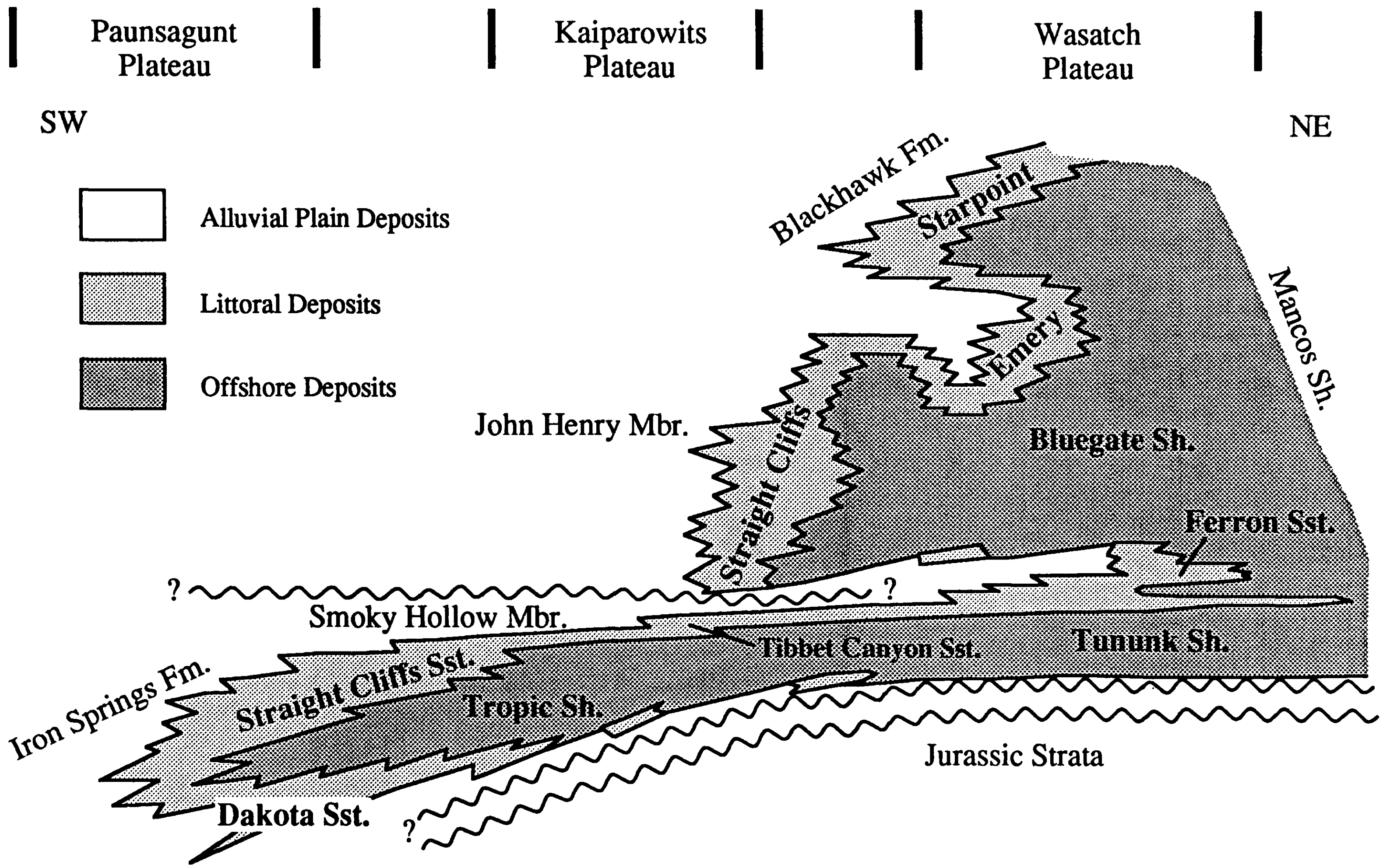


Figure 3. Stratigraphic cross section illustrating lithostratigraphic relationships and nomenclature for Cretaceous strata in southern and central Utah. Modified from Ryer (1981b).

Biostratigraphy

Detailed paleontological studies of Cretaceous strata in the Western Interior Basin that began with the early territorial surveys (summarized in Waage, 1975) have resulted in a well defined biostratigraphic framework. These studies and their many refinements provide the basis for biostratigraphic correlation today. Significant biostratigraphic studies that recognize the utility of ammonites for purposes of widespread correlation, especially in marine shale strata, include Cobban (1951, 1973, 1976), Cobban and Reeside (1952), Gill and Cobban (1966), and Cobban and Scott (1972). Ammonite biostratigraphy was initially linked with radiometric dates based on a study of potassium-argon (K/Ar) isotopic variation obtained from widespread bentonite rich horizons present within known ammonite zones (Obradovich and Cobban, 1975). These radiometric-biostratigraphic correlation studies are ongoing with the absolute age dates in a constant state of flux as improved techniques become available (the effect of recent Ar/Ar dating is an example, Obradovich personal communication 1990).

Although ammonite zonation is extremely useful in marine shales, paleo-environmental conditions render it of more limited use in shoreface sediments. Kauffman investigated the use of Cretaceous bivalves, especially the Inoceramids, and found that not only did they have a wide environmental range but also a rapid evolution. By incorporating both ammonite and Inoceramid biozones, Kauffman (1975, 1977) and Kauffman et al. (1976) were able to construct a more detailed and more utilitarian biostratigraphic framework. Continued study of Cretaceous bivalves, especially the inoceramids, has resulted in ever-increasingly detailed biostratigraphic range charts (Fouch et al., 1983; Kauffman and Pratt, 1985; Merewether and Cobban 1986; Hancock et al., 1988; and

Collom 1991). This thesis utilizes the biostratigraphic zonation charts of Collom (1991) for purposes of biostratigraphic correlation (Fig. 4).

Fossil collections from middle Cretaceous strata in the Kaiparowits Plateau region are limited to those gathered by Peterson (1969a), Eaton (1987) and this study, reflecting the limited number of stratigraphic and sedimentologic studies that have been conducted within the plateau. Fossils collected from the marine Tropic Shale range from the upper Cenomanian *Sciponoceras gracile* biozone to the middle Turonian *Collignoniceras woollgari woollgari* biozone (Peterson, 1969a; Eaton, 1987). The overlying shoreface strata of the Tibbet Canyon Member of the Straight Cliffs Formation contains fossils that indicate the middle Turonian *Collignoniceras woollgari woollgari* biozone in the the southwestern part of the Kaiparowits Plateau and fossils indicative of the upper part of the middle Turonian *Prionocyclus hyatti* biozone in the central and eastern Kaiparowits Plateau. This age range is consistent with the progradational nature of the Tibbet Canyon Member. Age diagnostic fossils have yet to be found throughout much of the nonmarine strata of the Smoky Hollow Member, although a single inoceramid with lower Coniacian affinities (*Cremnoceramus deformis (early) or Cremnoceramus erectus (late)*) has been found approximately 3 m below a regionally extensive transgressive surface along the eastern Kaiparowits Plateau (R. D. Hettinger, personal communication 1990). The lowest marine strata of the John Henry Member contains fossils belonging to the middle Coniacian *Scaphites ventricosus* biozone. Shoreface strata of the John Henry Member have not yielded rich fossil collections, perhaps reflecting the high energy nature of these strata and/or the acidic nature of groundwaters generated within adjacent mires. Shoreface deposits of the lower John Henry have yielded lower Santonian fossils indicative of the *Scaphites depressus stantoni* biozone whereas the uppermost portions of the John Henry Member contain fossils

Figure 4. Biostratigraphic range chart summarizing Inoceramidae and Ammonoidea biozones for the upper Cenomanian through lower Campanian modified from Collom (1991). These biozones are listed opposite the reference section from Pueblo, Colorado. The ages of stage boundaries have been taken from Haq et al. (1988).

Series	Stage	Substage	Age (myr)	Formation & Mbr., Pueblo Section		Biostratigraphy - Western Interior Craton, North America: Inoceramidae zones	Ammonoidea zones	
Middle Cretaceous	Turonian	Middle		Carlile	Fairport	*I. cuvieri (late)*	*Collignoniceras woolgari regulare*	
						Mytiloides hercynicus *I. cuvieri (early)*		
						M. subhercynicus *M. labiatus labiatus*	*Collignoniceras woollgari woollgari*	
		Lower		Greenhorn Limestone Fm.	Bridge Creek Lst.	*M. labiatus (early)*		
						M. mytiloides arcuata	*Mammites nodosoides*	
						M. mytiloides mytiloides	*Watinoceras coloradooense* *Vascoceras birchbyi*	
						Mytiloides opalensis *Mytiloides duplicostatus*	*Watinoceras reesidei* *Pseudaspidoceras flexuosum*	
						Mytiloides submytiloides		
	Cenomanian	Upper	92			*I. pictus pictus*	*Neocardioceras juddi*	*Nigericeras scotti*
								Vascoceras cauvini *Vascoceras gamai*
						I. tenuiumbonatus	*Sciponoceras gracile*	*Euomphaloceras septemseriatum*
								Vascoceras diartianum
					Hartland	*I. pictus neocaledonicus*	*Metoicoceras mosbyense* *Dunveganoceras albertense*	
						I. flavus pictoides *I. pictus gracilistriatus*		
					Lincoln Lst.	*I. prefragilis stephensoni*	*Calycoceras canitaurinum* *Dunveganoceras pondi*	
						I. prefragilis prefragilis	*Plesiacanthoceras wyomingense*	

Figure 4

Series	Stage	Substage	Age (myr)	Formation & Mbr., Pueblo Section		Biostratigraphy - Western Interior Craton, North America: Inoceramidae zones	Ammonoidea zones	
	Con		89	Niobrara	Ft. Hays	*Cremnoceramus erectus (early)*	*Peroniceras haasi*	
Middle Cretaceous	Turonian	Upper				*Mytiloides fiegei fiegei* *Mytiloides incertus* *Mytiloides dresdensis dresdensis*	*Prionocyclus quadratus*	*Scaphites corvensis*
				Carlile	Sage Breaks	*I. aviculoides* *Mytiloides striatoconcentricus*		*Scaphites nigricolensis*
						I. perplexus perplexus	*Scaphites whitfieldi* *Prionocyclus novimexicanus*	
					Juana Lopez	*I. dimidius (late)*	*Prionocyclus wyomingensis*	*Scaphites ferronensis* *Scaphites warreni*
						I. dimidius dimidius	*Prionocylus macombi*	*Coilopoceras inflatum* *Coilopoceras colleti*
		Middle			Codell	*I. howelli* *I. costellatus (late)*	*Prionocyclus hyatti*	*Coilopoceras springeri*
					Blue Hill	*I. securiformis* *I. costellatus (early)*		*Hoplitoides sandovalensis* *Scaphites carlilensis*
						I flaccidus	*Prionocyclus percarinatus*	
					Fairport	*I. cuvieri (late)*	*Collignoniceras woolgari regulare*	
						Mytiloides hercynicus *I. cuvieri (early)*		

Figure 4-cont.

Series	Stage	Substage	Age (myr)	Formation & Mbr., Pueblo Section			Biostratigraphy - Western Interior Craton, North America: Inoceramidae zones	Biostratigraphy - Western Interior Craton, North America: Ammonoidea zones	
			88						
Upper Cretaceous	Coniacian	Upper		Niobrara	Smoky Hill	Lower Lst	*Magadiceramus subquadratus*	*Baculites codyensis*	
						Lower Shale	*Mytiloides stantoni stantoni*	*Scaphites ventricosus*	*Baculites asperiformus*
							Volviceramus involutus involutus		*Scaphites* \ *impendicostatus*
		Middle					*Cremnoceramus wandereri* *Cremnoceramus schloenbachi*		
						Shale & Lst.	*Cremnoceramus koeneni* *Cremnoceramus schloenbachi*	*Scaphites preventricosus*	*Forresteria forresteri*
							Cremnoceramus browni *Cremnoceramus inconstans*		*Peroniceras westphalicum*
		Lower			Ft. Hays		*Cremnoceramus deformis (late)* *Cremnoceramus inconstans*		*Scaphites mariasensis*
							Cremnoceramus deformis deformis		
							Cremnoceramus deformis (early) *Cremnoceramus erectus (late)*		*Forresteria hobsoni*
							Cremnoceramus erectus erectus		
							Cremnoceramus rotundus *Cremnoceramus erectus (early)*		*Peroniceras haasi*

Figure 4-cont.

Series	Stage	Substage	Age (myr)	Formation & Mbr., Pueblo Section			Biostratigraphy - Western Interior Craton, North America: Inoceramidae zones	Biostratigraphy - Western Interior Craton, North America: Ammonoidea zones
Upper Cretaceous	Campanian	Lower		Niobrara Limestone Fm.	Smoky Hill Mbr.	Upper Chalk		
							I. dariensis (?)	*Baculites obtusus*
								Scaphites leei
							I. vancouverensis	*Haresiceras natronense*
								Scaphites hippocrepis III
						Upper Shale	Inoceramids not well known	*Haresiceras placentiforme*
								Scaphites hippocrepis II
							Inoccramus elegans	*Haresiceras montanaense*
							Sphenoceramus lingula	*Scaphites hippocrepis I*
	Santonian	Upper	84					*Desmoscaphites bassleri*
							Sphenoceramus patootensis	*Desmoscaphites erdmanni*
						Middle Chalk	*Cordiceramus bueltenensis*	*Clioscaphites choteauensis*
		Middle				Middle Shale	*Cordiceramus cordiformis*	*Clioscaphites vermiformis*
							Platyceramus platinus	*Clioscaphites saxitonianus*
		Lower					*Cladoceramus undulatoplicatus*	*Scaphites depressus stantoni*
			88			Lwr. Lst.	*Magadiceramus subquadratus*	*Baculites codyensis*

Figure 4-cont.

belonging to the the lower Campanian *Scaphites hippocrepis* biozone. These uppermost fossils were interpreted by Eaton (1987) to belong to the upper Santonian *Desmoscaphites bassleri* biozone.

PREVIOUS WORK WITHIN THE KAIPAROWITS REGION

Because of the remote nature of the Kaiparowits Plateau there have been relatively few geological investigations within the plateau. The first comprehensive report concerning the geology of the region was gathered by Gregory and Moore between 1915 and 1927. The results of their study were published as a U.S.G.S. Professional Paper in 1931. This work describes scattered observations made by earlier travelers to the region and established the stratigraphic framework and nomenclature that is still in use today with minor revisions. Prior to the 1960s, the only geological investigations of note within the Kaiparowits Plateau were by Zeller (1955), who conducted a preliminary study of the uranium potential of the region, and Dow and Batty (1961) who described the occurrence of titaniferous sandstones in the John Henry Member.

During the 1960s, Cretaceous strata in the Kaiparowits region became the focus of several long-term geological investigations. The ongoing search for commercial coal reserves in Utah resulted in several studies being commissioned by the Utah Geological Survey. These were oriented towards providing an estimate of the coal reserves within the plateau and are summarized in Doelling and Graham (1972). Increased interest in the coal resources of this region prompted the U. S. Geological Survey and the Bureau of Mines to begin research in the Kaiparowits Plateau area. General geological reports for the Bureau of Mines were prepared by Grose (1965), and Grose et al. (1967). These were followed by detailed U.S.G.S. quadrangle maps (Peterson and Horton, 1966; Peterson and Waldrop, 1966; Waldrop and Peterson, 1966; Waldrop and Sutton, 1966a, b, c; Peterson, 1966, 1973; Bowers, 1973a, b, c, 1975, 1981, 1983; Peterson and Barnum, 1973a, b; Stephens, 1973; Zeller, 1973a, b, c, d, 1978, 1990a, 1990b; Zeller and Stephens, 1973; Zeller and Vaninetti, 1990). These reports did not attempt detailed investigations of facies architecture, sedimentology, or regional sequence stratigraphic relationships.

Much of the stratigraphic data collected by the U.S.G.S. including formal designations and descriptions of type sections for the members within the Straight Cliffs Formation are found in Peterson's doctoral dissertation (1969a, b). This and subsequent reports (Peterson and Ryder, 1975; Peterson and Kirk, 1977; and Peterson et al., 1980; Molenaar, 1983a) attempt to provide a regional framework for Turonian through Campanian strata in the Kaiparowits Plateau region.

Detailed studies of facies relationships of Cretaceous strata in the Kaiparowits region are scant. Vaninetti (1978; Johnson and Vaninetti, 1982) considered the Straight Cliffs Formation to be a wave dominated deltaic setting similar in many respects to the Book Cliffs region of central Utah. Eaton (1987) summarized previous sedimentological work and studied vertebrate fossils in the southern Kaiparowits Plateau region. Sanchez and McCabe (1988) studied limited exposures of the lower portion of the John Henry Member in the vicinity of the Shakespeare Mine and found ample evidence of tidal processes. A detailed study of the 'Calico bed' portion of the Smoky Hollow Member is in progress by Margaret Bobb at the University of Colorado, Boulder, Colorado (Bobb and Ryer 1990; Bobb, 1991).

METHODOLOGY

The nature of this project required a multifaceted approach. Sequence stratigraphic relationships required detailed sections measured from the Tropic Shale to the Driptank Member of the Straight Cliffs Formation. Interpretation of these sections identified significant facies tract dislocations associated with sequence boundary unconformities, transgressive surfaces of erosion (ravinement surfaces), condensed sections and their nonmarine counterparts, and parasequence stacking patterns. Sections were measured in Alvey Wash, Left Hand Collet Canyon, Rock House Cove, Tibbet Canyon, Blue Cove, and Coyote Canyon (Fig. 2). Stratal correlations are based on analysis of the stacking patterns of parasequences, and visual correlation both in the field and on extensive panorama photographs.

Treatment of the facies architecture and its relationship to sequence stratigraphy required a combination of closely spaced detailed sections and panorama photographs within the framework established by the larger scale sequence stratigraphic study; in essence a series of small scale detailed studies have been conducted within the framework of a larger scale study. Detailed analyses of shoreface to coal-bearing strata were carried out in Left Hand Collet Canyon. The transition from coal-bearing to barren strata was studied in Tibbet Canyon, incised valley fill strata were studied in the Rock House Cove-Blue Cove area, and tidally reworked shoreface strata were studied throughout much of the southern plateau.

All sections have been measured so as to record stratigraphic variation at the centimeter scale. Measured sections were drafted at a scale of 1:40 which allows almost all of the recorded sedimentological variation to be recorded. Where talus obscured much of the fine-grained interval, shovels and mattocks were used to trench through the talus so that as complete a section as possible could be obtained. All measured sections averaged more than 95% stratigraphic completeness. Lateral variations were described and recorded through careful field photography, acquisition of smaller detailed sections, and by walking beds out.

Because of the nature of this research and the scale of the outcrops in the Kaiparowits Plateau, it has not been possible to accurately describe all facies relationships throughout the plateau. Detailed studies were conducted in several areas where critical changes were observed. By carefully monitoring the facies succession throughout the plateau it was possible to accurately characterize the facies architecture and sequence stratigraphy of these strata.

Chapter 3

PREDICTING FACIES ARCHITECTURE THROUGH SEQUENCE STRATIGRAPHY-AN EXAMPLE FROM THE KAIPAROWITS PLATEAU, UTAH

ABSTRACT

Recognition of depositional sequences in Turonian through Campanian strata in the Kaiparowits Plateau allows examination of facies-tract geometries within coeval shoreface, alluvial, and coal-bearing strata. Changes in depositional architecture, sandstone-connectedness, sand-shale ratios, coal-bed geometry, and degree of shoreface and foreshore preservation are related to position within a depositional sequence. Base-level falls produced regionally extensive sequence boundary unconformities and a basinward shift in facies tracts. Slow rates of base-level rise resulted in amalgamated fluvial channel complexes, thin discontinuous coal beds, and progradational shoreface parasequence sets. More rapid rates of base-level rise produced vertically isolated meander-belt sandstones, thick extensive coal beds, and aggradational shoreface parasequence sets. The highest rates of base-level rise resulted in tidally influenced fluvial systems present at least 60 km inland of coeval shoreface deposits, restricted coal beds, and retrogradational shoreface parasequences. The prediction of depositional architecture from a limited understanding of broad basin stratigraphy based on outcrop models derived from the Kaiparowits Plateau may substantially help in the search for economic deposits hosted in sedimentary sequences.

INTRODUCTION

The ability to predict depositional architecture from limited data has significant economic implications for the exploration and development of petroleum reservoirs, sediment-hosted mineral deposits, coal-resource evaluation, and aquifer management. Recently developed sequence stratigraphic models (e.g., Vail et al., 1977; Haq et al., 1987; Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990) suggest that depositional facies are arranged in a predictable fashion within the confines of a depositional sequence. These concepts, combined with those of facies architecture, suggest that sediment-body geometry varies in a systematic manner depending on position within a depositional sequence. The implications of an ordered arrangement of sedimentary facies are profound; fluvial channel sandstone interconnectedness, net sandstone ratios, coal-bed extent, and degree of shoreface and foreshore preservation should be predictable by studying sequence-stratigraphic relations and variations in facies patterns. In this paper we show how depositional architecture in alluvial, coal-bearing, and shoreface strata vary within a sequence stratigraphic framework and conclude that depositional architecture may be accurately predicted when viewed in a sequence stratigraphic context. Because the results of this work are considered in terms of base-level response they are applicable to a wide variety of basin types, not just the mid-Cretaceous of southern Utah.

Prior to widespread application of sequence stratigraphic concepts, facies variations in sedimentary strata were generally interpreted to be dominated by autocyclic processes (e.g., Walker, 1984; Reading, 1986). These models make no suggestion that facies tracts occur in a predictable pattern. The advent of sequence stratigraphic concepts and their merging with detailed sedimentologic investigations has shown that many depositional systems, including some that were once thought to be dominated by autocyclic processes are strongly influenced by allocyclic processes (e.g., Boyd et al., 1989).

In this paper, we examine the sequence stratigraphy of Turonian through Campanian strata of the Kaiparowits Plateau (Fig. 1) and the facies architecture of alluvial, coal-bearing, and shoreface sediments. We suggest criteria that allow transgressive and highstand systems tracts (Posamentier and Vail, 1988) to be recognized in both marine and nonmarine strata.

SEQUENCE STRATIGRAPHIC MODELS

Mitchum et al. (1977, p. 53) defined a depositional sequence as a "stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities." The development of depositional sequences and their response to changes in relative sea level were first outlined in conceptual models proposed by Vail et al. (1977), and have subsequently undergone several modifications (e.g., Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990). These conceptual models have been combined with more rigorous numerical models (e.g., Jervey, 1988) to more accurately relate changes in depositional facies with changes in relative sea level. The combination of these two types of models with the ideas of accommodation space (Jervey, 1988) resulted in recognition of depositional systems tracts as subdivisions of depositional sequences (Posamentier et al., 1988). This allows changes in depositional architecture to be related to fluctuations in rates of base-level change and stratal position within a sequence. An underpinning of these models has been that depositional architecture is largely determined by the rate at which

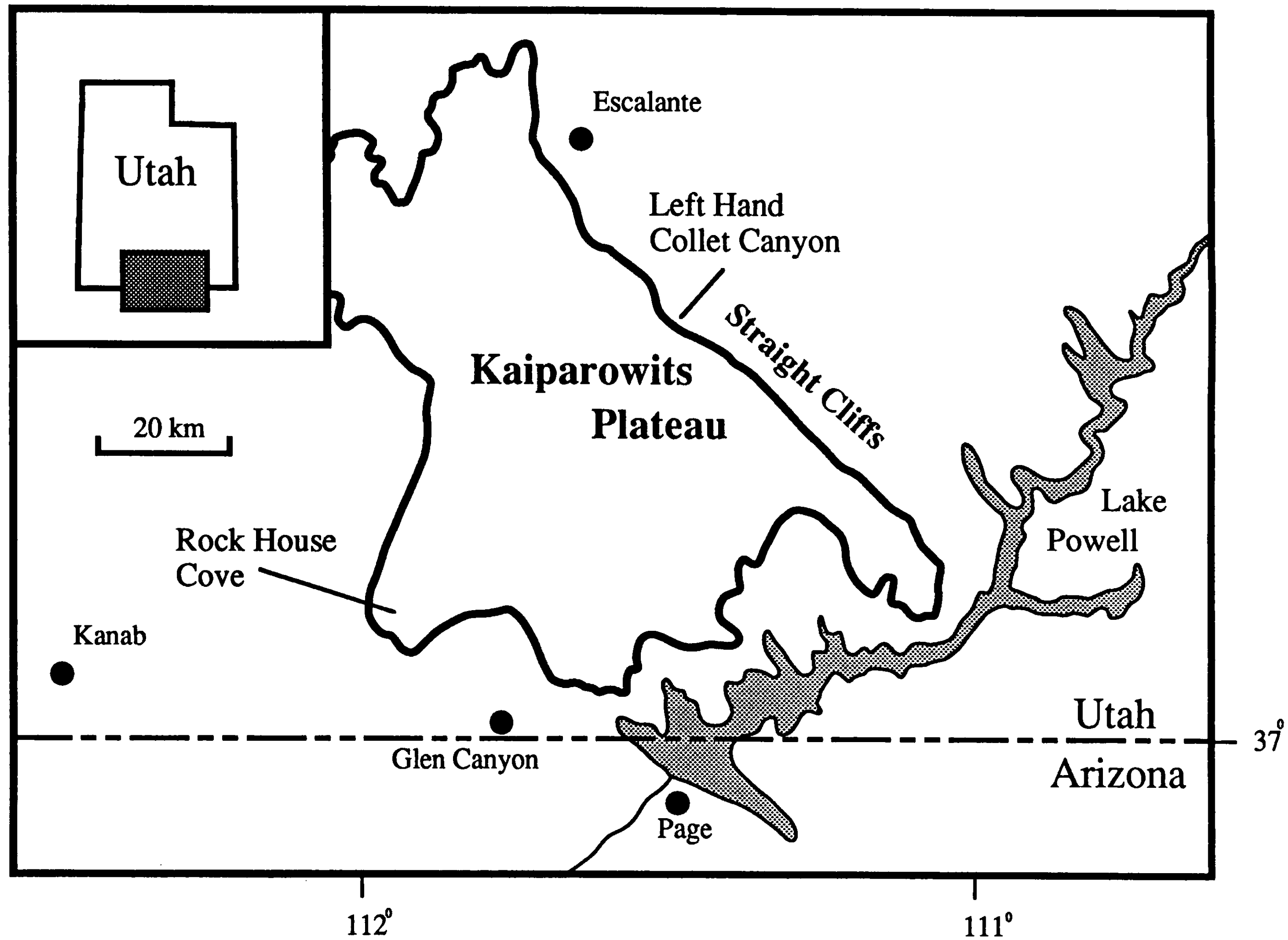


Figure 1. Location map for the Kaiparowits Plateau showing the locations of Rock House Cove and Left Hand Collet Canyon. In general, the northeastern part of the plateau consists of shoreface deposits which grade into coal-bearing strata in the central plateau. These in turn grade into alluvial strata towards the west and southwest.

accommodation space is created and the manner in which that space is filled with sediment (e.g., Jervey, 1988; Posamentier and Vail, 1988; Lawrence et al., 1990; Ross, 1990). Accommodation space reflects changes in base level, which, in turn, reflects the integration of tectonic subsidence and eustasy. Base level in this sense refers to an imaginary "equilibrium surface ... above which a particle can not come to rest and below which deposition and burial is possible" (Sloss, 1962, p. 1051). In the nonmarine realm base level may be approximated by the concept of a graded stream profile (Mackin, 1948) whereas at shoreline and shallow shelf positions base level is more accurately represented by sea level and the concept of a graded shelf (e.g., Swift, 1970; Ross, 1990).

Several workers (e.g., Swift et al., 1987; Blair and Bilodeau, 1988; Heller et al., 1988; Flemings and Jordan, 1990) have urged caution when applying sequence stratigraphic concepts to active foreland basins. These arguments have generally centered on the increased rates of tectonic subsidence in the proximal foreland over-riding eustatic changes and preventing the formation of sequence boundary unconformities. Several workers including Plint et al. (1988), Posamentier and Chamberlain (1989), Devlin et al. (1990) and Van Wagoner et al. (1990), however, have successfully applied sequence stratigraphic concepts within the Cretaceous Western Interior foreland basin of Canada and the United States.

THE KAIPAROWITS PLATEAU

The Kaiparowits Plateau (Fig. 1) covers some 3600 km^2 in south-central Utah. Outcrops consist of gently undulating, north-northwest-trending folds that are locally broken by high-angle normal faults; structural dip varies between 0 and 5°. Exposures within the study interval range from middle Turonian to Campanian and from 300 to 370 m in thickness. The northeastern escarpment of the plateau, known as the Straight Cliffs, provides approximately 80 km of exposure along depositional strike. The southern margin of the plateau is dissected by numerous canyons and provides almost 80 km of exposure oriented slightly oblique to depositional dip. The limited structural complexity and lack of vegetation provide excellent conditions for the study of facies architecture and sequence stratigraphy.

The initial stratigraphic framework for the plateau was established by Gregory and Moore (1931) and refined by Peterson (1969a, 1969b) and Vaninetti (1978). These studies combined with our own research have delineated broad lithofacies belts of alluvial plain, mire, coastal plain, shoreface, and open marine sediments within the John Henry Member of the Straight Cliffs Formation. Outcrops along the Straight Cliffs are dominated by shoreface sandstones (Fig. 2). Equivalent strata along the western margin of the plateau, however, are dominated by finer-grained alluvial sediments (Fig. 3). The overall arrangement of lithofacies types provides an unusual opportunity to compare sedimentary architecture across a wide spectrum of coeval depositional environments. In particular, these outcrops allow us to directly compare shoreface architecture, for which there are a variety of sophisticated stratigraphic models, with more poorly understood coal-bearing and barren alluvial strata.

Based on the geometric arrangement of shoreface strata, we recognize progradational and aggradational shoreface stacking patterns in the Kaiparowits Plateau. These stacking patterns coupled with sequence boundary unconformities allow us to subdivide Turonian-Campanian strata into five unconformity-bounded depositional sequences. The sequence-boundaries and the highstand and transgressive systems tracts can be recognized across the

Figure 2. View to the northeast of Left Hand Collet Canyon in the vicinity of the measured section illustrated in Fig. 4. Left Hand Collet Canyon is dominated by shoreface and shallow marine strata. Sequence boundaries, condensed section deposits, and systems tracts are shown for comparison with Fig. 4. Because of the slight structural dip to the west, the Drip Tank Member is not exposed in this photograph. Within 2 km to the west of this locality, shoreface strata grade abruptly into coal-bearing strata.

Figure 3. View to the east of Rock House Cove in the vicinity of the measured section shown in Fig. 4. This area is dominated by alluvial strata. Sequence boundaries, alluvial equivalents of condensed section deposits and systems tracts are shown for comparison with Fig. 4. The contrast between isolated channel sandstones of the highstand systems tract and amalgamated channel sandstones of the transgressive systems tract is clearly seen.

plateau. The remainder of this paper will utilize outcrop examples to describe the criteria by which sequence boundaries, systems tracts, and the sedimentary architecture within depositional facies may be recognized in the Kaiparowits Plateau.

Sequence Boundary Unconformities

Within the Kaiparowits Plateau we recognize two types of regionally significant unconformities that differ in the degree of facies tract offset or dislocation. Local depth of erosion is, unfortunately, not a criterion by which major and minor sequence boundaries may be distinguished. The most severe facies tract dislocations observed in these strata are associated with two major unconformities. The Calico sequence boundary (Fig. 4) separates coarse-grained and pebbly sandstones and thin conglomerates of the Calico bed, interpreted as braided river deposits, from underlying fine-grained siltstones, sandstones, and carbonaceous shales that are interpreted as coastal-plain deposits (Fig. 4). This facies juxtaposition and the marked contrast between the Calico bed and the fine-grained shoreface strata of the underlying Tibbet Canyon Member of the Straight Cliffs Formation suggest a sequence boundary. Shanley and McCabe (1989) interpreted this contact to represent a late Turonian base-level fall resulting in a significant basinward shift in facies tracts. The Ferron Sandstone Member of the Mancos Shale located to the east of this study area (Ryer, 1981) is interpreted by us to have been deposited following this base-level change.

The Drip Tank sequence boundary unconformity (Fig. 4) separates coarse-grained and pebbly braided river deposits, of the Drip Tank Member of the Straight Cliffs Formation, (Fig. 4) from the underlying John Henry Member which consists of fine-

Figure 4. Correlation of sequence boundaries (SB), condensed section deposits and their alluvial equivalents (CS), and systems tracts between Rock House Cove and Left Hand Collet Canyon, a distance of approximately 60 km (TST-transgressive systems tract, HST-highstand systems tract). Conventional stratigraphic nomenclature (Peterson, 1969b) and biostratigraphic stages (Peterson, 1969a, b; Eaton, 1987; this study) are shown for reference purposes.

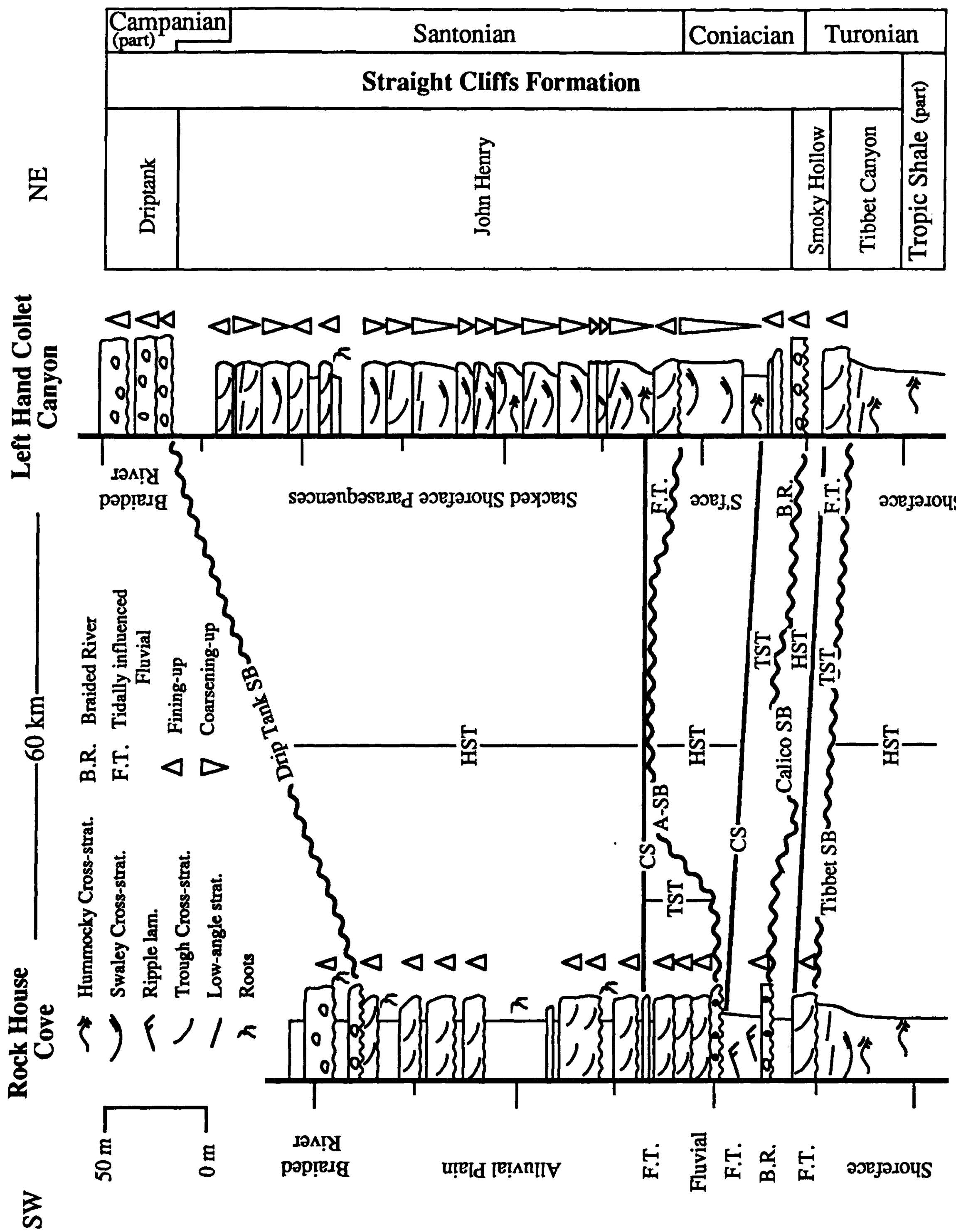

SW
NE
Rock House Cove
Left Hand Collet Canyon
60 km
50 m
0 m
Hummocky Cross-strat.
Swaley Cross-strat.
Ripple lam.
Trough Cross-strat.
Low-angle strat.
Roots
B.R. Braided River
F.T. Tidally influenced Fluvial
Fining-up
Coarsening-up
Campanian (part)
Santonian
Coniacian
Turonian
Straight Cliffs Formation
Driptank
John Henry
Smoky Hollow
Tibbet Canyon
Tropic Shale (part)
Braided River
Stacked Shoreface Parasequences
F.T.
S'face
B.R.
F.T.
Shoreface
Drip Tank SB
HST
CS
A-SB
TST
HST
TST
CS
HST
Calico SB
TST
Tibbet SB
HST
Braided River
Alluvial Plain
F.T.
Fluvial
F.T.
B.R.
F.T.
Shoreface

Figure 4

grained alluvial strata in the southwestern plateau, coeval fine-grained crevasse splay and coal-bearing strata in the central plateau, and coeval paralic strata in the eastern plateau.

Less dramatic facies tract dislocations are associated with two minor sequence boundary unconformities. The Tibbet Canyon sequence boundary (Fig. 4) separates overlying fine-grained, trough cross-bedded sandstones containing evidence of fluvial and tidal processes (Fig. 4) from fine-grained hummocky and swaley cross stratified sandstones. The unconformity has erosional relief of up to 10 m. The shoreface sandstones below the sequence boundary and the channel deposits above the unconformity are formally known as the Tibbet Canyon Member of the Straight Cliffs Formation. The A-sequence boundary (Fig. 4), occurs within the John Henry Member. In the western part of the plateau this unconformity separates laterally amalgamated, trough cross bedded sandstones, interpreted as low sinuosity channel sandstones within an incised valley, from fine-grained alluvial siltstones and sandstones and tidally influenced river deposits (Shanley and McCabe, 1989). This unconformity can be correlated to the eastern part of the plateau where it cuts through swaley and hummocky cross-stratified sandstones locally referred to as the "A-sandstone". Tidally influenced channel sandstones erosionally overlie the shoreface deposits in this part of the plateau.

Transgressive Systems Tracts

Transgressive systems tracts record regional coastal transgression due to base-level rise. We have documented three examples of transgressive systems tracts within alluvial strata in the Kaiparowits Plateau. This allows a high-resolution chronostratigraphic correlation between marginal marine and alluvial strata. Because there are both major and minor sequence boundaries, suggesting base-level falls of differing magnitudes, and because of differing rates of coastal transgression, the criteria that identify the transgressive systems tracts are different in each case. The most easily recognized transgressive systems tract involves the strata overlying the Calico sequence boundary (Fig. 4). In the eastern Kaiparowits Plateau, braided river deposits of the Calico bed grade up into medium- and fine-grained channel sandstones containing sigmoidal bedding, multiple reactivation surfaces, bi-directional current orientations, compound cross stratification, and double mud drapes. These structures suggest a strong tidal influence and the sediments probably accumulated in an estuarine setting. These tidally influenced strata are erosionally overlain by a thin pebble and cobble conglomerate, interpreted as a transgressive lag deposit, that in turn is overlain by swaley and hummocky cross-stratified shoreface deposits (Fig. 4). Continued transgression above the pebble and cobble lag is recorded by a thinning upward succession of hummocky and swaley cross-stratified beds that culminate in a thin fossiliferous lag containing ammonites, inoceramids, and sharks' teeth that is interpreted as a condensed section representing the maximum flooding surface (Fig. 4). This surface caps the transgressive systems tract.

In the western part of the plateau this same transgressive systems tract is represented by alluvial strata and recognition criteria are more subtle. Braided-river deposits of the Calico bed are overlain by rooted shales, carbonaceous shales, and thin cross-laminated sandstones that are interpreted as alluvial-plain deposits (Fig. 4). These in turn are erosionally overlain by fine-grained, cross-laminated and lenticular bedded, heterolithic channel deposits containing bi-directional current orientations, mud drapes that extend from the top of point bar surfaces to their base, and brackish water trace fossils (Fig. 4). These heterolithic channel deposits are interpreted as tidally influenced river deposits located at least 60 km inland of their coeval shoreline. These strata represent the time of maximum flooding within the alluvial plain and are temporally equivalent to the condensed section deposit previously described from the eastern plateau.

Transgressive systems tract deposits associated with minor sequence boundaries are illustrated by the strata overlying the A-sequence boundary within the John Henry Member. In the eastern Kaiparowits Plateau,tidally influenced channel deposits overlying the sequence boundary are themselves overlain by a regionally persistent pebble lag interpreted as a transgressive lag. The lag deposit is overlain by deeper water, hummocky-bedded sandstones. In the western part of the plateau correlation of detailed measured sections and stacking patterns suggest this same transgressive systems tract is represented by a change in alluvial architecture. Laterally and vertically amalgamated, trough cross-bedded channel sandstones, with little preserved fine-grained overbank sediment immediately overlie the A-sequence boundary (Fig. 4). These amalgamated channel deposits grade vertically into more isolated channel sandstones in which more complete fining upward successions, from trough cross-bedded to ripple-laminated sandstones are preserved. The isolated channel sandstones in the uppermost part of this systems tract contain brackish water trace fossils and sedimentary structures suggestive of mixed fluvial and tidal conditions. The upward decrease in the degree of channel amalgamation, the increased preservation of fine-grained overbank material and the presence of brackish water trace fossils and sedimentary structures suggestive of tidal influence are interpreted to reflect increased rates of base-level rise and increased accommodation space. Within a limited area such as the Kaiparowits Plateau, these fluvial deposits might be interpreted as lowstand deposits (Posamentier and Vail, 1988; Allen et al., 1989; Henry Posamentier, personal communication), however, when viewed in a broader context within the foreland basin we feel they are more accurately interpreted as the basal part of a transgressive systems tract deposit.

Highstand Systems Tracts

Two distinct highstand systems tracts have been recognized in the Kaiparowits Plateau. These equate to the early and late highstand deposits of Posamentier et al. (1988). The alignment and overall thickness of shoreface-foreshore parasequences that comprise the John Henry Member along the northeastern margin of the plateau form an impressive escarpment. These strata are composed of 10-15 m thick, upward coarsening units that grade from hummocky cross stratification into swaley cross stratified and low-angle to parallel-bedded strata. Individual parasequences are arranged in an aggradational stacking pattern (Fig. 4) suggestive of an early highstand systems tract. Immediately behind the Straight Cliffs escarpment, the aggradational shoreface units grade into nonmarine strata containing thick, low-ash coals. In the central part of the plateau, coal-bearing strata interfinger with crevasse splays, carbonaceous shales, small channel sandstones, and thin coals. These strata are interpreted as anastomosed alluvial deposits along the margins of a raised mire complex. In the southwestern part of the plateau, the highstand systems tract is entirely composed of alluvial strata (Fig. 3). Trough cross-bedded and ripple-laminated sandstones interpreted as meander-belt sandstones are surrounded by rooted shales and thin ripple laminated sandstones interpreted as overbank deposits (Fig. 4); there are no coal-bearing strata in this region. This change from amalgamated to isolated channel deposits and the accompanying increase in preserved fine-grained sediment records the transition from transgressive to highstand systems tract in the alluvial part of the John Henry Member (Figs. 3 and 4). The observed isolated channel deposits of the early highstand systems tract are in agreement with the predictions of the conceptual models discussed in Posamentier and Vail (1988).

Because of limited accommodation space, late highstand systems tracts are characterized by strongly progradational shoreface parasequences. The lower part of the Tibbet Canyon Member, below the Tibbet Canyon sequence boundary, is composed of coarsening upward parasequences (Fig 4). Sedimentary structures grade upward from hummocky cross-stratification to swaley, to low angle, and finally parallel stratification that reflects shallowing from offshore to upper shoreface and foreshore deposits. Biostratigraphic data (Peterson, 1969a) suggest the Tibbet Canyon Member prograded 80 km from southwest to northeast in 1.5 m.y. Alluvial strata associated with this late highstand systems tract contain thin carbonaceous shales, discontinuous thin coals, and localized channel sandstones.

DISCUSSION

Recognition and correlation of stacking patterns in shoreface, alluvial, and coal-bearing strata in the Kaiparowits Plateau and their interpretation in terms of base-level changes provides a new model based on outcrop exposures for understanding the evolution and significance of changes in sedimentary architecture. Our results corroborate conceptual models proposed by Posamentier et al. (1988) and Posamentier and Vail (1988). Sequence boundaries may be recognized by basinward shifts in facies tracts or by changes in the degree of amalgamation of channel sandstones. Amalgamated fluvial channel deposits with little associated fine-grained overbank material are associated with the lowermost part of transgressive systems tract and overlie regionally extensive sequence boundary unconformites. At their basinward extent, these amalgamated channel deposits are coeval with a basinward shift in facies tracts manifested by tidally-influenced channel deposits that overlie shoreface strata. Isolated, tidally influenced fluvial sandstones within an otherwise alluvial succession are correlated with maximum flooding surfaces in the marine realm and provide the basis for separating transgressive from highstand deposits. Alluvial strata with isolated meanderbelt sandstones and significant amounts of fine-grained overbank deposits are characteristic of highstand systems tracts and are associated with aggradational shoreface parasequences and the development of thick coal-bearing strata.

The use of sequence stratigraphic concepts in conjunction with detailed facies analysis result in a far greater degree of temporal resolution than is otherwise possible, especially in alluvial strata. In the Kaiparowits Plateau, for example, application of these concepts provides four regionally significant sequence boundary unconformities and two regionally extensive alluvial flooding surfaces which may be used for chronostratigraphic correlation. Equally important are the economic implications; through an understanding of sequence stratigraphy and facies architecture it is possible to predict sandstone interconnectedness, sand-shale ratios, coal bed thickness and lateral persistence and shoreface-foreshore preservation in areas with only limited sedimentological and stratigraphic data.

Chapter 4

SEQUENCE STRATIGRAPHIC EVOLUTION OF THE KAIPAROWITS PLATEAU, SOUTHERN UTAH, U.S.A. - IMPLICATIONS FOR RESERVOIR PREDICTION

ABSTRACT

Outcrop study of Turonian through Campanian strata in the Kaiparowits Plateau of southern Utah allows examination of facies tract development within the context of unconformity-bounded depositional sequences. This approach provides a new perspective on regional chrono- and lithostratigraphic relationships. Previous interpretations suggested that Turonian through Campanian strata comprise a regressive-transgressive cycle of relatively conformable strata with the regressive and transgressive maxima located within the Ferron Sandstone Member of the Mancos Shale and the John Henry Member of the Straight Cliffs Formation respectively.

We now recognize five unconformity-bounded depositional sequences within these strata in the Kaiparowits Plateau. These sequences are defined by regional surfaces of erosion that juxtapose amalgamated fluvial deposits over shoreface, alluvial plain, or coal-bearing strata. These erosional surfaces reflect an abrupt basinward shift in facies tracts. Between these sequence boundaries, field examination of stratigraphic architecture suggest that these strata can be related to transgressive and highstand systems tracts. Transgressive systems tracts are characterized by a progression from amalgamated channel deposits to isolated meanderbelts that have evidence of tidal influence, even when contained within an alluvial succession. These tidally influenced fluvial strata are temporally equivalent to

marine maximum flooding surfaces. Early-highstand systems tract deposits are characterized by thick, aggradational shoreface parasequences, thick, extensive coal seams, and isolated meanderbelt sandstones encased in thick, fine-grained floodplain strata. Late-highstand systems tract deposits are relatively thin and are characterized by progradational shoreface parasequences, thin, discontinuous coal seams, and fine-grained channel deposits. We interpret these changes in stratigraphic architecture to reflect base-level changes that we believe are also manifested in coeval strata in adjacent outcrop belts in the Wasatch Plateau of central Utah, Black Mesa region of northern Arizona, and the San Juan Basin in New Mexico. We have compared our data with the eustatic curves of Haq et al. (1988) and have found the correlation to be quite good. Based on our work, however, we suggest the presence of an additional eustatic cycle at the base of the Coniacian. By interpreting our data in terms of base-level change, or relative we have synthesized our observations from the Kaiparowits Plateau and proposed a model that allows the geometry and interconnectedness of sedimentary facies to be predicted within the context of parasequence stacking patterns. This has economic implications for the prediction of petroleum reservoirs.

INTRODUCTION

Sequence stratigraphic concepts suggest the stratigraphic record is strongly ordered. This sense of order imparts a degree of predictability which is of economic appeal to those searching for petroleum reservoirs or those wishing to further develop existing reservoirs. As the search for new petroleum reserves intensifies, and with increased emphasis on the efficient drainage of already discovered reserves, significantly improved geological models are needed that afford a better understanding of the temporal and physical relationships of reservoir-bearing strata. Furthermore, sequence stratigraphic concepts, and the correlations they suggest, allow the construction of a chronostratigraphic framework of far greater resolution than is normally possible through either radiometric or biostratigraphic means. When combined with advances in geophysics, process-oriented sedimentology, and facies architecture, modern sequence stratigraphic concepts suggest that sedimentary rocks of differing depositional environments and tectonic settings are predictable in terms of occurrence and geometry.

The recent proliferation of sequence stratigraphic studies has resulted in re-interpretations of many marine and marginal marine strata (e.g., Payton, 1977; Weimer, 1983, 1989; Schlee, 1984; Berg and Woolverton, 1985; Wilgus et al., 1988; Van Wagoner et al., 1990). Application of these concepts to alluvial and coal-bearing strata, however, has been limited, owing perhaps, to abrupt lateral facies changes, abundant internal erosion surfaces, and the limited conventional chronostratigraphic resolution that characterize these strata (e.g. Shanley and McCabe, 1990b-in review; Walker, 1990).

Outcrops of middle Turonian through Campanian strata in the Kaiparowits Plateau of southern Utah permit the examination of coeval nearshore, coal-bearing, and alluvial strata along both strike and dip oriented exposures. As a result, changes in parasequence stacking patterns of shoreface strata can be compared with changes in the architecture of coeval alluvial and coal-bearing strata. This allows stratigraphic models developed in nearshore strata to be extended into nonmarine strata producing a more unified and synergistic interpretation of stratigraphic evolution and reservoir prediction. In addition, the sequence stratigraphic framework developed in the plateau suggests alternative chronostratigraphic correlations with adjacent areas such as the Wasatch Plateau, Black Mesa Basin, and the San Juan Basin (Fig. 1).

KAIPAROWITS PLATEAU, UTAH

Physical setting

The Kaiparowits Plateau covers some 3600 km^2 in the southwestern part of the Colorado Plateau (Fig. 1). The plateau has gentle, north- to northwest-trending asymmetrical folds (Peterson, 1969) that plunge slightly northwest; structural dip within the plateau is generally less than 3°. The northeastern escarpment of the plateau, known as the Straight Cliffs (Fig. 2), provides almost 80 km of depositional strike oriented exposure. The southern margin of the plateau provides approximately 80 km of exposure oriented slightly oblique to depositional dip. Regional lithofacies relationships coupled with superb exposures and overall lack of vegetation combine to make the Kaiparowits Plateau an ideal field laboratory in which to study facies architecture and sequence stratigraphic relationships.

During the middle and Late Cretaceous, flexural loading of the lithosphere by successive thrust plates and synorogenic sediment derived from the Sevier orogenic belt to the west resulted in the development of a foreland basin (e.g. Armstrong, 1968; Jordan,

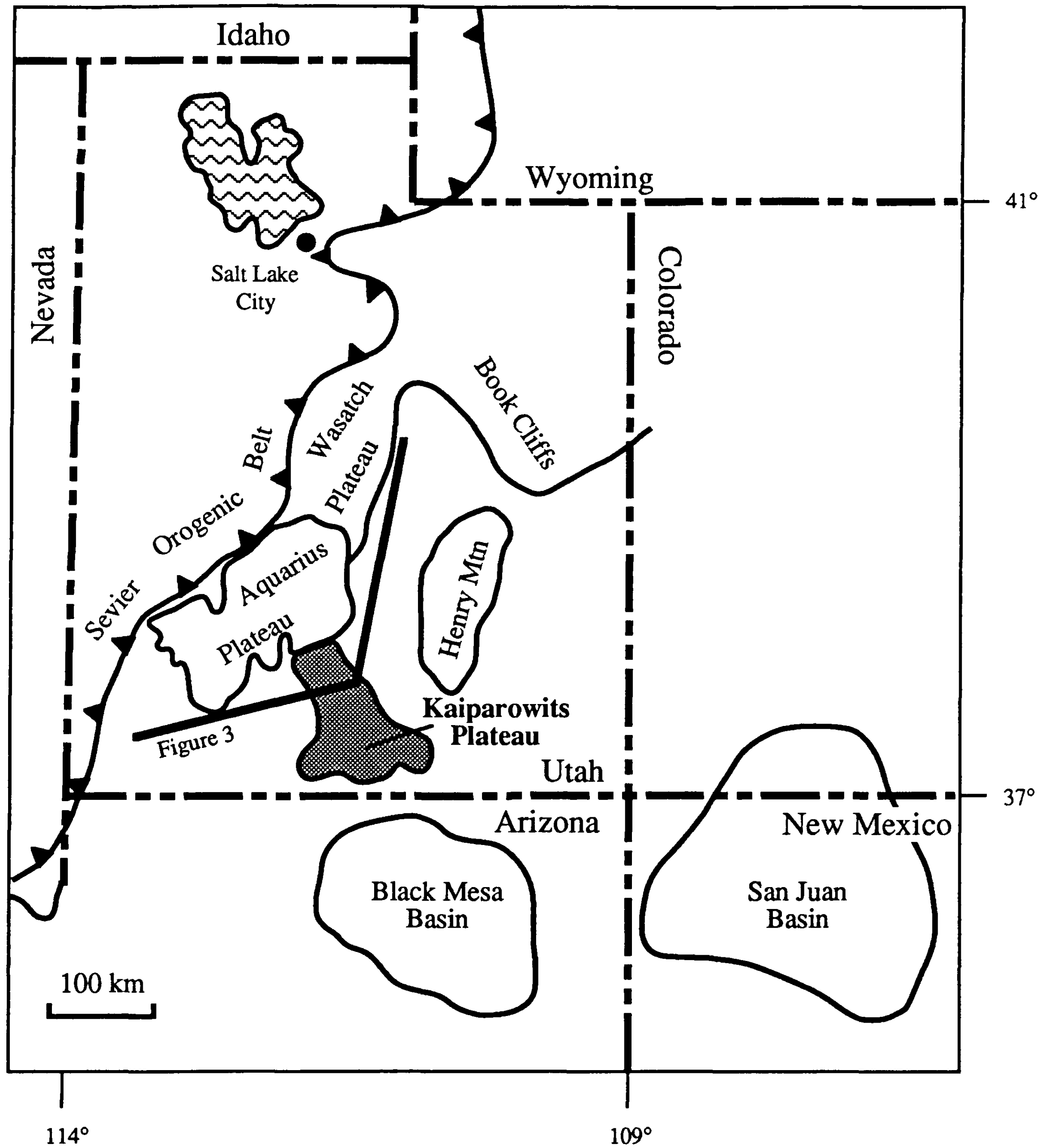


Figure 1. Regional map illustrating the location of the Kaiparowits Plateau within the context of the southern Colorado Plateau. Also shown are the locations of the Wasatch Plateau, Henry Mountain Basin, Book Cliffs, San Juan Basin, Black Mesa Basin, and the leading edge of the Sevier orogenic belt. The line of sectiopn shown is illustrated in Figure 3.

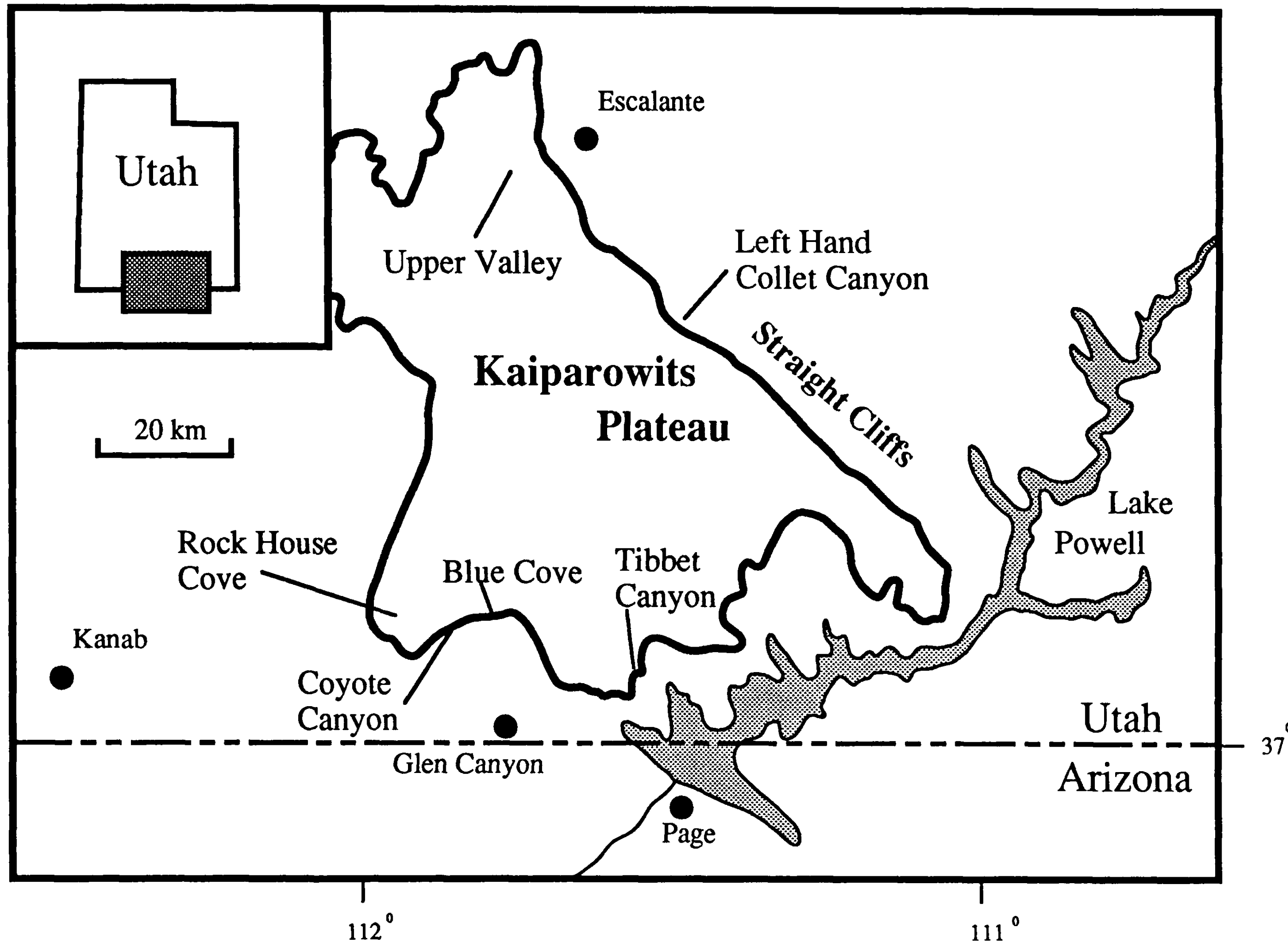


Figure 2. Map showing the locations of prominent canyons where detailed studies of facies transitions were carried out. In general the northeastern part of the plateau consists of shoreface deposits which grade into coal-bearing strata in the centralplateau. These in turn grade into alluvial strata towards the west and southwest.

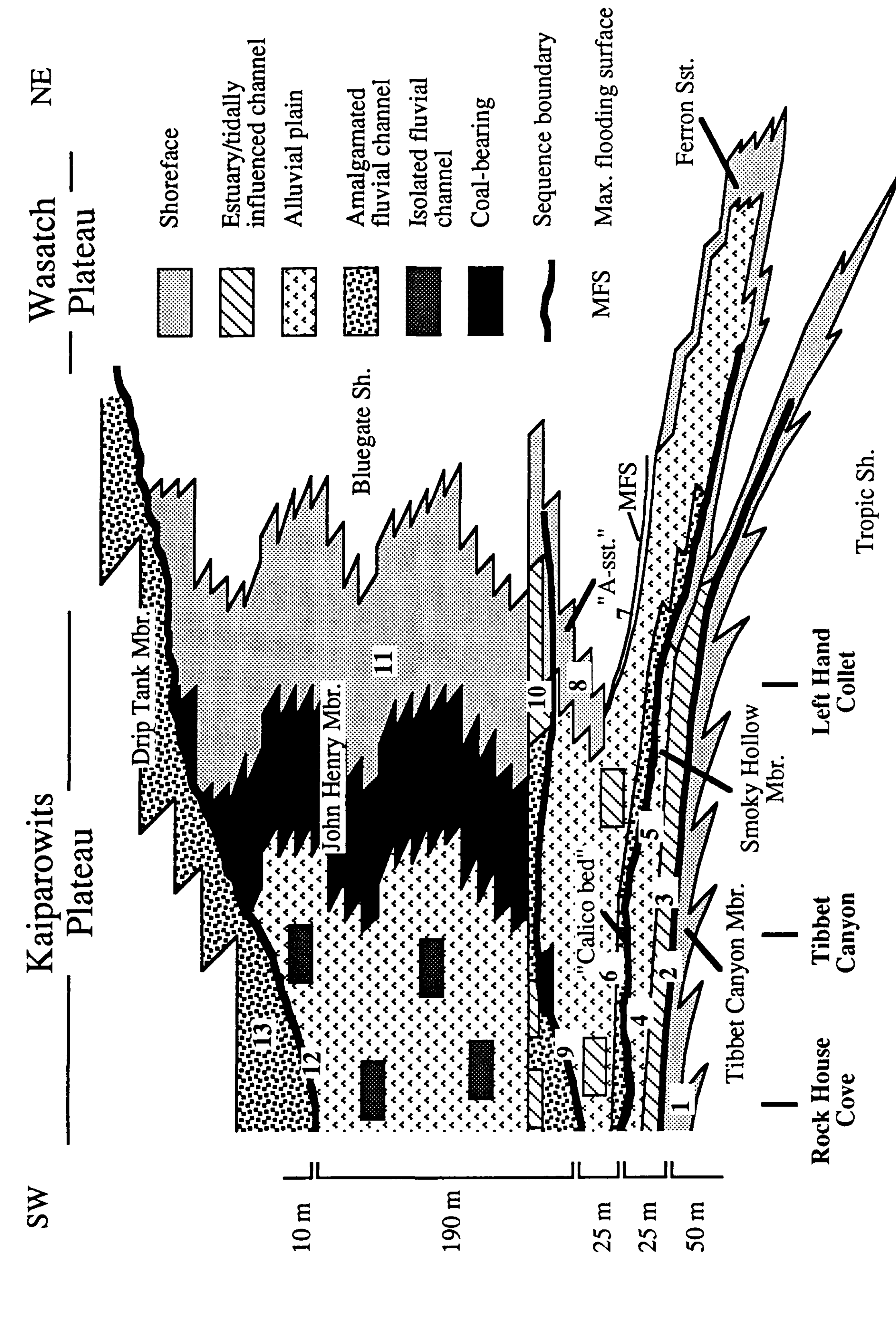
1981; Cross, 1986). The Kaiparowits Plateau was located along the western margin of this actively subsiding basin, approximately 120 km east of the leading edge of the thrust front. Between the early Turonian and Campanian, the foreland basin was inundated by the Western Interior seaway. During maximum eustatic highstand, the seaway extended from present-day Arctic Canada to the Gulf of Mexico, a distance of some 5000 km, and from western Utah to Iowa, a distance of some 1500 km (Williams and Stelck, 1975).

The present outcrop configuration was largely established by the Miocene (e.g., Lucchitta, 1979, 1989) as the Colorado River assumed its present course and began to control headward erosion into the broad plateaus of the Colorado Plateau. Although the Kaiparowits Plateau is locally cut by several high-angle normal faults, displacements are minimal and do not hamper detailed stratigraphic and sedimentological studies.

Methodology

The integration of detailed sedimentological studies of several facies tracts within the context of a broader sequence stratigraphic investigation necessitated a multi-faceted approach. To develop an understanding of sequence stratigraphic relationships, detailed sections were measured from the Tropic Shale to the Drip Tank Member of the Straight Cliffs Formation (Fig. 3a). These sections identified significant facies tract dislocations associated with sequence-boundary unconformities, transgressive surfaces of erosion (ravinement surfaces), marine condensed sections and their nonmarine counterparts, and shoreface parasequence stacking patterns. Treatment of the facies architecture and its relationship to sequence stratigraphy required a combination of closely spaced measured sections and panorama photographs. Detailed analyses were conducted on the transitions from shoreface to coal-bearing strata in Left Hand Collet Canyon; the transition from coal-

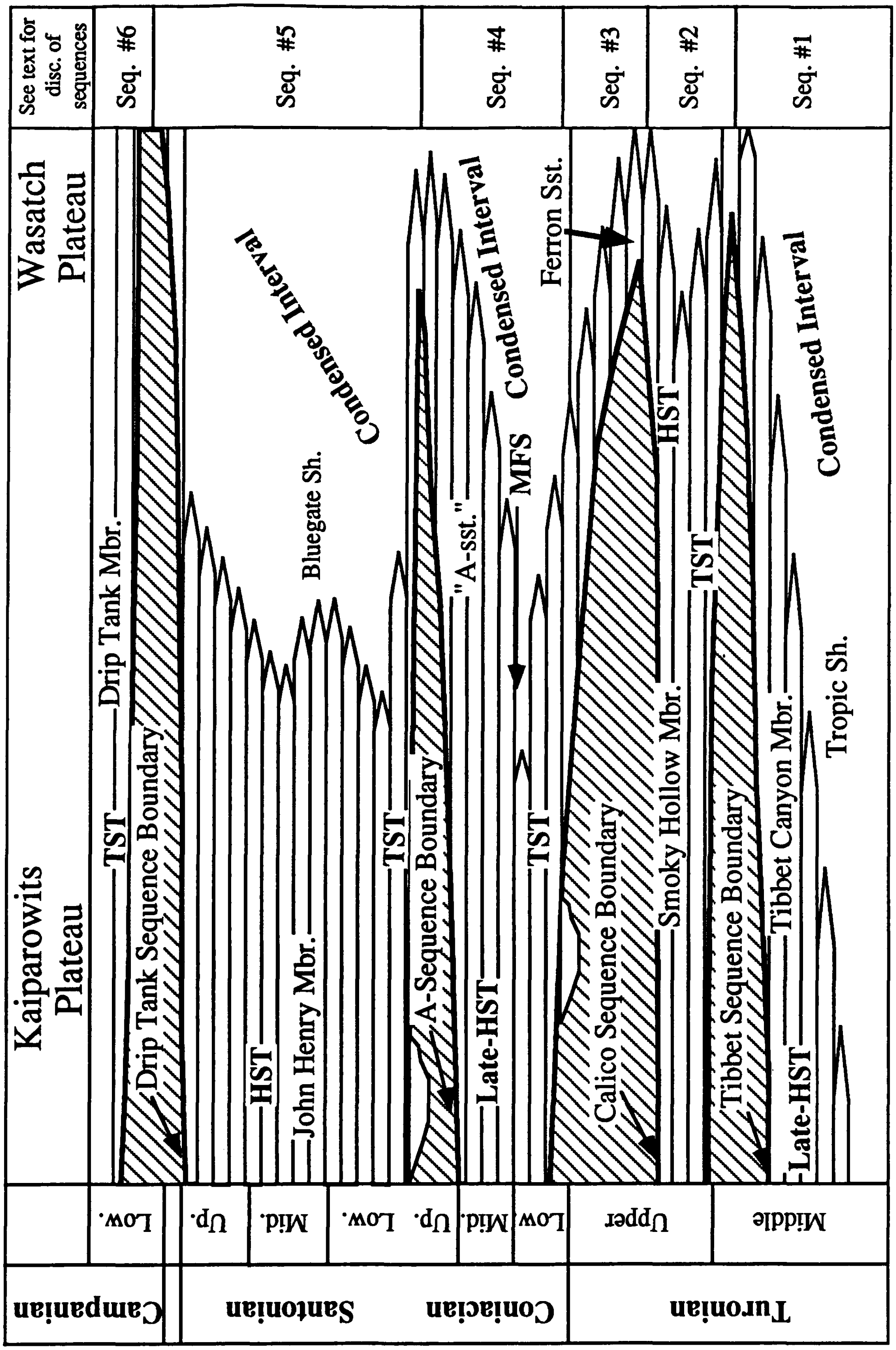
Figure 3a. Sequence stratigraphic cross section of Turonian through lower Campanian strata from the Kaiparowits Plateau (southwest) to the Wasatch Plateau (northeast). The line of section is shown on Figure 1. This cross section is based on detailed sections measured at Rock House Cove, Blue Cove, Coyote Canyon, Tibbet Canyon, Left Hand Collet Canyon and Alvey Wash. Sequence boundary unconformities, or their correlative conformities, are shown. These allow the strata to be subdivided into chronostratigraphic units across at least 65 km of depositional dip from alluvial to shoreface deposits. Within the Kaiparowits Plateau, this diagram is drawn to scale with a horizontal datum at the top of the A-sandstone flooding event. The portion of the diagram in the Wasatch Plateau is not drawn to scale but is drawn so as to portray stratigraphic relationships. Increased rates of tectonic subsidence in the Wasatch Plateau resulted in a thick accumulation of Turonian-Santonian strata. The problems introduced by high rates of subsidence are discussed in the text. The bold-face numbers along the left margin of the figure refer to the sequence stratigraphic discussion in the text.



SW
NE
Kaiparowits Plateau
Wasatch Plateau
Shoreface
Estuary/tidally influenced channel
Alluvial plain
Amalgamated fluvial channel
Isolated fluvial channel
Coal-bearing
Sequence boundary
MFS
Max. flooding surface
Drip Tank Mbr.
John Henry Mbr.
Bluegate Sh.
"Calico bed"
"A-sst."
MFS
Ferron Sst.
Tropic Sh.
Tibbet Canyon Mbr.
Smoky Hollow Mbr.
1
2
3
4
5
6
7
8
9
10
11
12
13
Rock House Cove
Tibbet Canyon
Left Hand Collet
10 m
190 m
25 m
25 m
50 m

Figure 3a

Figure 3b. Chronostratigraphic diagram (Wheeler diagram) to accompany the sequence stratigraphic cross section in Fig. 3a. The horizontal axis portrays distance while the vertical axis denotes geologic time. This diagram attempts to portray the geologic time represented by preserved strata as well as the time occupied by major erosion surfaces, periods of sediment bypass, and coastal transgression. HST=highstand systems tract, TST=transgressive systems tract, SB=sequence boundary, MFS=maximum flooding surface.



Kaiparowits Plateau
Wasatch Plateau
See text for disc. of sequences
Seq. #6
Seq. #5
Seq. #4
Seq. #3
Seq. #2
Seq. #1
Campanian
Santonian
Coniacian
Turonian
Low.
Up.
Mid.
Low.
Up.
Mid.
Low
Upper
Middle
Drip Tank Sequence Boundary
TST
Drip Tank Mbr.
HST
John Henry Mbr.
Bluegate Sh.
Condensed Interval
TST
A-Sequence Boundary
Late-HST
"A-sst."
Condensed Interval
MFS
TST
Ferron Sst.
Calico Sequence Boundary
Smoky Hollow Mbr.
HST
TST
Tibbet Sequence Boundary
Tibbet Canyon Mbr.
Late-HST
Tropic Sh.
Condensed Interval

Figure 3b

bearing to barren strata in Tibbet Canyon; incised valley-fill strata in Rock House Cove, Coyote Canyon, Upper Valley, and Blue Cove; tidally-influenced fluvial strata in Left Hand Collet Canyon, Rock House Cove, Coyote Canyon, Blue Cove, Upper Valley, and Tibbet Canyon, and tidally reworked shoreface deposits throughout much of the southern plateau (Fig. 2).

STRAIGHT CLIFFS FORMATION

Stratigraphic setting

The strata discussed in this paper belong to the Straight Cliffs Formation which ranges from middle Turonian to Campanian in age and from 300-370 m in thickness (e.g., Peterson, 1969a,b). The stratigraphy of the Straight Cliffs Formation was established by Gregory and Moore (1931) in the first comprehensive report on the geology of the plateau. Recognition of mapable members within the Straight Cliffs Formation, identification of type sections and general sedimentological descriptions were provided by Peterson (1969a, b). This work, coupled with that of Vaninetti (1978), led to the general interpretation of these strata in terms of a barrier island coast and wave dominated delta that graded landward into low-lying coastal swamps and alluvial facies. Age assessments of strata exposed in the Kaiparowits Plateau are based on biostratigraphic data reported in Peterson (1969a, b), Peterson and Kirk (1977), Eaton (1987, 1991-in press), Eaton et al. (1987), Eaton and Cifelli (1988), Hettinger et al. (1990), as well as our own research. These data have been correlated to biostratigraphic range charts that incorporate both ammonoidea and inoceramidae biozones (Kauffman and Pratt, 1985; Collom, 1991). These data form the basis for our chronostratigraphic interpretations of the sequence stratigraphy.

Biostratigraphic data are further interpreted in light of stratal stacking patterns and regional stratigraphic correlations.

Correlation of detailed measured sections (Appendix) allows recognition of at least five unconformity-bounded depositional sequences and their associated highstand and transgressive systems tracts within the Straight Cliffs Formation. These sequences are shown somewhat schematically in Figure 3a which illustrates this interpretation as a stratigraphic cross-section. (Within the Kaiparowits Plateau, thickness relationships and placement of critical boundaries are drawn to scale, however, thickness relationships illustrated for the Wasatch Plateau are not drawn to scale. This reflects the high subsidence rates in the Wasatch Plateau and is discussed in greater detail elsewhere in this paper). The ensuing discussion of sequence and chronostratigraphy describes the lateral extent of critical surfaces and facies relationships as seen in the Kaiparowits Plateau, thereby allowing confidence limits to be placed on the cross section itself. Figure 3b provides a chronostratigraphic interpretation (Wheeler diagram) of these same strata in which geologic time, as represented by both deposition and erosion, is accounted for. These depositional sequences are found throughout the plateau in both marine and terrestrial strata, are compatible with existing paleontologic and radiometric data sets, and provide a framework within which variations in facies architecture can be analyzed.

Lithofacies and paleoenvironments

Detailed sedimentological descriptions and interpretations are contained in Shanley and McCabe (1990a-in review, b-in review) and Shanley et al., (1990-in review) and are summarized here.

Nearshore marine strata

(1) Offshore facies. Interbedded, bioturbated siltstones and mudstones (10-40% siltstone, 90-60% mudstone) characterize this facies. Siltstone beds rarely exceed a few centimeters in thickness. Where preserved, sedimentary structures include asymmetrical ripples as well as wavy and lenticular bedding (Reineck and Wunderlich, 1968). Recognizable trace fossils include *Chondrites*, *Skolithos*, and *Planolites* burrows. These strata are gradational over several meters of vertical section with underlying fissile, dark grey claystones and mudstones, and together compose the Tropic Shale. Strata included in this facies are interpreted to reflect deposition below storm wave base where sedimentation is primarily from suspension.

(2) Offshore-transition facies. Offshore siltstones and mudstones grade vertically into centimeter and decimeter- to meter-thick very fine- to fine-grained sandstones that are interbedded with siltstones and mudstones. Both the number and thickness of individual sandstone beds increases upwards while the thickness of the intervening siltstones decreases upwards. The sandstones have sharp bases that frequently load and truncate laminae in the underlying siltstones, especially in the lower parts of the facies where the sandstone beds are thinner and siltstones predominate. Mica and finely comminuted organic material are common near the base of these sandstones. Internal sedimentary structures grade from parallel laminae in thin (< 15 cm) sandstones at the base of the facies to discrete decimeter- to meter-thick hummocky cross-stratified (HCS) sandstones, and finally to meter thick, amalgamated HCS sandstones near the top of this facies tract. Both symmetrical and assymmetrical, straight-crested ripples, with ripple indices of 10-14, are common at the top of HCS sandstones. Trace fossils, including *Ophiomorpha,*

Thallasanoides, Skolithos, Planolites, and Asterosoma are common in the upper part of these sandstones beds and bioturbation is generally more intense in thin sandstones.

This facies, like other HCS strata, is interpreted to reflect sedimentation under alternating storm and quiet-water conditions between fair weather and storm wave base in an overall progradational setting (e.g., Bourgeois, 1980; Howard and Reineck, 1981; Dott and Bourgeois, 1982; Walker, 1985; Elliott, 1986; Greenwood and Sherman, 1986). This bathymetric region is sometimes referred to as 'lower shoreface' (e.g., McCubbin, 1982). Both wave ripples and combined flow ripples suggest an approximate shoreline orientation of N45°W for both the Tibbet Canyon and John Henry Members of the Straight Cliffs Formation.

(3) Shoreface facies. The offshore-transition facies are abruptly overlain by thick (2-9 m), very-fine, and fine-grained, swaley cross-stratified (SCS) and trough cross-stratified sandstones. Swaley cross stratification (Leckie and Walker, 1982) is transitional with HCS and is characterized by superimposed concave-upward erosional surfaces. Individual 'swales' decrease in amplitude upwards, and increase in width from approximately 0.5 m to more than 3 m. Basal erosion surfaces within the SCS sandstones are frequently lined with chert granules, scattered pebbles, and inoceramid debris. Internal laminations are gently curved, rarely exceed 10° dip, and follow the basal erosion surface of the swale (Leckie and Walker, 1982). SCS sandstones are locally interbedded with trough cross-bedded sandstones which occur in 1 to 5 m thick cosets. Scattered inoceramid and bivalve debris is common throughout this facies, as are the trace fossils *Ophiomorpha* and *Thallasanoides*. Paleocurrents from each coset of trough cross-stratified sandstones are

quite uniform, however, when compared with similar measurements from other cosets they show a diversity of onshore, offshore, and along-shore transport directions.

Strata in this facies are interpreted to have been deposited between fair weather wave base and mean low water in a high energy, storm-dominated shoreface associated with a progradational coastline. They are similar to strata described by Leckie and Walker (1982), McCrory and Walker (1986), and Allen and Underhill (1989). The abrupt contact between offshore and shoreface strata is thought to reflect the transition from below, to above fair weather wave base. The development of multi-directional, trough cross stratified sandstones within the SCS sandstones probably reflects the development of longitudinal bars along portions of the coastline (c.f. Davidson-Arnott and Greenwood, 1976; Hunter et al., 1979).

(4) Foreshore facies. In completely preserved shallowing-upward cycles of sedimentation, shoreface strata are overlain by 1 to 3 m of fine-grained sandstone characterized by low-angle and planar stratification. These laminae generally dip in a seaward direction, however, they are interupted by numerous small-scale erosion surfaces. Scattered inoceramid and bivalve debris is common in this facies. The uppermost portion of this facies is generally mottled and all traces of primary lamination have been obscured by bioturbation. These strata are interpreted to reflect deposition in a foreshore environment. The lack of lamination in the uppermost portion of this facies generally reflects bioturbation by roots which penetrated the foreshore from overlying alluvial plain strata.

Nearshore parasequence stacking patterns. Nearshore marine facies are generally arranged in upward-coarsening and upward-shallowing units that can be physically traced over a distance of several 100's of meters to perhaps a few kilometers in a depositional dip direction. These units are abruptly capped by marine flooding surfaces; gradually deepening upwards facies are not usually observed. These progradational units (parasequences of Van Wagoner,1985; Van Wagoner et al., 1990), are interpreted to have been deposited during progradation of a strandplain coastline. Parasequences themselves can be arranged in progradational (seaward stepping), retrogradational (landward stepping), and aggradational (vertically stacked) stacking patterns (e.g., Van Wagoner, 1985; Van Wagoner et al., 1990). Progradational parasequence-stacking patterns predominate in the Tibbet Canyon Member and the lower part of the A-sandstone in the John Henry Member of the Straight Cliffs Formation (Fig. 3a) but aggradational parasequence stacking patterns characterize the vast majority of the John Henry Member (Fig. 3a).

Terrestrial strata

(1) Amalgamated fluvial facies tract. Strata included in this facies tract are represented by the Calico bed of the Smoky Hollow Member, portions of the A-sandstone within the lower portion of the John Henry Member and the lower portions of the Drip Tank Member of the Straight Cliffs Formation (Fig. 3a). These strata form widespread mappable units that erosionally overlie a broad spectrum of marine and nonmarine lithofacies including, fine-grained channel sandstones, rooted mudrocks, carbonaceous shales and thin, discontinuous coal beds, and shoreface and foreshore sandstones.

The Calico bed and Drip Tank Member both consist of poorly sorted, granule to medium grained sandstones with interbedded pebble conglomerate lenses; the A-sandstone is predominantly a medium- to coarse-grained sandstone. Each sandstone is composed of several distinct storeys (terminology from Friend et al., 1979) that can be traced laterally for distances of 10 to 100 m. Internal storey scours are generally marked by a thin granule or pebble lag. At the base, individual storeys are generally less than 1 m thick, show little grain size variation, and are trough-cross stratified. Within the upper part of each sandstone, storeys are thicker (3-8 m), have more complete fining upward units, and a greater variety of sedimentary structures. Trough cross beds and planar tabular cross beds generally pass upward to ripple-laminated, fine-grained sandstones. Paleocurrents in all these strata suggest transport directions to the east-northeast.

We interpret the Calico bed and the Drip Tank Member to reflect deposition within shallow (2-5 m deep), coarse-grained, low-sinuosity rivers (Shanley and McCabe, 1990b-in review). The abundant mud clast conglomerates and woody debris associated with the base of these channel systems suggests these river systems were eroding fine-grained, mudrock-dominated, vegetated floodplains. We interpret the A-sandtone to have been deposited within somewhat deeper (4-6 m deep), finer-grained, moderate to high sinuosity rivers (Shanley and McCabe, 1990b-in review). In all three fluvial systems, we interpret the vertical increase in storey preservation, increase in fine-grained sediment, and increase in preserved lateral accretion deposits to reflect greater rates of fluvial aggradation (c.f. Bridge and Leeder, 1979; Posamentier and Vail, 1988).

<u>(2) Isolated fluvial facies tract</u>. Sandstones within this facies tract occur throughout the middle and upper portions of the John Henry Member and locally within the Smoky

Hollow Member of the Straight Cliffs Formation (Fig. 3a). These multistorey sandstones erosionally overlie, and are surrounded by fine-grained, rooted, carbonaceous mudrocks. Internal sedimentary structures within the sandstones consist of trough cross-stratified, medium-grained sandstones that fine upwards to ripple lamination, massive bedding and, occasionally, convolute lamination. Paleocurrents suggest transport to the northeast. The primary distinction between strata belonging to this facies versus the amalgamated sandstone facies previously described is the degree of channel sandstone amalgamation and preservation of fine-grained sediment. These strata are interpreted to reflect deposition in moderate to high-sinuosity rivers approximately 7 to 9 m deep (Shanley and McCabe, 1990b-in review). The erosional bases, abundant clay intraclasts, clay clast conglomerates and woody debris suggest these channels were eroded into vegetated, fine-grained floodplains.

(3) Tidally influenced fluvial facies tract. This facies tract exhibits the greatest variation in both lithology and sedimentary structures across the plateau and occurs in the Tibbet Canyon, Smoky Hollow, and John Henry Members (Fig. 3a). Along the northeastern margins of the plateau, this facies is sandstone dominated with both trough and planar-tabular cross beds that contain sigmoidal bedding, double mud drapes, complex-compound bedding and multiple reactivation surfaces (Shanley et al., 1990-in review). These strata become increasingly heterolithic towards the west and southwest. Sedimentary structures include synaeresis cracks, wavy and lenticular bedding, and inclined heterolithic stratification (Shanley et al., 1990-in review). Paleocurrents are normal, or at high angle to the paleoshoreline orientation for both the Tibbet Canyon and John Henry Members of the Straight Cliffs Formation. Body fossils such as inoceramid

debris are common along the northeastern margin of the plateau becoming rare towards the west and southwest. Trace fossils including *Teredolites*, *Arenicolites*, and *Skolithos* are common throughout this facies. These facies are interpreted to reflect deposition within tidally influenced rivers and estuaries (Shanley et al., 1990-in review). Broad, open estuaries along the northeastern margin of the plateau change, in a landward direction, to tidally influenced rivers towards the west and southwest.

(4) Alluvial plain facies tract. Strata comprising this facies tract are the principal component of the Smoky Hollow and John Henry Members of the Straight Cliffs Formation throughout the western and southwestern portions of the plateau (Fig. 3a). This facies is composed of rooted siltstones and very fine-grained sandstones, laterally discontinuous, ripple-laminated, very fine-grained sandstones, thin, claystones and thin discontinuous coals. These strata are interpreted as fine-grained floodplain deposits that accumulated on broad alluvial plains primarily during periods of overbank flooding (Shanley and McCabe, 1990b-in review).

(5) Coal-bearing facies. The Kaiparowits Plateau contains 42% of the coal resources in Utah with an estimated 13.7 billion metric tons of subbituminous C/high-volatile bituminous-A coal in Turonian through Campanian strata (Doelling and Graham, 1972). These coals are restricted to a sedimentary belt, approximately 25 km wide, that parallels both the present day Straight Cliffs escarpment and the paleoshoreline trend. Along the northeastern margin of the plateau, nearshore marine strata interfinger with coal-bearing strata. Detailed study of this facies transition (McCabe and Shanley, 1988, 1990) has shown that the transition from coal-bearing terrestrial to nearshore marine strata occurs over

a distance of only 2-4 km. In the western and central part of the plateau these same coal-bearing strata interfinger with channel and crevasse splay deposits. Our work in the plateau (McCabe and Shanley, 1988, 1990) suggests that these coals formed from peats that accumulated under raised mire conditions close to areas of active siliciclastic deposition.

Alluvial stacking patterns. Alluvial strata in the Kaiparowits Plateau are generally arranged in units that fine-upward, become increasingly less amalgamated upwards, and show an increase in tidal influence upwards (Shanley and McCabe, 1990b-in review; Shanley et al., 1990). Coarse grained, amalgamated fluvial deposits of the Calico bed, for example, are overlain by tidally influenced fluvial strata. Along the northeastern margin of the plateau these tidally influenced strata are sandstone dominated, while towards the west and southwest, the Calico bed is overlain by heterolithic, tidally influenced strata. Amalgamated fluvial sandstones of the A-sandstone grade upwards into isolated fluvial sandstones and tidally-influenced fluvial sandstones (Fig. 3a). Thick successions of isolated fluvial sandstones and alluvial plain strata overlie tidally-influenced fluvial strata of the A-sandstone sequence and are directly correlated with thick coal-bearing deposits (Fig. 3a).

SEQUENCE - AND CHRONO - STRATIGRAPHIC EVOLUTION - KAIPAROWITS PLATEAU

Introduction

Subdivision of the stratigraphic record into unconformity-bounded depositional sequences and their attendant systems tracts requires criteria that allows recognition of sequence boundaries and maximum-flooding surfaces in both nearshore marine and alluvial strata. These surfaces, in concert with detailed sedimentological observations allow subdivision of depositional sequences into their component systems tracts. Although such criteria have been well documented in nearshore marine strata (e.g., Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner, 1985; Van Wagoner et al., 1990), similar criteria are still being developed for alluvial strata (e.g., Shanley and McCabe, 1990b-in review; Shanley et al., 1990-in review).

In nearshore-marine strata, sequence boundaries are identified as erosional surfaces of regional extent that juxtapose shallow-water strata over significantly deeper-water facies. These relationships suggest an abrupt basinward shift in sedimentary environments and a break in normal shoreline progradation. Examples of these basinward shifts (also referred to as downward shifts) in facies tracts include fluvial valleys that are incised into marine strata, the presence of subaerial exposure, such as root zones, within marine strata, and regional subaerial erosion and subsequent stratal onlap (e.g., Weimer, 1983, 1989). Maximum-flooding surfaces in marine strata are associated with condensed sections and are generally characterized by the deepest-water facies within a given position on a depositional profile (e.g., Loutit et al., 1988). Sedimentary features that suggest a maximum-flooding surface include, regional stratal geometries interpreted as downlap, thin-bedded marine strata rich in volcanic ash deposits, thin-bedded marine strata with bioturbation as well as benthic and pelagic fossils, and thin-bedded marine strata that cap a succession of thinning-upwards beds and which are overlain by shallowing- and thickening-upwards beds.

Sequence boundaries and the nonmarine equivalents of maximum-flooding surfaces are often difficult to recognize in alluvial strata because of the numerous internal erosion surfaces and the abrupt lateral facies changes that characterize these strata. Within alluvial strata, the position of sequence-boundaries are suggested by an abrupt change in fluvial stacking pattern from isolated, moderate to high sinuosity deposits to coarser-grained, low sinuosity, amalgamated fluvial strata (Shanley and McCabe, 1990a-in review, b-in review). Maximum-flooding surfaces within nonmarine strata are indicated by the presence of tidally influenced fluvial deposits. Shanley et al. (1990-in review) described Holocene examples where tidal influence extended as much as 100 km inland of microtidal coastlines and documented Upper Cretaceous examples from the Kaiparowits Plateau where tidal influence could be recognized as much as 65 km inland of coeval shoreline deposits. These tidally influenced river deposits provide a key to chronostratigraphic correlation in nonmarine strata.

It is important to emphasize that we do not couch our interpretation in terms of 'sea level' change or 'tectonics.' Similar to Posamentier and Vail (1988), we consider stratal geometry in terms of base-level changes and the effect those changes have on accommodation space regardless of whether base-level changes are induced by tectonic subsidence, a change in eustasy or some combination of the two (the most likely case). Although accommodation space was only recently defined (Jervey,1988), it was manifested in earlier models (e.g., Barrell, 1917; Sloss, 1962; Allen, 1964). The concept of accommodation space is quite simple. "...In order for sediments to accumulate, there must be space available below base level (the level above which erosion will occur)" (Jervey, 1988, p. 47). Sloss (1962, p. 1051) described base level as "...an equilibrium surface ... above which a particle can not come to rest and below which deposition and burial are possible." In nonmarine strata, base level may be approximated by the concept of a graded-stream profile (Mackin, 1948) while at shoreline and shallow shelf positions base level is more accurately represented by sea level and the concept of a graded shelf respectively (e.g., Swift, 1970; Ross, 1990). Relative sea level and base level coincide at the shoreline. We shall use the term 'base level' because much of our work involves nonmarine strata and we feel that the term 'relative sea level' may be somewhat misleading.

Tectonic processes are a dominant control on the creation of accommodation space in foreland basins for large-scale cycles ('second-' and some 'third-order') of 4 Ma and greater duration (Devlin et al., 1990; Devlin and Shaw, 1990; Vail et al., 1990-in press). Superimposed on these large-scale cycles, however, are higher frequency cycles ('third- to fourth-order') of 0.5 to 4 Ma duration that control much of the detail of stratigraphic architecture (Devlin et al., 1990; Devlin and Shaw, 1990; Vail et al., 1990-in press) and often reflect changes in accommodation driven by eustatic fluctuations. Angevine et al. (1990), for example, recognized higher frequency cycles modifying longer-term, tectonically driven cycles and suggested that they might reflect variations in sea level.

Within the Kaiparowits Plateau, tectonic and eustatic events have influenced the accumulation of between 300 and 400 m of strata within the Straight Cliffs Formation. By analyzing these strata in a sequence stratigraphic context, thirteen discrete events are recognized that help establish a high-resolution chronostratigraphy for the plateau. By considering changes in stratigraphic architecture to be a function of base-level change, the results from the Kaiparowits Plateau can be applied to a variety of tectonic settings across a broad spectrum of geologic time.

1. Rapid strandplain progradation

Decreasing rates of base-level rise during the middle Turonian resulted in a thin, but regionally persistent, succession of progradational offshore and strandplain related parasequences (Fig. 3a) that can be observed throughout the plateau. These strata comprise the upper portions of the Tropic Shale and the lower part of the Tibbet Canyon Member (Fig. 4) and correspond to a late highstand systems tract (Posamentier and Vail, 1988; Posamentier et al., 1988; Van Wagoner et al., 1990). The condensed section associated with these strata likely occurs within a bentonite rich zone in the Tropic Shale located approximately 80 m below the Tibbet Canyon Member and described by Eaton et al. (1987). Age assessments of these strata suggest this highstand systems tract prograded a distance of at least 190 km, from the vicinity of Cedar City, Utah to the eastern margin of the Kaiparowits Plateau, during a time span of approximately 1.8 ma. This systems tract is capped by the Tibbet Canyon sequence boundary (Fig. 3a).

2. A slight seaward shift in facies tracts

Shoreface, and occasionally foreshore, deposits related to progradation of the Tibbet Canyon Member strandplain are everywhere overlain by channel deposits of the uppermost part of the Tibbet Canyon Member (Figs. 3a and 5). Although these channel fill deposits have an unconformable relationship with underlying strata, their occurrance in the Tibbet Canyon Member at the type section (Peterson, 1969b) dictates that they be included in the Tibbet Canyon Member. The contact separating shoreline related strata from channel deposits has erosional relief of several meters and has been recognized in all measured sections throughout the plateau. At Wiregrass Canyon, for example (Fig. 2), offshore-transitional facies are abruptly overlain by thick, plane-bedded sandstones that contain flute and prod marks and that grade into ripple-laminated sandstones and carbonaceous shales with thin, discontinuous coals (Fig. 6). These strata are interpreted as thin meandering river deposits erosionally overlying offshore-transitional strata. The unconformity surface separating these distinct depositional facies is interpreted to reflect either a base-level

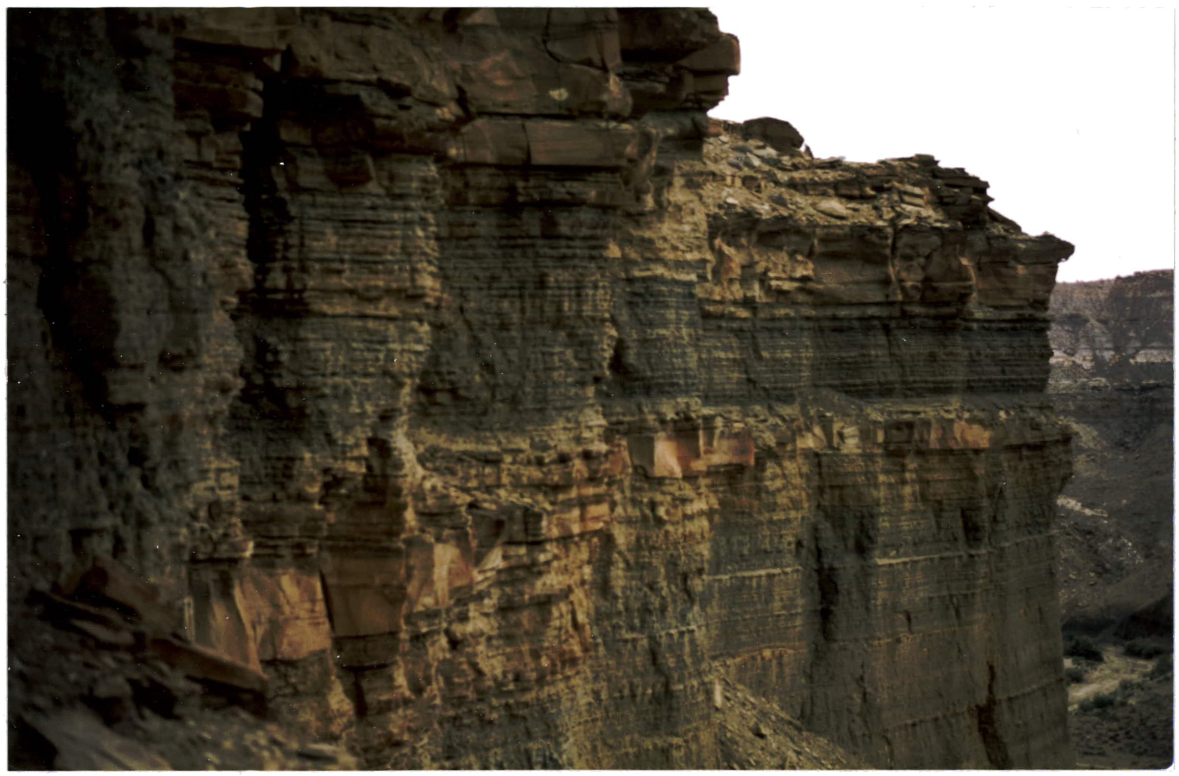


Figure 4. View of the Tropic shale and Tibbet Canyon Member from Tibbet Canyon. Parasequences in the Tibbet Canyon Member consist of HCS bedded sandstones that progressively shallow and thicken upwards and are capped by an abrupt flooding surface. Occasionally, as in this case, a thin succesion of progressively deepening and thinning upwards sandstones overlie the flooding surface.

Figure 5. An erosional surface within the Tibbet Sandstone Member separates shoreface parasequences from overlying channel deposits. This channel fill consists of at least three distinct sandbodies which, in general, are fluvial dominated at the base and tidally-influenced at the top. This erosional surface is the Tibbet Canyon sequence boundary and is located within Tibbet Canyon.

Figure 6. In Wiregrass Canyon, the Tibbet Canyon sequence boundary separates meandering river deposits and thin, discontinuous coal seams (#1) from underlying HCS bedded sandstones(#2).

stillstand or, more likely, a slight base-level fall followed by a basinward shift in facies tracts. Although we have not physically traced this surface throughout the plateau, we have observed and described these stratigraphic relationships at all sections studied thus far. The regional extent of this erosional surface coupled with the basinward shift in facies tracts leads us to interpret this surface as a sequence boundary (Tibbet Canyon sequence boundary). Biostratigraphic data are somewhat limited and we suggest this base-level fall occurred during the late-middle Turonian.

3. Aggradation of fluvial and tidally influenced strata

Renewed base-level rise following formation of the Tibbet Canyon sequence boundary resulted in aggradation of fluvial and tidally influenced fluvial deposits (Figs. 3a and 5). Multistorey, fining-upwards sandbodies generally show a change from fluvial-dominated sandstones in more deeply scoured channels to tidally influenced fluvial sandstones in the upper portions of the channel complex. Medium-grained, trough cross-bedded sandstones with clay-clast lags and clay-clast conglomerates give way to fine-grained sandstones with multiple reactivation surfaces, double mud drapes, and scattered shell debris. The abrupt change in depositional processes recorded across the sequence boundary, combined with the evidence of tidally influenced fluvial processes is interpreted to reflect base-level rise, coastal transgression and development of a transgressive systems tract during the late-middle to early-late Turonian. Development of coeval shoreline deposits that must have existed during this fluvial aggradation are not observed within the Kaiparowits Plateau and were likely located to the east.

4. Alluvial aggradation during a highstand

Tidally-influenced fluvial deposits of the Tibbet Canyon Member are everywhere overlain by fine-grained, isolated channel deposits, thin, discontinuous coal beds, and rooted alluvial plain strata (Figs. 3a and 7). These strata comprise the lower portion of the Smoky Hollow Member of the Straight Cliffs Formation and are interpreted as late Turonian alluvial, early highstand systems tract deposits related to shoreline progradation and aggradation east of the Kaiparowits Plateau region.

5: Major seaward shift in facies tracts

Erosionally overlying the fine-grained alluvial-plain and isolated channel deposits of the Smoky Hollow early highstand systems tract are bleached, coarse-grained, pebbly sandstones and conglomerates of the Calico bed which forms the uppermost portion of the Smoky Hollow Member (Figs. 3a and 8). Significantly, there are no pebbles or conglomerate lenses similar to those found in the Calico bed in underlying channel deposits of the Smoky Hollow Member, or underlying shoreface deposits of the Tibbet Canyon Member. We have physically traced the Calico bed throughout much of the plateau through a combination of measured sections, walking of stratal units, panorama photographs, and low-angle photographs aquired during a helicopter survey of the plateau. Based on the facies tract dislocation across this erosional surface and the development of this surface as one of regional extent throughout the Kaiparowits Plateau, we suggest it may be interpreted as a sequence boundary (Calico sequence boundary) caused by a fall in base level. Significantly, the lower portion of the Calico bed is generally bleached and has undergone dissolution of feldspar. It appears that dissolution of feldspars and intense weathering of the Calico bed may reflect prolonged periods of subaerial exposure with little net

Figure 7. Carbonaceous shales, thin, discontinuous coal seams, and rooted, fine-grained strata comprise the Smoky Hollow Member. Photograph from Coyote Canyon.

Figure 8. Coarse-grained sandstones and pebble conglomerates of the Calico bed erosionally overly fine-grained alluvial plain strata of the Smoky Hollow Member. This contact marks the Calico sequence boundary. Photograph from Tibbet Canyon.

sedimentation. We suggest that portions of the Calico bed represent the preservation and nonmarine reworking of coarse-grained fluvial terrace deposits that formed during a base-level fall (Shanley and McCabe, 1990b-in review). Biostratigraphic dates are limited in these nonmarine deposits and our age assessment of the Calico sequence boundary is based on stacking patterns and regional stratigraphic relationships. Given these caveats, we suggest that this sequence boundary is a composite unconformity representing a significant period of sediment bypass spanning much of the late Turonian and earliest Coniacian.

6: Aggradation of coarse fluvial strata

Renewed base-level rise following formation of the Calico sequence boundary resulted in additional aggradation of coarse-grained and pebbly, laterally amalgamated fluvial strata (Figs. 3a and 8). Facies analysis of these strata suggest they were deposited in relatively shallow, low-sinuosity rivers (Shanley and McCabe, 1990b-in review). The high degree of lateral amalgamation that typifies much of the Calico bed and the change to tidally influenced river deposits above is interpreted as fluvial aggradation during periods of slow base-level rise. A similar conclusion was arrived at by Eaton et al., (1987) and Bobb and Ryer (1990). Those fluvial deposits within the Calico bed that have been interpreted as fluvial terrace deposits (see #5 above) may represent deposition as part of a lowstand systems tract. The additional aggradation of the Calico bed that occurred during the base-level rise is more likely equivalent to the lower part of a transgressive systems tract.

Biostratigraphic data are not available within these coarse-grained fluvial deposits. Age estimates are, therefore, constrained by paleontological data from overlying tidally influenced strata and underlying marine deposits and biased by inferred correlation with strata from adjacent outcrop areas. We suggest part of the Calico bed accumulated from late Turonian to early Coniacian.

7: Development of a maximum-flooding surface

Increased rates of base-level rise following deposition of the Calico bed are reflected by more complete preservation of fining-upwards fluvial deposits, as well as the juxtaposition of tidally influenced strata above the Calico bed. Along the northeastern margin of the plateau tidally influenced strata, interpreted as deposits of an open estuary, overlie the Calico bed and record this base-level rise (Fig. 3a). These tidally influenced strata in turn are overlain by a persistent pebble lag followed by offshore-transition and offshore strata (Fig. 9) that culminate in a thin bed of HCS sandstone containing a fossiliferous lag (Fig. 10). In the central and western part of the plateau, the Calico bed is overlain by tidally-influenced, heterolithic fluvial strata (Fig. 11).

The stratal succession along the northeastern margin of the plateau is interpreted to reflect coastal transgession, development of a ravinement surface, and maximum marine flooding resulting in deposition of a condensed section. The transgressive lag and condensed section deposit have been recognized throughout the northeastern margin of the plateau. These same processes of coastal transgression are reflected in the central, western, and southwestern portions of the plateau where alluvial strata grade upwards into tidally influenced alluvial deposits; these tidally influenced fluvial strata are interpreted as temporal equivalents to the maximum-flooding surface along the northeastern margin of the plateau (Shanley et al., 1990-in review). Biostratigraphic data suggests the maximum-flooding surface is of late-early to possibly middle Coniacian in age along the northeastern

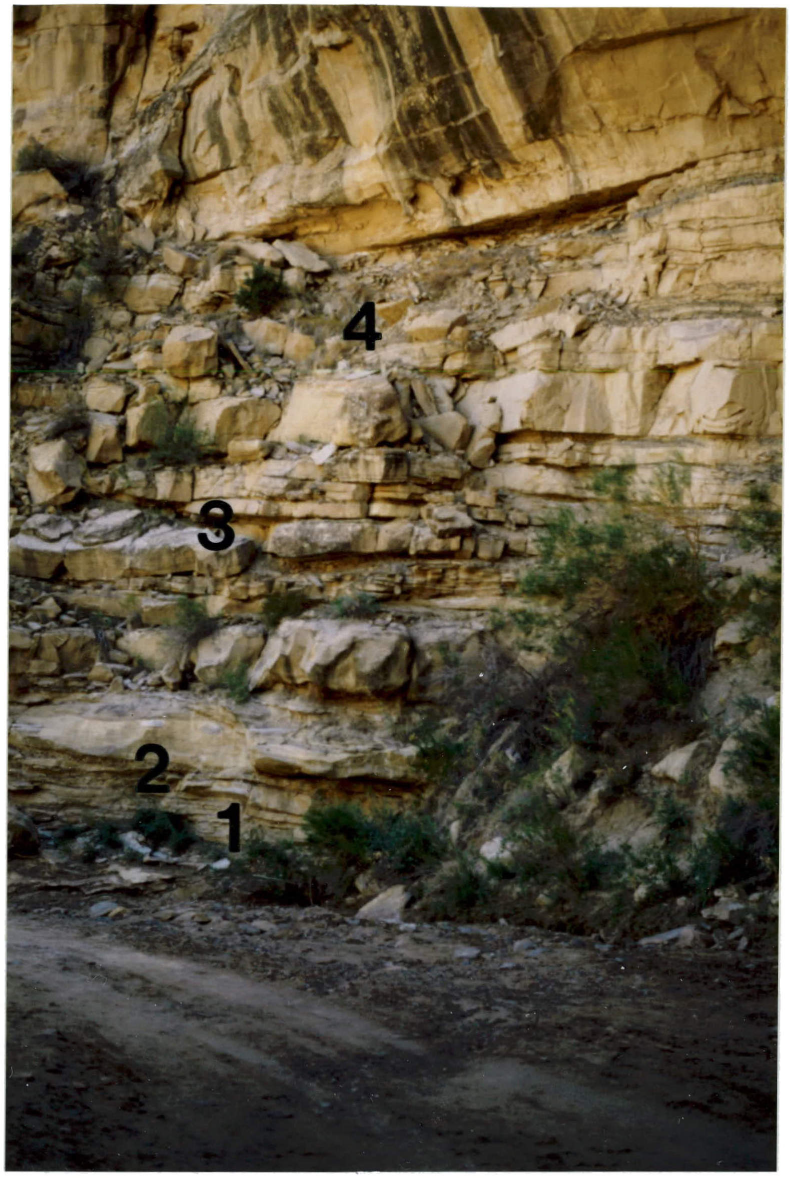


Figure 9. In Left Hand Collet Canyon a transition from coarse-grained fluvial deposits of the Calico bed (in the canyon floor at this locality) to tidally-influenced fluvial deposits (#1), HCS-bedded sandstones (#3), and a condensed zone (#4) can be observed. A pebble conglomerate interpreted as a transgressive lag is located at #2. This records coastal transgression during the early and middle Coniacian. In Upper Valley to the north, the condensed section deposit that denotes the maximum flooding surface can be observed directly on the transgressive lag near the actual transgressive maxima.

Figure 10. A fossiliferous lag containing ammonites, inoceramid debris, and sharks teeth can be found throughout the northeastern escarpment of the plateau. This deposit is a condensed section deposit interpreted as a maximum flooding surface that separates transgressive deposits from highstand deposits. In this photograph from Upper Valley, the condensed section is located immediately above a pebble conglomerate interpreted as a transgressive lag.

Figure 11. In the western and southwestern part of the plateau, coarse-grained fluvial deposits of the Calico bed grade upwards into tidally-influenced fluvial deposits. These tidally-influenced fluvial deposits in Tibbet Canyon are temporally equivalent to the maximum flooding surface.

margin of the plateau. Together with much of the coarse-grained fluvial deposits of the Calico bed, these strata comprise a transgressive systems tract.

8: Renewed strandplain progradation

A decrease in the rate of base-level rise resulted in progradation of nearshore parasequences informally refered to as the A-sandstone (Fig. 3a). These strata comprise the lowest portion of the John Henry Member of the Straight Cliffs Formation (Hettinger et al., 1990). These shoreface strata prograded a distance of approximately 12 - 16 km as part of a strandplain coastline between the middle and late Coniacian . In the central and western portions of the Kaiparowits Plateau, tidally influenced fluvial deposits are overlain by fine-grained floodplain deposits, and isolated, fine-grained channel sandstones. These strata are equivalent to highstand and late-highstand systems tract deposits (Posamentier and Vail, 1988; Posamentier et al., 1988) and are overlain by the A-sandstone sequence boundary.

9: A slight seaward shift in facies tracts

Along the northeastern margin of the plateau, offshore transitional and shoreface strata of the A-sandstone are erosionally overlain by tidally influenced sandstones which have also been included in the A-sandstone (Fig. 3a). The erosional surface separating these strata has been recognized throughout the northeastern margin of the plateau where detailed work suggests the existence of a deeply incised valley (Hettinger et al., 1990). This incised valley reflects a base-level lowering and formation of a sequence boundary (Fig. 12). In the southwestern portion of the plateau where coeval strata are dominated by alluvial deposits, this same basinward shift in facies tracts is reflected by a change in fluvial

Figure 12. Progradational shoreface parasequences of the A-sandstone are erosionally overlain by tidally-influenced fluvial deposits. The erosional surface shown in Left Hand Collet Canyon marks the A-sequence boundary which can be recognized throughout much of the plateau in both alluvial and nearshore strata.

architecture (Shanley and McCabe, 1990b-in review). Fine-grained alluvial-plain facies containing well developed root structures, soil zones and isolated channel sandstones are erosionally overlain by medium to coarse-grained, laterally amalgamated channels. This channel complex has been physically traced from Rock House Cove to Blue Cove where it pinches out abruptly into rooted, fine-grained floodplain deposits. We have interpreted this sandstone complex as an incised valley deposit (Shanley and McCabe, 1990b-in review). The regional extent of this erosional surface coupled with the basinward shift in facies tracts suggests this surface is a sequence boundary (A-sequence boundary). Biostratigraphic data suggest a late Coniacian date for this base-level fall.

10: Aggradation of fluvial and tidally-influenced strata

Renewed base-level rise following formation of the A-sequence boundary resulted in aggradation of tidally influenced estuarine and fluvial strata along the northeastern margin of the plateau and tidally-influenced fluvial and fluvial deposits in the central and southwestern part of the plateau (Fig. 3a). Detailed descriptions of these strata are found in Shanley et al. (1991-in review). Tidally influenced strata in the northeastern part of the plateau are sandstone dominated and suggest open estuarine to shelf processes. These strata are locally overlain by a thin pebble conglomerate separating tidally influenced valley fill deposits from overlying offshore and offshore-transitional strata. This conglomerate is interpreted as a transgressive lag (Fig. 13). Tidally influenced valley-fill deposits become increasingly heterolithic towards the west and southwest as tidal processes are progressively replaced by fluvial processes (Fig. 14). In the central and southwestern part of the plateau, alluvial strata associated with the A-sandstone consist of fluvial dominated, amalgamated channel sandstones at the base that become increasingly isolated and possess

Figure 13. A pebble conglomerate overlies tidally-influenced fluvial deposits which have aggraded the A-sandstone incised valley. Sporadic in occurrence, this pebble conglomerate varies in thickness from a single pebble layer to several centimeters and is interpreted as a transgressive lag. This lag separates tidally-influenced fluvial deposits below, from overlying offshore and lower shoreface strata. Photograph from Left Hand Collet Canyon.

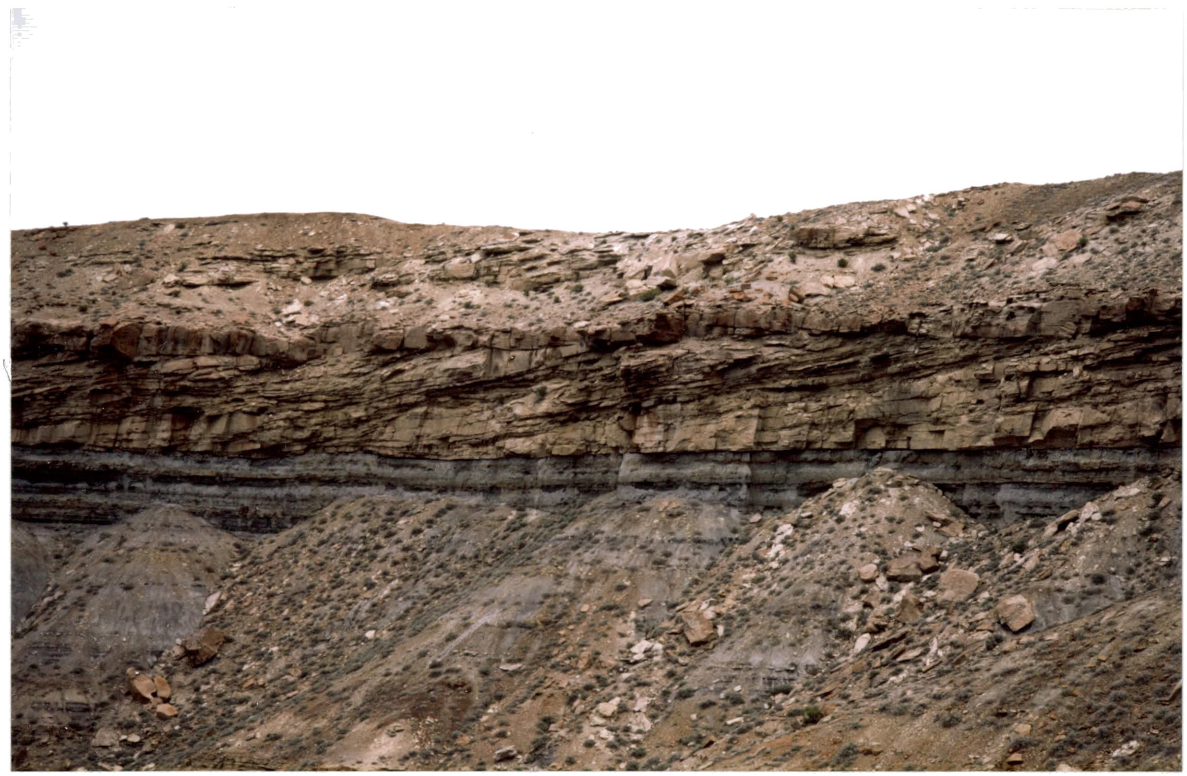


Figure 14. Heterolithic fluvial deposits within the A-sandstone in Tibbet Canyon reflect the development of tidally-influenced river conditions well inland from their coeval shoreline.

increasingly greater evidence of tidal processes towards the top. This trend in alluvial stacking patterns coupled with the tidally influenced strata observed along the northeastern margin of the plateau suggest these strata were deposited during a base-level rise and may be considered a transgressive systems tract. Biostratigraphic data from overlying and underlying strata suggest these strata were deposited during the latest Coniacian and, possibly, the early Santonian.

11: Vertical aggradation during a highstand

Vertically aggraded nearshore, coal-bearing, and alluvial strata characterize the John Henry Member (Fig. 3a). In the southwestern part of the plateau, there are more than 125 m of fluvial deposits in which the meanderbelt sandstones are isolated within fine-grained floodplain strata (Fig. 15). In the western and central part of the plateau, these isolated channel deposits have been physically traced, in the field and on photographs, into a thick succession of crevasse-splay deposits, thin ribbon-like fluvial sandstones interbedded with thick coal seams. Along the northeastern margin of the plateau, there are over 220 m of shoreface and nearshore strata arranged as aggradational parasequences (Fig. 16). Detailed study shows the landward pinchouts of successive parasequences to vary between a few hundred meters to perhaps 2 km. Foreshore deposits and capping root horizons pinchout towards the edge of the Straight Cliffs escarpment suggesting theat the seaward pinchouts of these nearshore sandstones occurred in close proximity to the Straight Cliffs. These nearshore sandstones have been physically traced into the thick coal-bearing deposits that occur throughout most of the central plateau. Based on this stacking pattern of alluvial, coal-bearing, and nearshore strata we interpret these deposits as a highstand systems tract. The geometric arrangement of strata agrees quite well with the conceptual models suggested

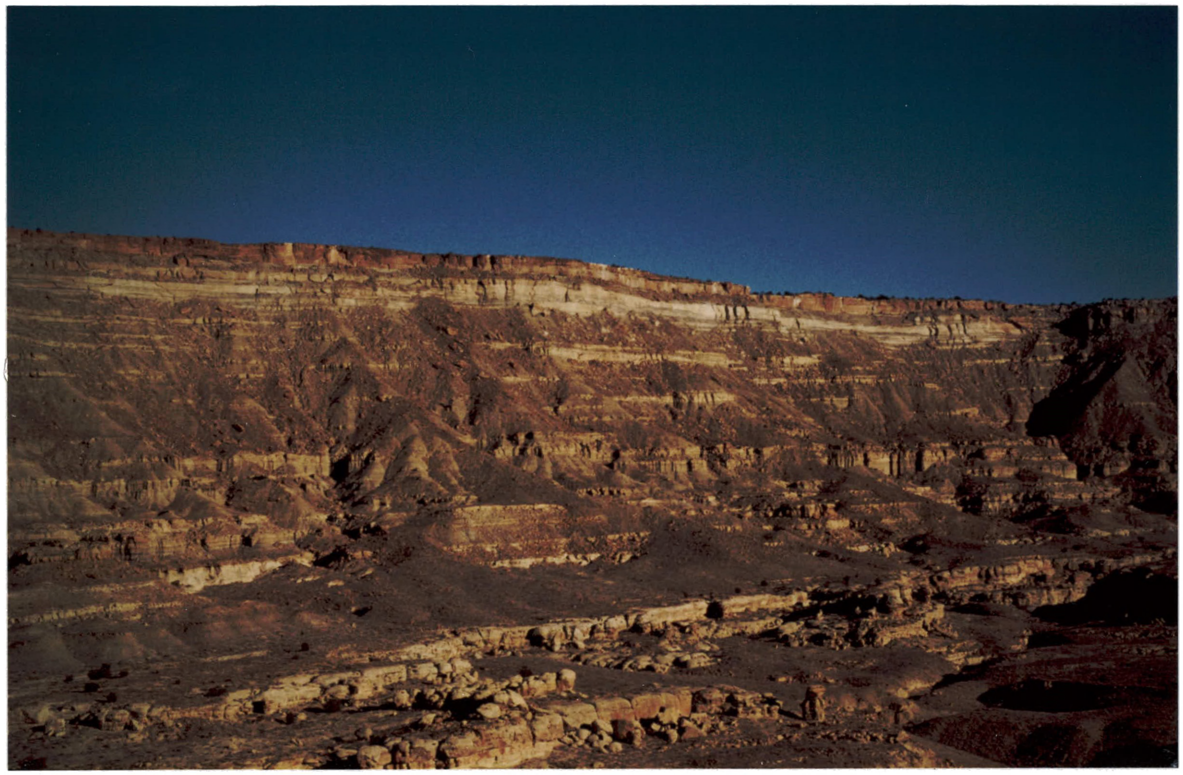


Figure 15. Isolated meanderbelt sandstones that appear to 'float' in a fine-grained matrix of alluvial plain strata comprise the highstand systems tract within alluvial strata. The prominent bench of sandstone that forms the foreground marks the top of amalgamated sandstone associated with the A sequence boundary. The Drip Tank sequence boundary is annotated at the top of the photograph. Photograph from Blue Cove.

Figure 16. Along the eastern and northeastern escarpment of the plateau, stacked shoreface to foreshore sandstones comprise the highstand systems tract that characterizes the John Henry Member. These nearshore strata are replaced by coal-bearing strata to the west within a few kilometers of this location. Minor facies tract offsets within this aggradational complex suggest the presence of high-frequency sequence boundaries, however, we have not been able to recognize these events in the alluvial strata to the west. Photograph looking to the west from just outside Left Hand Collet Canyon.

for highstand systems tracts by Posamentier and Vail (1988). Our work suggests that additional sequences may be present in association with major coal zones, however, we have not been able to recognize equivalent units in alluvial strata to the west and southwest, and have therefore, been reluctant to include them in this discussion. Biostratigraphic data within nearshore strata indicates these highstand deposits range in age from early to late Santonian.

12: A second major seaward shift in facies tracts

Fine-grained alluvial plain and isolated channel deposits, thick crevasse splay and coal-bearing strata, and fine-grained nearshore strata associated with the John Henry Member highstand systems tract (previously described) are erosionally overlain by coarse-grained, laterally-amalgamated, pebbly sandstones and conglomerates of the Drip Tank Member (Figs. 3a and 17). The brownish weathering color of the Drip Tank has allowed it to be physically correlated in the field and on photographs across most of the plateau. Significantly, there are no pebbles or conglomerate lenses similar to those found in the Drip Tank Member in underlying strata, suggesting there is no facies relationship across the contact. Although the surface at the base of the Drip Tank Member has local erosional relief of several meters, regional correlations across the plateau suggests that as much as 50 m of additional erosion may have taken place in the southwestern part of the plateau. Based on the facies tract juxtapositions across this erosional surface and the development of this surface as one of regional extent throughout the plateau, we interpret it as a sequence boundary (Drip Tank sequence boundary) related to a fall in base level. Age assessments from marine strata of the underlying John Henry Member suggest the highstand systems tract is of late Santonian age, whereas the overlying Wahweap Formation contains early

Figure 17. Coarse-grained sandstones and pebble conglomerates of the Drip Tank Member erosionally overlie fine-grained alluvial strata, carbonaceous shales, coal-bearing strata, and shoreface deposits. In this photograph the Drip Tank overlies carbonaceous shales and coals in Lower Trail Canyon. The erosional surface marks the Drip Tank sequence boundary.

Campanian mammals (Eaton, 1991-in press). Within these constraints and based on regional stratigraphic relationships, we suggest the Drip Tank sequence boundary is of latest Santonian to earliest Campanian age.

13: Aggradation of coarse fluvial strata

Renewed base-level rise following formation of the Drip Tank sequence boundary resulted in aggradation of coarse-grained and pebbly, laterally-amalgamated fluvial strata of the lower part of the Drip Tank Member (Figs. 3a and 17). Facies analysis of these strata suggest they were deposited in relatively shallow, low sinuosity rivers (Shanley and McCabe, 1990b-in review). The high degree of lateral amalgamation is interpreted as fluvial aggradation during a period of slow base-level rise. Biostratigraphic data are not available within these coarse-grained deposits and age assessments are based on adjacent strata and regional correlations. These data suggest the Drip Tank is of early Campanian age.

CHRONOSTRATIGRAPHIC CORRELATIONS BETWEEN THE KAIPAROWITS PLATEAU AND ADJACENT AREAS

Introduction

Sequence stratigraphic concepts provide a framework within which temporal and physical relationships amongst sedimentary rocks might be better understood. These concepts also illuminate areas in which stratigraphic problems might be anticipated while at the same time offering possible explanations to those problems. Within a localized study area, recognition of sequence boundaries, transgressive surfaces, and maximum-flooding surfaces refine the interpretation of stratigraphic evolution across a broad spectrum of depositional environments and suggest a methodology for developing chronostratigraphic correlations. Recognizing that depositional sequences reflect base-level change and their effect on accommodation space allows these same concepts to be applied to regional chronostratigraphic problems. An implicit assumption of sequence stratigraphic concepts is that critical surfaces, such as sequence boundaries and maximum-flooding surfaces, as well as sytems tracts and parasequence stacking patterns may be anticipated across a broad area.

In the Cretaceous foreland basin, differing rates of tectonic subsidence introduce an additional complication to chronostratigraphic correlation. Sequence-boundary unconformities well developed in areas of relatively low tectonic subsidence may be represented by correlative conformities in areas of higher subsidence. As a result, Type 1 sequence boundaries may change along strike to Type 2 sequence boundaries due to changes in tectonic subsidence (sequence boundary terminology from Posamentier et al., 1988). Examining coeval strata from areas of differing subsidence histories, however, allows the relative effects of tectonic subsidence and sea-level change to be better understood. Chronostratigraphic correlation in the Cretaceous foreland basin is facilitated by a detailed biostratigaphic framework based on ammonidea and inocermidea (e.g. Fouch et al., 1983; Kauffman and Pratt, 1985; Collom, 1991). Figure 18 presents chronostratigraphic correlations between the Kaiparowits Plateau, Black Mesa, the southwestern San Juan Basin, and the Wasatch Plateau. This chart accounts for existing biostratigraphic data, stratal stacking patterns, and facies-tract dislocations. In a general sense, both the Kaiparowits Plateau and Black Mesa are on depositional strike with each other and are located landward of the San Juan Basin and Wasatch Plateau throughout much of the Cretaceous. Examination of thickness trends suggests that subsidence rates in

Figure 18. Stratigraphic correlation chart for the southern Colorado Plateau and Wasatch Plateau. Chronostratigraphic position is based on published biostratigraphic collections. Within the Kaiparowits Plateau, biostratigraphic data are reported in Peterson (1969a, b), Peterson and Kirk (1977), Eaton (1987, 1991-in press), Eaton et al. (1987), Eaton and Cifelli (1988), and Hettinger et al. (1990). Within Black Mesa, biostratigraphic data are reported in Franczyk (1988). Within the San Juan Basin, biostratigraphic data are reported in Hook et al. (1983), Molenaar (1983a, b), Franczyk (1988), and Cobban and Hook (1989). In the Wasatch Plateau, biostratigraphic data are reported in Katich (1954), Cobban (1976), Ryer (1981b), Ryer and McPhillips (1983), Schwans (1988). A closed circle denotes recovered fossil data, pinpointing the biostratigraphic age of a particular lithostratigraphic unit at a certain locality.

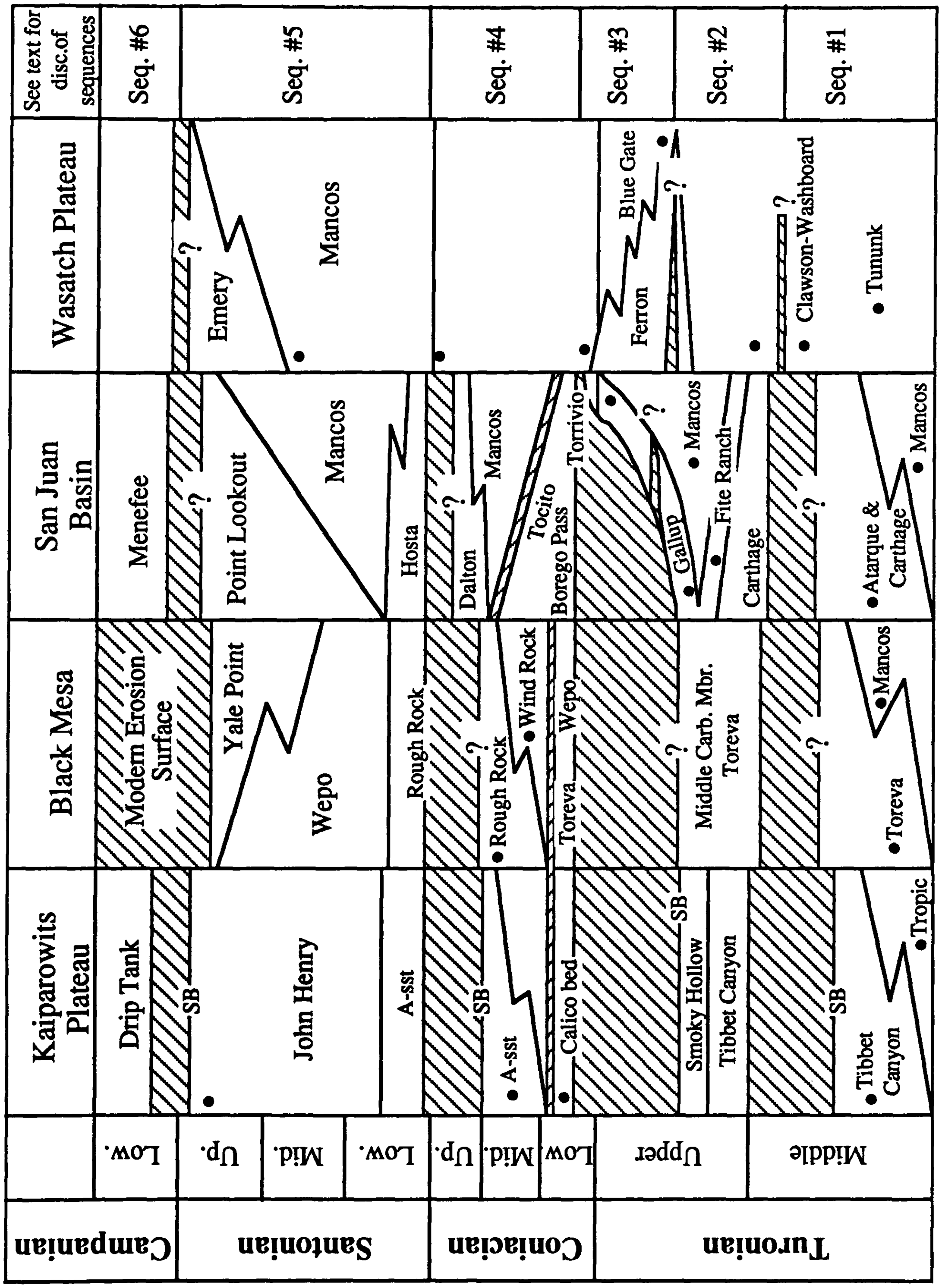

Kaiparowits Plateau
Black Mesa
San Juan Basin
Wasatch Plateau
See text for disc.of sequences
Seq. #6
Seq. #5
Seq. #4
Seq. #3
Seq. #2
Seq. #1
Campanian
Santonian
Coniacian
Turonian
Low.
Up.
Mid.
Low.
Up.
Mid.
Low
Upper
Middle
Drip Tank
SB
John Henry
A-sst
SB
A-sst
Calico bed
Smoky Hollow
SB
Tibbet Canyon
SB
Tibbet Canyon
Tropic
Modern Erosion Surface
Yale Point
Wepo
Rough Rock
?
Rough Rock
Wind Rock
Toreva
Wepo
?
Middle Carb. Mbr.
Toreva
?
Mancos
Toreva
Menefee
?
Point Lookout
Mancos
Hosta
?
Dalton
Mancos
Tocito
Borego Pass
Torrivio
?
Gallup
Mancos
Fite Ranch
Carthage
?
Atarque &
Carthage
Mancos
?
Emery
Mancos
Blue Gate
Ferron
?
?
Clawson-Washboard
Tununk

Figure 18

the Wasatch Plateau were significantly greater than those in either the Kaiparowits Plateau, Black Mesa, or the San Juan Basin. Although the ability to recognize similar sequence-stratigraphic characteristics across a broad region does not necessarily argue for a similar driving mechanism, we find it intriguing that stratigraphic 'problems', recognized as either unusual facies juxtapositions or abrupt changes in stacking patterns, can be identified across a broad area at approximately equivalent times and may be elegantly explained though base-level changes.

Middle Turonian - sequence 1:

Middle Turonian strata in Black Mesa and the San Juan Basin are dominated by shoreline progradation (Hook et al., 1983; Molenaar, 1983a; Franczyk, 1988; Cobban and Hook, 1989) while the Wasatch Plateau at this time was dominated by offshore marine shales of the Tununk Member of the Mancos Shale. In Black Mesa, shoreline dominated strata of the Toreva Formation are capped by channel sandstones across much of the region (Franczyk, 1988) while at Upper Nutria, in the vicinity of the San Juan Basin, nonmarine strata of the Carthage Member of the Tres Hermanos Formation directly overlie offshore, marine shales of the Mancos (Hook et al., 1983). In both areas, we suggest that these facies relationships may reflect a basinward shift and a sequence boundary equivalent to the Tibbet Canyon sequence boundary in the Kaiparowits Plateau.

In the Wasatch Plateau, late-middle Turonian sandstones of the Clawson and Washboard units of the Ferron Sandstone (Cotter, 1975) overlie the Tununk Member of the Mancos Shale. Although a dramatic facies tract dislocation is not immediately evident, regional stacking patterns suggest a significant basinward shift at the base of the Ferron Sandstone (e.g., Katich, 1954; Hale and van de Graaf, 1964; Doelling and Graham, 1972;

Hale, 1972; Ryer, 1981a, b, 1984; Ryer and McPhillips, 1983; Schwans, 1988). Biostratigraphic data (e.g. Katich, 1954; Cobban, 1976) indicate that this basinward shift occurred during the late-middle, to late Turonian suggesting it may be temporally associated with the Tibbet Canyon sequence boundary. The nature of the basinward shift in facies tracts suggests rates of base-level lowering in the plateau were not sufficient to cause a significant facies tract dislocation indicating the sequence boundary in the Wasatch Plateau is perhaps represented by a correlative conformity. A similar hypothesis was advanced by Schwans (1988). It is also possible that the rate of base-level rise simply decreased resulting in a Type 2 sequence boundary similar to the conceptual models of Posamentier et al. (1988). Alternatively, sedimentologic and stratigraphic descriptions of the lower Ferron Sandstone (Cotter, 1975, 1976) suggest that the Clawson and Washboard units represent progradation of offshore and lower shoreface deposits that are locally eroded into by channel deposits of the Farnham unit. It is possible that this erosion reflects a sequence boundary and may be temporally equivalent to the Tibbet Canyon boundary.

Late Turonian - sequence 2

Tidally influenced river deposits of the Tibbet Canyon Member in the Kaiparowits Plateau overlie the Tibbet Canyon sequence boundary and are interpreted to reflect base-level rise. In Black Mesa, coeval strata include channel deposits, carbonaceous shales, and fine-grained strata of the Middle Carbonaceous Member of the Toreva Formation (Franczyk, 1988). In the San Juan Basin, nonmarine deposits of the Carthage Member, retrogradational shoreface parasequences of the Fite Ranch Member of the Tres Hermanos Formation, and marine shales at the base of the Pescado Tongue of the Mancos Shale are considered temporal equivalents (Hook et al., 1983). Biostratigraphic data (Hook et al.,

1983) indicate the presence of a downlap surface within the Pescado Tongue further suggesting these strata may comprise a transgressive systems tract.

In the Wasatch Plateau to the northeast, the lower Ferron Sandstone (Clawson and Washboard units) is overlain by a widespread flooding surface (Ryer, 1981a, b; Ryer and McPhillips, 1983). We suggest this flooding surface may be early-late Turonian in age and equivalent to the transgressive systems tract observed elsewhere. However, detailed biostratigraphic data that might constrain the age of this flooding surface are not available.

Fine-grained deposits of the Middle Carbonaceous Member of the Toreva Formation in Black Mesa and similar deposits of the Smoky Hollow Member in the Kaiparowits Plateau reflect coastal plain aggradation. These strata may be correlated to initial shoreline progradation of the Gallup Sandstone in the San Juan Basin and upper Ferron Sandstone in the Wasatch Plateau. In the Kaiparowits Plateau these alluvial-plain deposits are overlain by the Calico sequence boundary which records a significant basinward shift in facies tracts and marks a prolonged period of sediment bypass. In Black Mesa, coarse-grained and pebbly, amalgamated channel deposits of the Upper Sandstone Member of the Toreva Formation are regionally incised into underlying strata throughout the region (Franczyk, 1988). We suggest that this incision in Black Mesa reflects a sequence boundary similar to the Calico sequence boundary.

In the San Juan Basin an abrupt basinward shift in shoreface parasequences occurs within the lower portion of the Gallup Sandstone (e.g., Molenaar, 1983a, b; Anderson, 1989; Nummedal, 1990). In the Wasatch Plateau, an abrupt basinward shift in parasequence stacking patterns also occurs in the upper Ferron Sandstone, followed by aggradational and retrogradational parasequences (e.g., Ryer, 1981a, b; Ryer and McPhillips, 1983; Stapor and Adams, 1988, Frank Stapor and Roy Adams, personal communication 1990). These stratal stacking patterns, combined with available biostratigraphic data suggest the basinward shift in facies tracts in both areas may be temporally equivalent to the Calico sequence boundary in the Kaiparowits Plateau, an area of sediment bypass. Other workers (Doelling and Graham, 1972; Schwans, 1988) have also suggested that an unconformity, or its correlative conformity, may be present near the base of the upper Ferron in the Wasatch Plateau. Deposition of the Ferron Sandstone due to a base-level change has also been suggested by Angevine et al. (1990). The lack of a dramatic facies tract dislocation in the upper Ferron Sandstone in the Wasatch Plateau, however, suggests this sequence boundary may be represented by its correlative conformity at this locality, or as previously mentioned, may reflect the development of a Type 2 sequence boundary.

Late Turonian to early Coniacian - sequence 3

Shoreface parasequences in the upper portion of the upper Ferron and Blue Gate Shale in the Wasatch Plateau are arranged in a retrogradational fashion (e.g. Ryer and McPhillips, 1983). These stratal units may be interpreted as a transgressive systems tract. Biostratigraphic data (Cobban, 1976; Ryer 1981a, b; Ryer and McPhillips 1983) suggest these strata are older (due to onlap?) than any strata in the Kaiparowits Plateau or Black Mesa where continued exposure resulted in sediment bypass. In the San Juan Basin to the south, progradational shoreface parasequences of the Gallup Sandstone predominate.

The uppermost shoreface parasequences of the Gallup Sandstone in the San Juan Basin are abruptly overlain by coarse-grained channel deposits, nonmarine strata, and retrogradational estuarine strata (Molenaar, 1983a; Nummedal, 1990; Clive Jones and John Van Wagoner, personal communication 1990). These data suggest an extensive sequence boundary of early Coniacian age. Coeval strata in the Wasatch Plateau to the north, however, do not record a similar basinward shift in facies tracts at the top of the Ferron Sandstone (Cobban, 1976; Ryer 1981a, b; Ryer and McPhillips, 1983). We offer two explanations for these data. The first explanation, which we favor, suggests that increased subsidence rates in the Wasatch Plateau during the Coniacian resulted in a base-level rise in the plateau, preventing formation of a sequence boundary. In the San Juan Basin, however, subsidence rates during the Coniacian were significantly less, and a significant base-level fall was recorded by a change in stratal geometries. Our comments regarding subsidence rates are based on thickness comparisons of Coniacian and Santonian strata of similar depositional environments. In the Wasatch Plateau there are approximately 850 m of strata compared with only 250 - 300 m in the Kaiparowits Plateau, Black Mesa, and the San Juan Basin. Examination of the Henry Mountain Basin (Fig. 1), which was on depositional strike between the Wasatch Plateau and the San Juan Basin, suggests intermediate subsidence rates (425 m). Here, Peterson and Ryder (1975) reported an unconformity spanning much of the Coniacian; supporting data have also been acquired by Ryer (personal communication 1990). While some debate may exist concerning the correlation of pertinent biostratigraphic data (Kauffman et al, 1976), it is possible that the early Coniacian sequence boundary recorded in the San Juan Basin is also present in the Henry Mountains, but not present in the Wasatch Plateau due to higher subsidence rates. Throughout this time, both the Kaiparowits Plateau and Black Mesa were areas of sediment bypass. An alternative explanation for these data is that an early Coniacian unconformity is present in the Wasatch Plateau within the lower portions of the Mancos Shale but that it has not yet been detected.

Early Coniacian to late Coniacian/early Santonian - sequence 4

In the Kaiparowits Plateau the Calico bed grades vertically from coarse-grained, low sinuosity river deposits to tidally influenced river deposits. Along the northeastern margin of the plateau, these strata are capped with a transgressive lag and a deepening succession that culminates in a condensed section deposit interpreted to contain a maximum flooding surface. Biostratigraphic data suggests coastal transgression occurred during the early Coniacian with a maximum flooding surface developed during the middle Coniacian. A similar succession of strata was also described in Black Mesa (Franczyk, 1988). In the San Juan Basin, fluvial aggradation of the Torrivio Member of the Gallup Sandstone, retrogradational nearshore sandstones of the Tocito Sandstone, and the Mulatto Tongue of the Mancos Shale could be interpreted as an early to middle Coniacian transgressive systems tract. Coeval strata in the Wasatch Plateau are found in marine shales of the Blue Gate.

In Black Mesa, transgressive deposits of the Wepo Formation and Wind Rock Tongue of the Mancos Shale are overlain by progradational shoreface deposits of the Rough Rock Sandstone. Franczyk (1988) described extensive channel deposits within the upper part of the Rough Rock Sandstone. We suggest that these channel deposits may reflect the development of a sequence boundary similar to that described in the A-sandstone in the Kaiparowits Plateau.

In the San Juan Basin, coeval strata consist of progradational nearshore deposits of the Dalton Sanstone Member of the Crevasse Canyon Formation. Molenaar (1983a) suggests a basinward shift in nearshore stacking patterns which we suggest may reflect development of a sequence boundary similar to the A-sandstone.

In the Wasatch Plateau, temporally equivalent strata consist of the Blue Gate Shale with no available data to suggest a sequence boundary. Similar to the arguments presented for sequence 3, we suggest that the A sequence boundary may be represented by a correlative conformity in the Wasatch Plateau reflecting the higher subsidence rates during the Coniacian and Santonian.

Early to late Santonian - sequence 5

Shoreline aggradation in the Kaiparowits Plateau reflected by the John Henry Member is coeval with the Hosta Tongue of the Crevasse Canyon Formation and Satan Tongue of the Mancos Shale and the lower Point Lookout Sandstone in the San Juan Basin. In Black Mesa, coeval strata consist of the Wepo Formation and Yale Point Sandstone. Consideration of parasequence stacking patterns in the Kaiparowits Plateau as well as adjacent areas suggests that these strata may comprise transgressive and highstand systems tracts of Santonian age. Coeval deposits in the Wasatch Plateau are represented by the Blue Gate Shale and, towards the late Santonian, the Emery Sandstone.

Highstand deposits in the Kaiparowits Plateau are overlain by a regionally extensive sequence boundary (Drip Tank sequence boundary). In the San Juan Basin, Molenaar (1983a) has illustrated a pronounced change in parasequence stacking patterns within the Point Lookout Sandstone which may reflect a similar sequence boundary. In the Wasatch Plateau, parasequence stacking patterns presented by Chan (1990), suggest a sequence boundary within the progradational Emery Sandstone. Age dates are sparse in these strata, however, we suggest that the Drip Tank sequence boundary in the Kaiparowits Plateau may also be represented in the Emery Sandstone.

DISCUSSION

Base level and the Haq et al. curve

Based on our work we have constructed a 'base-level curve' for the Kaiparowits Plateau and southern Colorado Plateau (Fig. 19). Within the biostratigraphic framework previously discussed, and in an attempt to reconcile both biostratigraphic data as well as changes in facies architecture, age dates for sequence boundaries were determined by correlating sequence boundaries to their correlative conformities. The age dates were initially expressed in terms of biostratigraphic zones based primarily on ammonite data (Collom, 1991). Absolute age dates for stage boundaries were taken from Haq et al. (1988) and were used to subdivide stages and assign approximate age ranges to individual biozones. In this manner, an absolute age date could be assigned to each sequence boundary; an estimate of the error in each date is also shown in Fig. 19. By plotting the absolute age dates of sequence boundaries against the thickness of preserved strata (no correction for compaction), a general base-level curve could be constructed. It must be emphasized that the data consists of preserved sediment accumulation; there are few data, if any, to constrain the amount of sediment removed by erosion during the formation of these sequence boundaries. As previously discussed, the Calico sequence boundary in the Kaiparowits Plateau is thought to reflect a period of prolonged sediment bypass during which time there were two base-level cycles as shown by sequence boundaries associated with Gallup Sandstone/Ferron Sandstone and the Torrivio Sandstone (Fig. 18). When based on detailed facies analysis, curves such as these can be used to suggest possible chronostratigraphic correlation between areas of differing tectonic history and facies type.

Construction of base-level curves invites comparison with the eustatic curves proposed by scientists at EXXON Production Research Co. (Haq et al., 1988). Assuming

Figure 19. Base level curve for the Kaiparowits Plateau. The age of sequence boundaries were determined by tracing the sequence boundaries to their correlative conformities. Absolute age dates assigned to stage boundaries are from Haq et al. (1988). These age estimates were also used to assign absolute age dates to the sequence boundaries. An estimate of the error associated with the dating of each sequence boundary is shown.

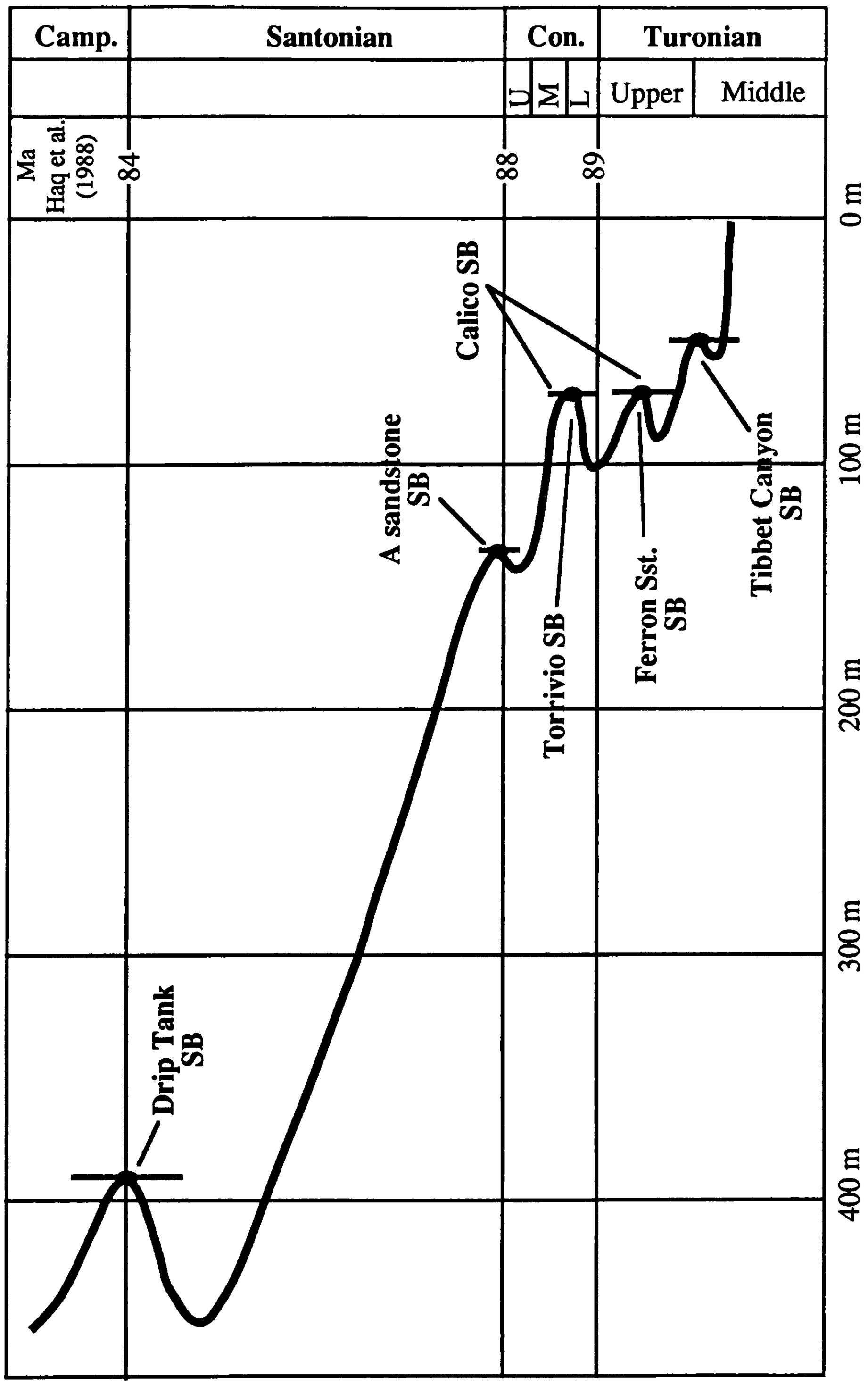

Camp.
Santonian
Con.
Turonian
U
M
L
Upper
Middle
Ma
Haq et al.
(1988)
84
88
89
0 m
100 m
200 m
300 m
400 m
Drip Tank
SB
A sandstone
SB
Torrivio SB
Calico SB
Ferron Sst.
SB
Tibbet Canyon
SB

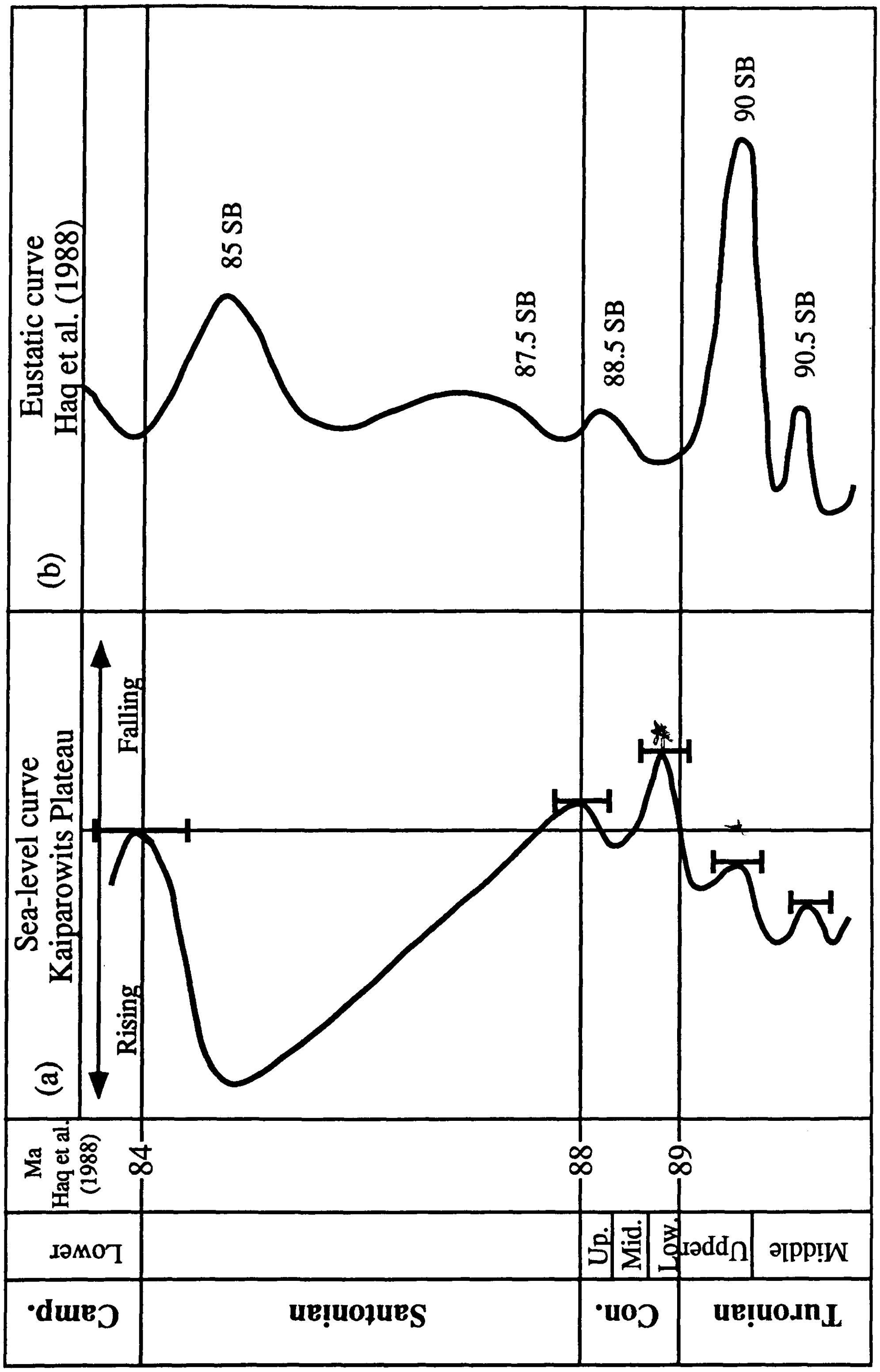
Figure 19

a linear subsidence rate over the 6 ma period of interest, a "eustatic curve" was constructed for the Kaiparowits Plateau (Fig. 20a) and compared to the Haq et al. (1988) curve (Fig. 20b). Attempts to correlate our observations with Haq et al. (1988) must recognize the following complications: differences in biostratigraphic resolution and zonation between the Western Interior of North America and similar schemes from Tethyan regions and northern Europe; the differences in absolute age dates for stage boundaries reported by Haq et al (1988) versus those in use in the Western Interior; their use of outcrop data predominantly from central and northern Europe as well as the Western Interior foreland basin; their concentration on accurate portrayal of third-order cycles (1-10 Ma) as opposed to higher frequency, fourth-order cycles; and although not explicitly stated, their conversion from a coastal onlap curve to a eustatic curve must conceptually account for tectonic subsidence. This last item, the accounting for tectonic subsidence, is not clear in Haq et al. (1988) yet likely has the most profound effect on the shape and magnitude of the resultant eustatic curve. Despite these caveats, the Turonian through Santonian portion of the Haq et al.(1988) curve (Fig. 20b) compares quite favorably throughout much of the interval of interest. The Tibbet Canyon, Calico, A, and Drip Tank sequence boundaries, are most likely the 90.5, 90, 88.5, and 85 Ma sequence boundaries reported by Haq et al. (1988).

The most apparent differences concern the upper Turonian and lowermost Coniacian where we suggest two significant eustatic falls (approximately 88.8 and 89.5 Ma; ages taken from Haq et al., 1988) as opposed to only one major fall in the late Turonian (90 Ma) on the Haq et al. (1988) curve. It is noteworthy, that within the Western Interior, Haq et al (1988) considered outcrops either in offshore and deep marine settings (Pueblo and Wolcott, Colorado), or in areas of relatively high subsidence, such as central Utah. As a

Figure 20a. A sea-level curve for the Turonian through Campanian from the Kaiparowits Plateau and southern Colorado Plateau region is illustrated. This curve is based on a base-level curve shown in Figure 19 and the assumption of linear subsidence within the interval of interest.

Figure 20b. The Turonian through Campanian portion of the Haq et al. (1988) short-term eustatic curve is reproduced here. While no technique is discussed, this curve implicitly accounts for tectonic subsidence. Note the overall high degree of correlation between the inflection points of this curve and the sea-level curve derived for the Kaiparowits Plateau. These data suggest that eustatic changes may control many of the details of stratal architecture, even within the foreland basin.



(a)
Sea-level curve
Kaiparowits Plateau
Rising
Falling
(b)
Eustatic curve
Haq et al. (1988)
85 SB
87.5 SB
88.5 SB
90 SB
90.5 SB
Ma
Haq et al.
(1988)
84
88
89
Camp.
Lower
Santonian
Con.
Up.
Mid.
Low.
Turonian
Upper
Middle

Figure 20

result, the EXXON cycle chart may not reflect the intricacies that emerge through study of stratal successions in areas of low subsidence such as the Kaiparowits Plateau or the San Juan Basin. In our discussion of regional chronostratigraphic correlations, we suggested how rapid subsidence during the Coniacian may have obscured the development of a sequence boundary in the Wasatch Plateau. In a study of Turonian strata in the Denver Basin, Weimer and Sonnenberg (1983) suggested a sea-level fall during both the middle Turonian (approximately 90.5 Ma on the Haq et al., 1988 curve) as well as a major sea-level fall at the Coniacian-Turonian boundary (approximately 89 Ma on the Haq et al., 1988 curve).

Within the Santonian, the EXXON cycle chart suggests a minor sea-level change in the lower Santonian (87.5 Ma) which we do not report in our study. It is possible that this cycle is represented in the Kaiparowits Plateau within the John Henry Member. As previously outlined, we have noted minor facies tract shifts within nearshore deposits, but have been unable thus far to extend these observations into alluvial strata in the western and southwestern part of the plateau.

Based on our correlations throughout much of the Colorado Plateau and the correlation between the Haq et al. (1988) eustatic curve and our outcrop observations, we suggest that eustatic changes within the Western Interior foreland basin are a significant control on stratal geometry and facies architecture. We do not discount the role of tectonic subsidence in the creation of depositional sequences in foreland basins, rather we suggest that tectonic subsidence exerts a greater control on the geometry of second-order sequences in a manner similar to Devlin et al. (1990) and Devlin and Shaw (1990).

Facies architecture, sequence stratigraphy, and reservoir prediction

Introduction

Our description and interpretation of strata in the Kaiparowits Plateau provides an example of how alluvial and nearshore siliciclastic facies are 'arranged', or partitioned within the framework of depositional sequences. Because we have been able to recognize these systematic variations in facies architecture, we suggest that the autocyclic controls that govern many of the details of facies architecture are themselves constrained by changes in accommodation space and base level. Similar conclusions may be drawn from studies of Quaternary nearshore deposits by Dominguez et al. (1987). We, therefore, believe that depositional facies are modified and partitioned in a predictable manner within an unconformity-bounded depositional sequence. Because these changes in architecture can be expressed in terms of base-level change and accommodation space, the observations and relationships derived from the Kaiparowits Plateau may be used to develop stratigraphic models applicable to a variety of depositional settings. These models are particularly useful for improving our understanding of petroleum reservoir distribution. Although this results in a better understanding of exploration play type (e.g. Van Wagoner et al., 1990), such models also allow the geometry, interconnectedness, and heterogeneities of petroleum reservoirs to be predicted through an understanding of systems tracts and parasequence stacking patterns at a level of detail useful to reservoir development. This relationship between parasequence stacking patterns and reservoir description is presented in the form of a matrix diagram (Fig. 21).

Figure 21. Matrix diagram illustrating changes in petroleum reservoir attributes in terms of shoreface parasequence stacking patterns. Observations in the Kaiparowits Plateau suggest that sedimentary architecture is strongly partitioned as a function of position within an unconformity-bounded depositional sequence.

Parasequence Geometry	Facies Characteristics: Shoreface	Facies Characteristics: Fluvial	Facies Characteristics: Coal-Bearing
Progradational	Foreshore preservation rare Reworked by fluvial & tidal processes - associated w/ SB & valley fill	Sediment bypass, some laterally amalgamated meanderbelts assoc. w/ SB & valley fill High net sst/gross sst	Fluctuating clastic input, slow rise (fall) in water level - thin peats Nonmarine roof rock
Aggradational	Foreshore preservation common Isolated tidal channels	Isolated meanderbelts - splay sst. common High net sst/gross sst w/in meanderbelt, low overall net/gross.	Long-lived mires, steady increase in water level - thick peats Nonmarine and marine roof rock
Retro-gradational	Thin transgressive deposits Not exposed in this study area	Thick, laterally amal-gamated meanderbelts. Coarser-grain sst in lower part. Tidally influenced - upper part. High net sst/gross sst	Reduced clastic input, rapid rise in water level - medium peats Marine roof rock

Figure 21

Model

Shoreface deposits associated with highly progradational shoreface parasequences, such as the Tibbet Canyon Member or the lower part of the A-sandstone (late highstand systems tract), are interpreted to reflect very slow rates of base-level rise or perhaps even very slow base-level fall. These strata are characterized by sand-dominated, strandplain or beach-ridge coastlines in which lagoons are not extensively developed, similar to the Nayarit strandplain in Mexico (Curray et al., 1969) or the east-southeast coast of Brazil (Dominguez et al., 1987). Because many present-day coastlines are undergoing widespread erosion, due in part to a slow eustatic rise in sea level, strandplain coasts are not widespread (Kraft and Chrzastowski, 1985; Niedoroda et al., 1985; Dominguez et al., 1987). The slow rates of base-level change generally results in subaerial erosion of the uppermost part of these highstand deposits resulting in formation of a sequence boundary unconformity. As a result, highly progradational shoreface parasequences rarely contain well-preserved foreshore strata in their uppermost parasequence. These shoreface strata that were deposited in a late-highstand systems tract are often erosionally overlain by strata reflecting a fluvial or tidally-influenced component, similar to the Tibbet Canyon Member and the A-sandstone in the Kaiparowits Plateau. Reservoirs associated with these strandplains are generally found in upper-shoreface strata and are thought to form well-interconnected units in which reservoir properties may be reasonably extrapolated without exhaustive data-sets. Abrupt changes in shoreface reservoir quality along either depositional strike or dip, however, may reflect incision by the overlying sequence boundary.

Nearshore strata associated with aggradational parasequences, such as those found in the John Henry Member (highstand systems tract), are dominated by strandplain coastlines and reflect somewhat higher rates of base-level rise. The aggradational geometry of these strata indicates a balance between base-level rise, and sediment supply. Because these strata are not generally overlain by sequence boundary unconformities, the coarser-grained fraction that comprises shoreface and foreshore strata are often preserved. Reservoirs, therefore, are expected to form well-interconnected units that are extensive along both depositional strike and dip. The more rapid rates of base-level rise associated with these highstand deposits also result in somewhat isolated tidal channels that are not thought to migrate extensively along the coastline. These channel deposits punctuate the shoreface and foreshore deposits and may act as high-permeabilty 'thief zones' within the reservoir; these heterogeneities are oriented normal to the paleocoastline.

Because of the Holocene sea-level rise, many modern coastlines are undergoing erosion and shoreface retreat. The dominant theme, therefore, is development of transgressive-shoreline deposits (Kraft and Chrzastowski, 1985). Coastlines undergoing transgression are dominated by barrier islands and extensive lagoonal deposits in which shoreface reworking by tidal channel and tidal inlet migration are significant (Kraft and Chrzastowski, 1985; Niedoroda et al., 1985; Dominguez et al., 1987). During periods of long-term base-level rise, retrogradational shoreface deposits characteristic of transgressive systems tracts are likely. Petroleum reservoirs associated with transgressive coastlines are likely to occur within shoreface sandstones, however, the continuity of the reservoirs is likely to be punctuated by tidal channels and inlets that have migrated a considerable distance along the paleoshoreline. As a result, high permeability 'thief zones' oriented normal to the paleoshoreline trend are likely components of the transgressive systems tract. Because of the low relief within the Western Interior seaway retrogradational shoreface deposits are not well developed in the Kaiparowits Plateau. Examination of nearshore deposits associated with transgressive systems tracts from elsewhere, however, suggests many similarities with Quaternary deposits. Reservoirs in the Upper Cretaceous Almond Sandstone on the Rock Springs Uplift in Wyoming consist of barrier island sandstones that have been eroded to varying degrees by shore-normal tidal channels and inlets (e.g. McCubbin and Brady, 1969; McCubbin, 1982; Weimer et al., 1982).

Consideration of fluvial reservoirs in terms of parasequence stacking patterns is an active area of research filled with controversy (e.g. Walker, 1990). Fluvial reservoirs account for more than 324 billion barrels of oil equivalent proven reserves (based on Carmalt and St. John, 1986) and are amongst the more difficult reservoirs to characterize (Tyler, 1988; Weber and van Geuns, 1990). Studies of many petroleum reservoirs hosted in fluvial deposits, however, suggests they are often composed of alternating amalgamated, interconnected, persistent channel sandstones with a relatively high net sandstone/gross sandstone value and more isolated, poorly connected, laterally discontinuous sandstones with a relatively low net /gross value (e.g.,Johnson and Krol, 1984; Ravenne et al., 1987; Atkinson et al., 1988; 1990; Ravenne and Beucher, 1988; Brown and Richards, 1989; Livera, 1989; McPherson and Miller, 1990; Miller et al., 1990). Based on a detailed study of the fluvial deposits in the Kaiparowits Plateau, we suggest (Shanley and McCabe, 1990b-in review) the following physical and temporal relationships are likely. Amalgamated meanderbelts are generally associated with progradational shoreface parasequences, are often contained within incised valleys, and immediately overlie sequence boundary unconformities. These deposits reflect low rates of base-level rise and correspond to the intial portions of lowstand systems tracts or transgressive systems tracts. In deeply incised valleys, fluvial deposits are dominated by riverine processes at the base which grade vertically into more tidally-influenced processes at the top of the valley fill reflecting base-level rise and coastal transgression. Shallow valleys are often areas of prolonged sediment bypass and frequently aggrade with tidally-influenced strata throughout. Amalgamated meanderbelts associated with the initial phase of the transgressive systems tract generally have a high net /gross reservoir sandstone value.

Alluvial strata associated with aggradational shoreface parasequences are dominated by isolated meanderbelts, common crevasse splay deposits, and pervasive fine-grained overbank deposits. These strata reflect somewhat higher rates of base-level rise (highstand and transgressive systems tract) resulting in considerable floodplain aggradation and preservation; meanderbelts tend to become encased within a 'matrix' of fine-grained overbank deposits. Unlike the amalgamated deposits, channel sandstones within the highstand are dominated by fluvial processes throughout. Within a discrete meanderbelt sandstone net/gross sandstone values may be quite high, however, these discrete meanderbelts are difficult to predict, interconnectedness between meanderbelts is generally poor, and the net/gross value within the systems tract is usually quite low.

Alluvial strata associated with retrogradational shoreface parasequences (transgressive systems tract) reflect increasing rates of base-level rise. Coarse-grained, amalgamated sandstones generally give way to more fine-grained and isolated meanderbelts. These channel systems are dominated by fluvial processes at the base that grade into tidally-influenced deposits. Our work in the Kaiparowits Plateau (Shanley et al., 1990) suggests that tidal influence can extend many tens of kilometers to hundreds of kilometers inland of coeval shoreline deposits. Tidally-influenced fluvial sandstones deposited within open estuarine conditions tend to be sandstone dominated and may form reservoirs whose characteristics are similar to amalgamated fluvial deposits. These tidally-influenced fluvial deposits, however, become increasingly heterolithic in a landward direction significantly affecting reservoir suitability.

The presence of coal-bearing strata within the Kaiparowits Plateau has allowed us to extend our sequence stratigraphic model to these strata. While many coal studies have focused on the detailed facies relationships between coal-forming environments and adjacent siliciclastic realms, relatively few studies have attempted to characterize coal-deposits in terms of their sequence stratigraphic characteristics. We suggest that coals associated with progradational shoreface parasequences, such as those associated with the Tibbet Canyon sandstone, tend to be comparitively thin. While this almost certainly reflects the limited accommodation space available for peat-forming mires, it may also reflect fluctuating clastic influx combined with a slowly rising ground-water table (McCabe, 1984). These two factors, governed by changes in base level, result in peat deposits with a high-ash content that are subjected to frequent desiccation. These coals are generally overlain by nonmarine roof rock. Coal deposits associated with aggradational shoreface parasequences, such as the thick, extensive coal seams in the John Henry (highstand systems tract), are composed of thick, laterally extensive seams. Increased accommodation space combined with a steady increase in water level combine to form ideal peat-forming conditions. Furthermore, in climatic settings that permit the development of raised mires, these thick deposits can form in areas immediately adjacent to areas of active siliciclastic deposition. Coal seams within these highstand systems tracts are overlain by both marine and nonmarine roof rock. The rapid rise in water level associated with transgressive systems tracts often results in rather thick peat deposits. These coal deposits, however, reflect a delicate balance between rate of base-level rise and sediment supply. Under conditions of truly rapid base-level rise, siliciclastic influx is reduced, creating ideal conditions for peat accumulation, however this same base-level rise also causes a rise in ground water resulting in a drowning of mires and termination of peat accumulation. Many coal seams from transgressive systems tracts are characterized by marine roof rock conditions.

Continental deposits are often the most difficult strata to describe owing to their generally poor exposure. Nevertheless, we find better-developed paleosols to correlate with progradational shoreface parasequences. Continental deposits associated with aggradational shoreface parasequences are quite variable with intervals of both well developed and more-poorly developed paleosols. Thin lacustrine deposits are almost exclusively found associated with highstand systems tract deposits. Continental deposits which we correlate to transgressive systems tract deposits generally have poorly developed paleosols which we interpret to reflect the rising ground water table that accompanies a rapid rise in base level.

Conclusion

The application of sequence stratigraphic concepts is not simply the application of new terminology to older ideas, but rather provides a vantage from which sedimentary rocks may be analyzed that emphasizes physical correlation and recognition of stratal surfaces and their chronostratigraphic significance (e.g., Vail et al., 1977; Van Wagoner et al., 1990; Warme and May, 1990). Integration of detailed facies analysis based on superb exposures, such as those in the Kaiparowits Plateau, coupled with sequence stratigraphic, and base-level concepts result in new, and often innovative, stratigraphic and sedimentological interpretations. This approach has resulted in the following conclusions.

1. In the Kaiparowits Plateau, sedimentary facies representing a wide range of nearshore, coal-bearing, and alluvial depositional environments are found to vary in architecture in a systematic manner dependant on position within a depositional sequence. This suggests sedimentary facies are carefully partitioned within a sequence and that autocyclic controls, are themselves constrained within accommodation space controlled by allocyclic processes. This suggests a continuum of stratal relationships, similar to those described for depositional sequences, exists at a variety of scales from composite sequences (Mitchum and Van Wagoner, 1991-in press) all the way down to laminasets (Campbell, 1967).
2. Consideration of changes in sedimentary architecture in terms of base-level change allows a predictive model to be constructed that attempts to predict the occurrence and geometry of sedimentary facies in nearshore, coal-bearing and alluvial strata in terms of nearshore parasequence stacking patterns. This model suggests that knowledge of the geometry of a particular depositional facies may be used to predict the geometry of adjacent depositional systems. This has applicability to siliciclastic reservoirs at both the exploration and development scale.
3. Recognition of the relationship between facies architecture and sequence stratigraphy has resulted in innovative chronostratigraphic correlations between the Kaiparowits Plateau and adjacent outcrop belts. These correlations suggest that sequence boundary unconformities and maximum flooding surfaces observed in the Kaiparowits Plateau can be recognized in other exposures of coeval strata.
4. Comparison of a base-level curve derived from the Kaiparowits Plateau with the Haq et al (1988) curve reveals many similarities. This similarity, coupled with our correlations to adjacent regions leads us to conclude that eustatic fluctuation in the

foreland basin are a significant process in the development of facies architecture, even within an actively subsiding foreland basin.

Chapter 5

ALLUVIAL ARCHITECTURE IN A SEQUENCE STRATIGRAPHIC FRAMEWORK - A CASE HISTORY FROM THE UPPER CRETACEOUS OF SOUTHERN UTAH, U.S.A.

ABSTRACT

Fluvial architecture has been studied within the context of unconformity-bounded depositional sequences in Turonian through Campanian strata within the Kaiparowits Plateau in southern Utah. Because the rate of base level rise determines the rate at which accommodation space is created, changes in alluvial architecture may be interpreted in terms of changes in the rate of base level rise. As a result, criteria are developed that allow time-significant surfaces such as sequence boundary unconformities and the landward equivalent of maximum-flooding surfaces to be recognized within terrestrial strata. This advance results in a better understanding of alluvial architecture leading to improved models of alluvial sandstone geometry, sandstone interconnectedness, and sand/shale ratios.

Upper Turonian to Coniacian coarse-grained and pebbly sandstones, interpreted as braided stream deposits, reflect deposition following a significant seaward shift in facies tracts. These strata are approximately 10 m thick, laterally amalgamated, and interpreted to reflect low rates of base-level rise. These coarse-grained fluvial deposits grade vertically into tidally-influenced, finer-grained fluvial strata that are encased within an increasing proportion of floodplain mudstones. This change in depositional style is interpreted to reflect an increase in the rate of base-level rise such that laterally persistent, well-connected meanderbelt sandstones do not develop. The influence of tidal processes within fluvial

strata deposited many tens of kilometers from a coeval shoreline further supports a rapid base-level rise during the Coniacian. The tidally-influenced fluvial sandstones are erosionally overlain by 25 m of upper Coniacian-lower Santonian fluvial strata that are laterally amalgamated, finer grained, and coeval with progradational and aggradational shoreface parasequences. These strata are interpreted to represent slow rates of fluvial aggradation following a base level fall and development of a sequence-boundary unconformity. A subsequent increase in the rate of base-level rise during the late Coniacian and Santonian resulted in approximately 150 m of isolated meanderbelt sandstones and thick, floodplain mudstones. These strata correlate to thick coal-bearing units that in turn grade abruptly into approximately 200 m of vertically-stacked shoreface deposits. Within these isolated meanderbelt sandstones and overbank deposits, sand-shale ratios decrease markedly and meanderbelt sandstones are poorly connected. Following a significant seaward shift in facies tracts during the early Campanian, coarse-grained and pebbly sandstones, interpreted as braided river deposits, erosionally overlie shoreface, coal-bearing, and fine-grained floodplain strata.

The ability to relate changes in depositional architecture to changes in base level and position within a depositional sequence has important implications. At the scale of depositional sequences these concepts may greatly aid in chronostratigraphic correlation between marine and nonmarine strata. At a smaller scale, such as that employed in reservoir studies, parameters such as sand-shale ratios and sandstone connectedness may be predicted by understanding the position of fluvial strata within a depositional sequence.

INTRODUCTION

On a world-wide basis, alluvial reservoirs account for more than 324 billion barrels of oil-equivalent proven reserves (Larry Kellison and Frank Ethridge, personal communication 1990, based on Carmalt and St. John, 1986), are the host rock for major mineral deposits associated with placers and low-temperature secondary deposits (e.g., Miall, 1981; Turner-Peterson, 1986), and are important aquifers for both groundwater and contaminant waste disposal. The ability to predict alluvial architecture on the basis of scattered data sets, therefore, has important economic implications. Furthermore, reconstructions of basin evolution requiring a detailed chronostratigraphic framework between alluvial and shallow-marine strata may be significantly improved by understanding the relationship between alluvial architecture and sequence stratigraphy.

Exposures of Turonian through Campanian strata in the Kaiparowits Plateau of south-central Utah (Figs. 1 and 2) afford an opportunity to study coeval shallow-marine, alluvial, and coal-bearing strata across almost 80 km of depositional-dip oriented exposure. Changes in alluvial architecture can be directly compared with parasequence stacking patterns of coeval shoreface strata. As a result, the more sophisticated sequence stratigraphic models that have evolved in shoreface deposits (e.g., Van Wagoner et al., 1990) can be compared with observations regarding alluvial architecture. This comparison allows sequence-stratigraphic models to be modified and extended into alluvial plain strata.

Recently developed sequence stratigraphic models (e.g., Vail et al., 1977; Haq et al., 1988; Jervey, 1988; Posamentier 1988; Posamentier and Vail, 1988; Posamentier et al., 1988; Ross, 1990; Van Wagoner et al., 1990), as well as quantitative alluvial models (e.g., Allen, 1978, 1979; Bridge and Leeder, 1979; Alexander and Leeder, 1987; Lawrence et al., 1990; Ross, 1990) suggest that fluvial architecture may be interpreted in terms of base-

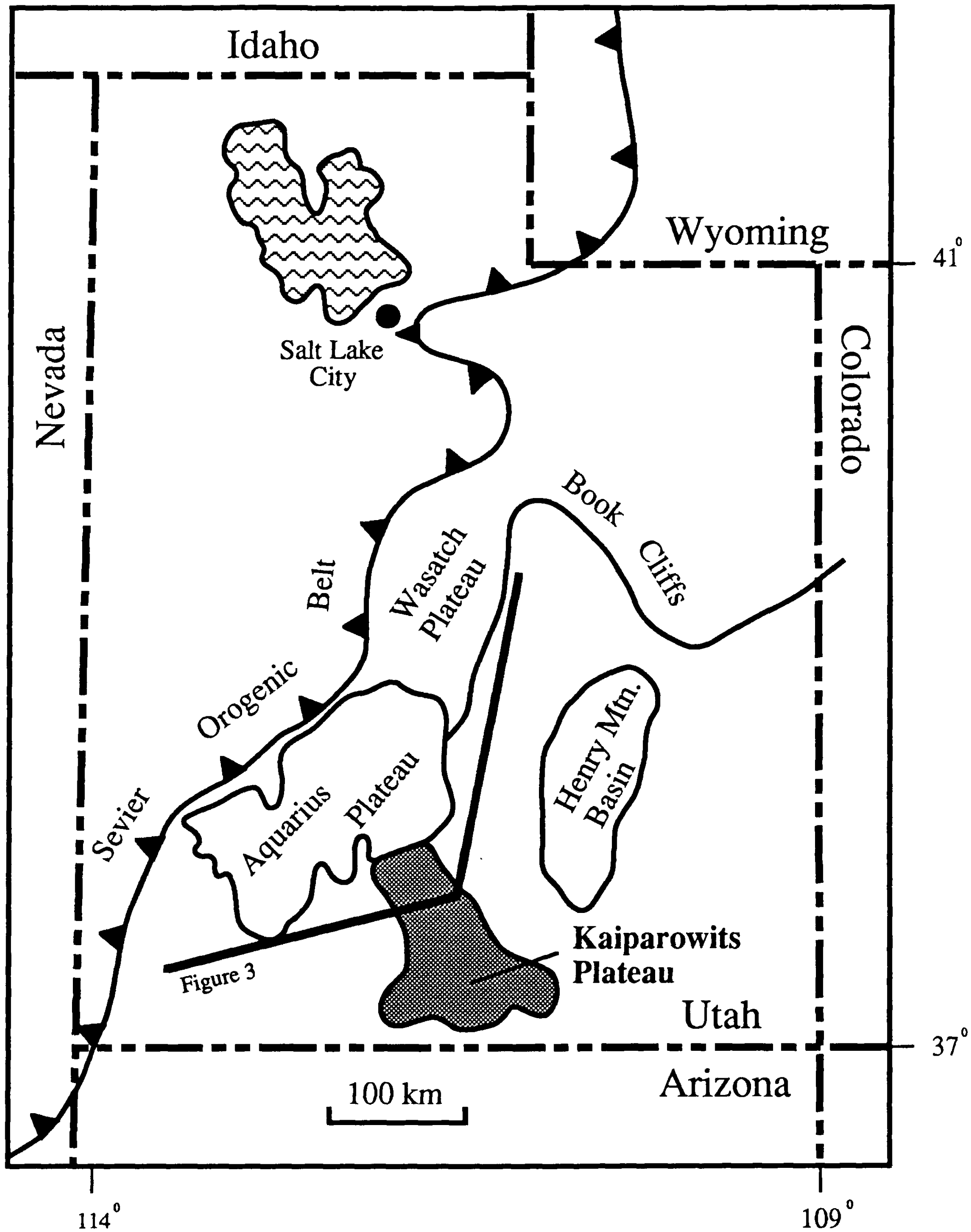


Figure 1. Regional map illustrating the location of the Kaiparowits Plateau within the state of Utah. Also shown are the trend of the leading edge of the Sevier orogenic belt, and locations of the Wasatch Plateau, Henry Mountain Basin, and the Book Cliffs. The line of section shown is illustrated in Fig. 3.

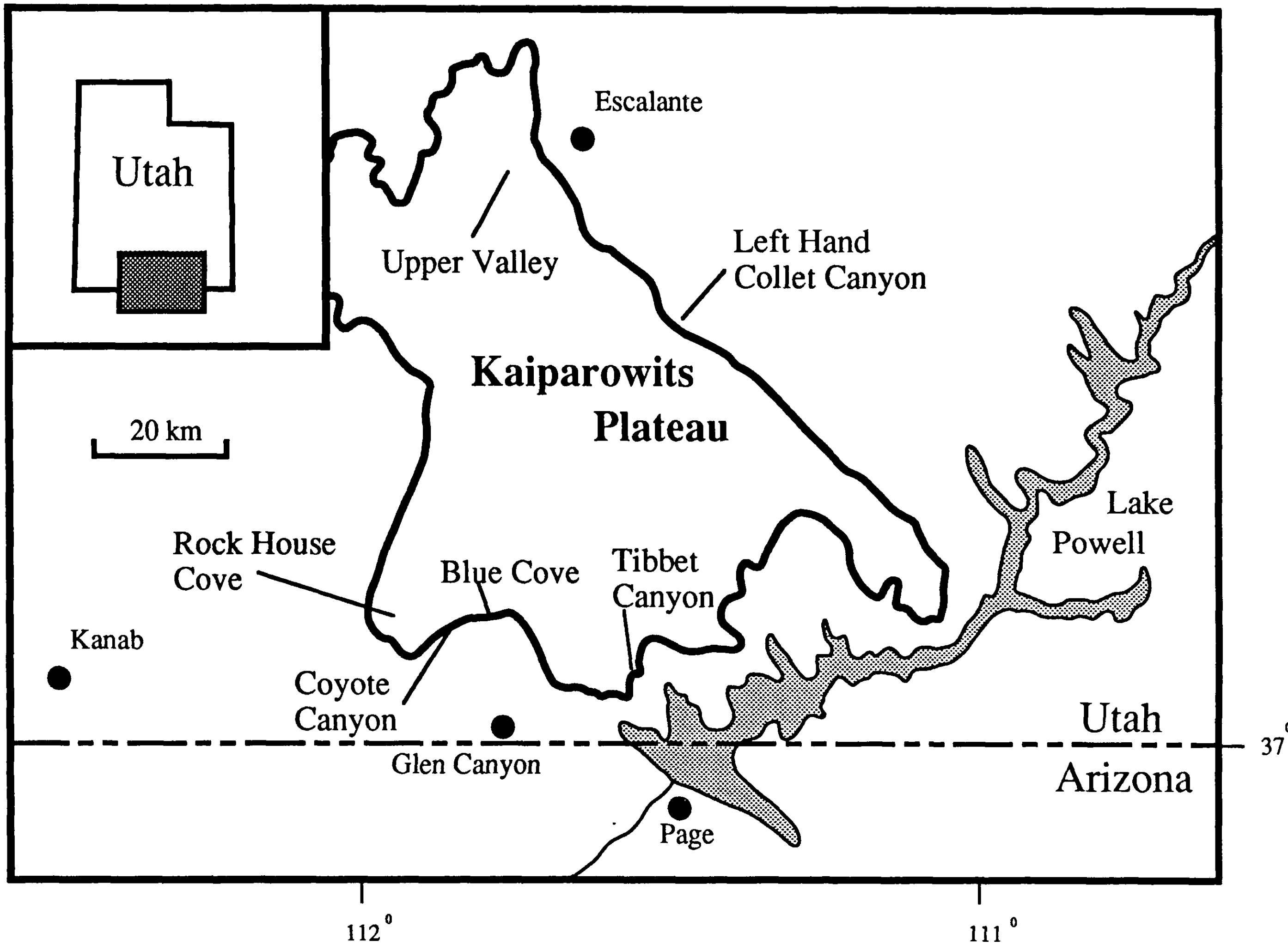


Figure 2. Map showing the locations of Rock House Cove, Blue Cove, Coyote Canyon, Tibbet Canyon, and Left Hand Collet Canyon. In general, the northeastern part of the plateau consists of shoreface deposits which grade into coal-bearing strata in the central plateau. These in turn grade into alluvial strata towards the west and southwest.

level change and its effect on accommodation space. Despite the proliferation of both quantitative and qualitative models, there are few outcrop-based studies that describe alluvial architecture in terms of sequence-stratigraphic evolution. Although studies of outcrops and subsurface data sets over the last fifteen years have encouraged the use of sequence-stratigraphic concepts in shallow-marine strata (e.g., Van Wagoner et al. 1990), similar studies of alluvial strata are still in their infancy. The recognition of sequence boundaries, condensed sections and depositional systems tracts in shallow marine strata has produced a methodology suggesting greatly improved stratal predictibility and temporal resolution. The presence of abrupt lateral facies changes, typically poor biostratigraphic resolution and limited absolute age-dating, numerous internal erosion surfaces and limited outcrops, however, are some of the many difficulties that have frustrated attempts to extend these models to alluvial strata. This frustration is summarized by Walker (1990, p. 781) who suggests that "...sequence stratigraphy, with its emphasis on bounding unconformities and marine flooding surfaces, cannot easily be applied to non-marine rocks (if at all)."

The emphasis of this paper, therefore, is to describe the architecture of alluvial strata within the context of unconformity-bounded depositional sequences as illustrated by the exposures in the Kaiparowits Plateau. Mitchum et al. (1977, p. 53) defined depositional sequences as "...a stratigraphic unit composed of relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities." As a result, we find that sediment architecture of both shoreface and alluvial strata varies in a systematic, and therefore, predictible manner depending on position within a depositional sequence (this paper focuses on the alluvial strata). Furthermore, this approach allows chronostratigraphic correlations to be extended inland for at least 60 km greatly improving temporal resolution for purposes of basin analysis and regional correlation. The recognition of an evolutionary trend in alluvial architecture within depositional sequences provides the necessary framework for further detailed, quantitative analyses of fluvial architecture. Our work strongly suggests that detailed studies of fluvial architecture within discrete channel belts, without an understanding of the sequence stratigraphic architecture, are of limited utility beyond the immediate study area or in areas of limited data. This paper suggests that the development of analog models is most successful when placed in a sequence-stratigraphic framework.

Physical setting

During the Cretaceous an extensive Cordilleran orogenic fold and thrust belt could be traced from northern Canada and Alaska into Mexico. In the central and southern Rocky Mountains of the United States this feature is known as the Sevier orogenic belt (Armstrong, 1968) (Fig. 1). A foreland basin developed parallel to this orogenic belt in response to flexural loading of the lithosphere by successive thrust plates and synorogenic sediment (e.g.,Armstrong, 1968; Jordan, 1981; Cross, 1986). From the Albian through Maastrichtian the foreland basin was inundated by a vast epicontinental sea. During maximum eustatic highstand the seaway extended from present-day Arctic Canada to the present Gulf of Mexico, a distance of some 5000 km, and from western Utah to Iowa, a distance of some 1500 km (Williams and Stelck, 1975). During the Turonian to Campanian, the region presently known as the Kaiparowits Plateau occupied a position along the western margin of the Cretaceous interior seaway, approximately 120 km to the east of the leading edge of the Sevier orogenic belt (Fig. 1).

Timing of structural deformation within the Sevier orogenic belt continues to be a topic of considerable debate. A substantial body of literature exists that addresses the various techniques used to date the onset of thrusting. Although the use of synorogenic strata as a means of dating thrust-fault movement has been questioned (e.g.,Blair and Bilodeau, 1988; Heller et al., 1988; Jordan et al., 1988), their use constrains the onset of thrusting in central Utah as mid-late Albian with episodic thrusting throughout the Late Cretaceous (e.g.,Wiltschko and Dorr, 1983; Lawton, 1985, Villien and Kligfield, 1986). Similar age-dates have been obtained from geohistory or backstripping analysis (Cross, 1986; Heller et al., 1988).

The Kaiparowits Plateau covers some 3600 km^2 in the southwestern portion of the Colorado Plateau structural and physiographic province (Fig. 2). The present outcrop configuration was largely established by the Miocene (Lucchitta, 1979, 1989) as the Colorado River assumed its present course and began to control headward erosion into the broad plateaus of the Colorado Plateau. The structural configuration of the Kaiparowits Plateau itself is one of gentle, north to northwest trending asymmetrical anticlines and synclines that plunge gently to the northwest. Structural dip within the plateau is generally less than 3°. The plateau is locally cut by several high-angle normal faults, however, displacement is minimal and they do not deter detailed stratigraphic and sedimentological investigations.

Exposures within the study interval belong to the Straight Cliffs Formation which ranges from Middle Turonian to early Campanian in age and from 300-370 m in thickness (Fig. 3). The northeastern escarpment of the plateau, known as the Straight Cliffs, provides approximately 80 km of depositional strike-oriented exposure extending from Lake Powell on the south to the town of Escalante, Utah to the north (Fig. 2). The southern margin trends east-northeast, is dissected by numerous canyons, and provides almost 80 km of exposure oriented slightly oblique to depositional dip (Fig. 2). Previous work (Shanley and McCabe, 1989; 1990, 1990a-in review, 1990b-in review; Shanley et al., 1990-in review), combined with earlier studies by Peterson (1969a, b) and Vaninetti (1978), have delineated broad, coeval lithofacies belts of alluvial plain, mire, coastal plain, shoreface, and open marine strata within the John Henry Member of the Straight Cliffs Formation (Fig. 3). This overall arrangement of lithofacies types provides an unusual opportunity to compare sedimentary architecture across a broad spectrum of coeval depositional environments. The lithofacies arrangement in the John Henry Member combined with adjacent strata in the Straight Cliffs Formation, the limited structural complexity, and lack of vegetation provide an ideal field laboratory for the study of alluvial facies architecture and sequence stratigraphy.

Stratigraphic setting

Because of its remote nature, there have been relatively few geological investigations within the Kaiparowits Plateau. The initial stratigraphic framework for the plateau was established during a series of geologic and geographic expeditions conducted between 1913 and 1923 (Gregory and Moore, 1931). Peterson (1969a, b) investigated the southern Kaiparowits Plateau and identified type sections for the various members of the Straight Cliffs Formation; his nomenclature is used in this paper. Detailed sedimentological investigations within the Kaiparowits Plateau are few. Peterson (1969a, b) and Vaninetti (1978) suggested a facies mosaic of coastal plain, lagoonal, deltaic and barrier island sediments for the Straight Cliffs Formation similar in many respects to the classic interpretations of the Book Cliffs region of central Utah (e.g.,Balsley, 1980).

Age determinations of the marine strata in the Kaiparowits Plateau are reasonably well constrained by biostratigraphic data based on ammonite and inoceramid collections (summarized in Shanley and McCabe, 1990b-in review). Similar assessments of alluvial and coal-bearing strata, however, are poorly constrained. The lack of magnetostratigraphic variation during the Turonian to Campanian, the paucity of regionally extensive ash beds, and the lack of detailed palynological investigations reduce the effectiveness of conventional chronostratigraphy. As a result, we have focused not only on the detailed sedimentology of these strata, but also on basinward shifts in facies tracts and deepening trends that can be traced throughout the plateau and which have regional significance (Shanley and McCabe, 1990b-in review). We interpret five unconformity-bounded depositional sequences and their associated highstand and transgressive systems tracts within the Straight Cliffs Formation. These sequences are recognized throughout the plateau and, when combined with available biostratigraphic data, provide a detailed level of chronostratigraphic resolution. A detailed description of the sequence-stratigraphic evolution of the plateau, including a more direct comparison between marine and alluvial strata, and their correlation to adjacent areas is contained in Shanley and McCabe (1990b-in review) and illustrated in Figure 3.

Field methods

To develop an understanding of sequence stratigraphic relationships, detailed sections were measured from the Tropic Shale to the Drip Tank Member of the Straight Cliffs Formation (Fig. 3). Significant facies-tract offsets associated with sequence boundaries, transgressive surfaces of erosion (ravinement surfaces), condensed sections and their nonmarine counterparts, and shoreface parasequence stacking patterns were interpreted

Figure 3. Sequence stratigraphic cross section of Turonian through lower Campanian strata from the Kaiparowits Plateau (southwest) to the Wasatch Plateau (northeast). The line of section is shown in Figure 1. Sequence boundaries, or their correlative conformities, are shown. These allow the strata to be subdivided into chronostratigraphic units across at least 65 km of depositional dip from alluvial to shoreface deposits. The construction of this diagram was discussed in Chapter 4.

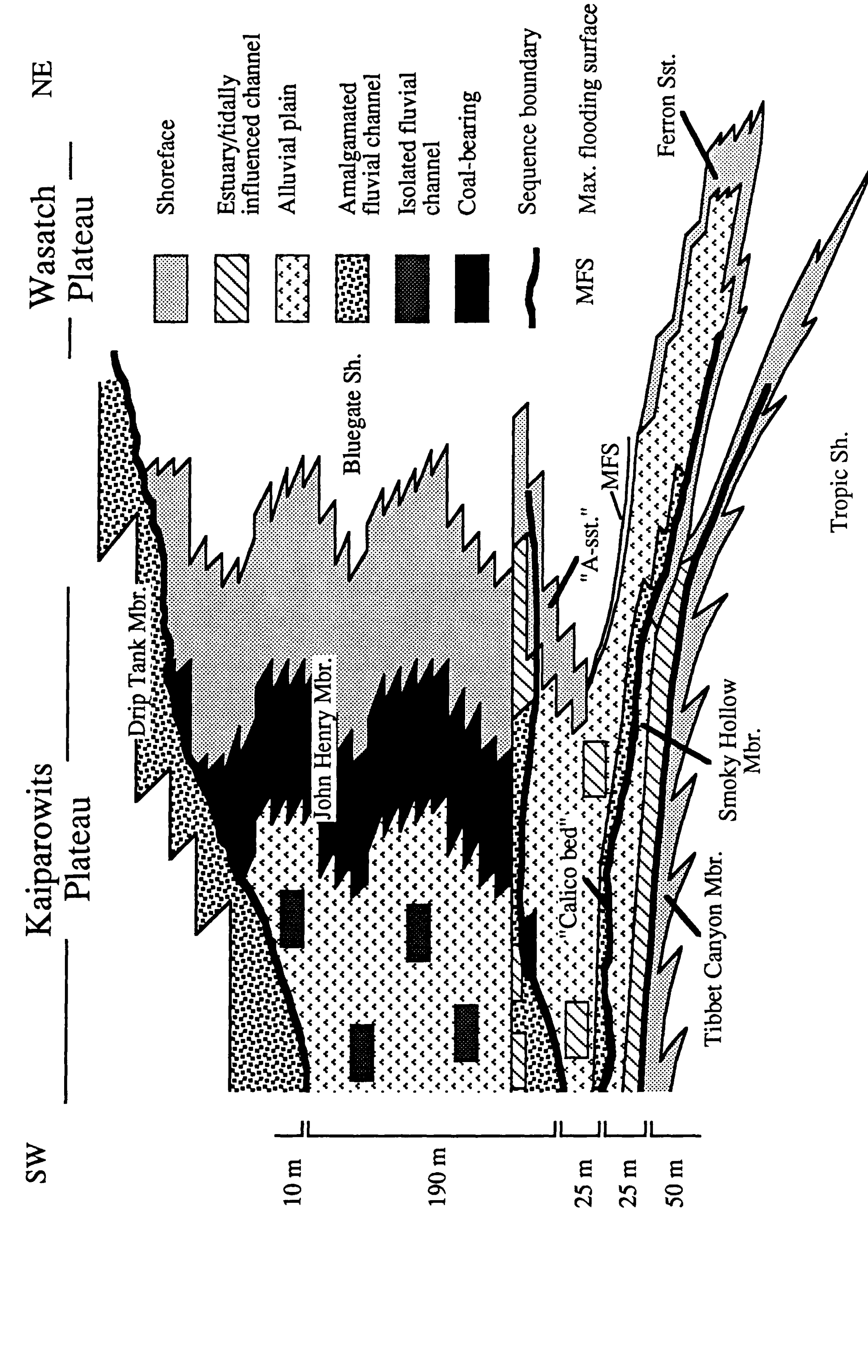

SW
NE
Kaiparowits Plateau
Wasatch Plateau
Shoreface
Estuary/tidally influenced channel
Alluvial plain
Amalgamated fluvial channel
Isolated fluvial channel
Coal-bearing
Sequence boundary
MFS
Max. flooding surface
Bluegate Sh.
Drip Tank Mbr.
John Henry Mbr.
"A-sst."
MFS
"Calico bed"
Ferron Sst.
Tropic Sh.
Smoky Hollow Mbr.
Tibbet Canyon Mbr.
10 m
190 m
25 m
25 m
50 m

Figure 3

from these sections. Stratal correlations are based on analysis of the stacking patterns of marine parasequences, visual correlation both in the field and on extensive panorama photographs, and review of low angle aerial photographs obtained from a helicopter survey of the entire plateau.

Treatment of the facies architecture and its relationship to sequence stratigraphy required a combination of closely spaced detailed sections and panorama photographs within the framework established by the larger scale sequence-stratigraphic study. Detailed analyses were conducted on the transitions from shoreface to coal-bearing strata in Left Hand Collet Canyon; the transition from coal-bearing to barren strata in Tibbet Canyon; and on incised valley-fill strata in Rock House Cove, Coyote Canyon, and Blue Cove. Tidally-reworked shoreface strata were studied throughout much of the southern plateau (Fig. 2).

All sections have been measured to record stratigraphic variation at the centimeter scale. Measured sections were initially drafted at a scale of 1:40 which allowed much of the sedimentological variation to be recorded. Where talus obscured the fine-grained interval, shovels and mattocks were used to trench through the talus so that as complete a section as possible could be measured. All measured sections have more than 95% stratigraphic completeness. Lateral variations have been described and recorded through careful field photography, acquisition of smaller detailed sections, and by walking beds out.

DESCRIPTION AND INTERPRETATION OF SEDIMENTARY FACIES

Introduction

Exposures of both sheet and ribbon alluvial sandbodies (terminology from Friend et al. 1979) dominate the western and west-central portions of the plateau and are emphasized in this study (Fig. 4). The nature of these outcrops are such that the sandstones form prominent ledges whereas the mudrocks are generally obscured by talus material. Observations regarding the mudrocks are, therefore, limited to exposures in trenches, gullies, and locations where overlying sandstones have sheltered the mudrocks from talus. To the east, these strata interfinger with crevasse splay deposits, thick coals and mudrocks, and thin, ribbon-like channel sandstones. Because thick coals are present in this region, extensive surface burns are common and have obscured much of the exposure. We have relied on petrologic data collected by Peterson (1969a) and refer to the rocks in terms of Folk's (1974) classification. For purposes of this paper, we have delineated five facies associations. It is the geometric arrangement of these facies associations that characterizes the architectural style of these strata and allows for comparison with marine strata along the eastern margin of the plateau.

Studies of ancient alluvial sequences are replete with attempts to classify strata based on channel morphology, i.e. meandering, braided, straight, or anastomosed channel patterns, or sediment load, i.e. suspended, mixed, or bedload channels (e.g.,Miall, 1978; Collinson and Lewin, 1983; Ethridge et al., 1987). Although such classification fulfills a desire to establish a sense of order to natural systems, it ignores the fact that a continuum exists between various channel patterns (Schumm, 1977, 1981). The continuum of channel patterns and the autocyclic processes responsible for these patterns, combined with longer term allocyclic processes and their effect on alluvial preservation suggest that

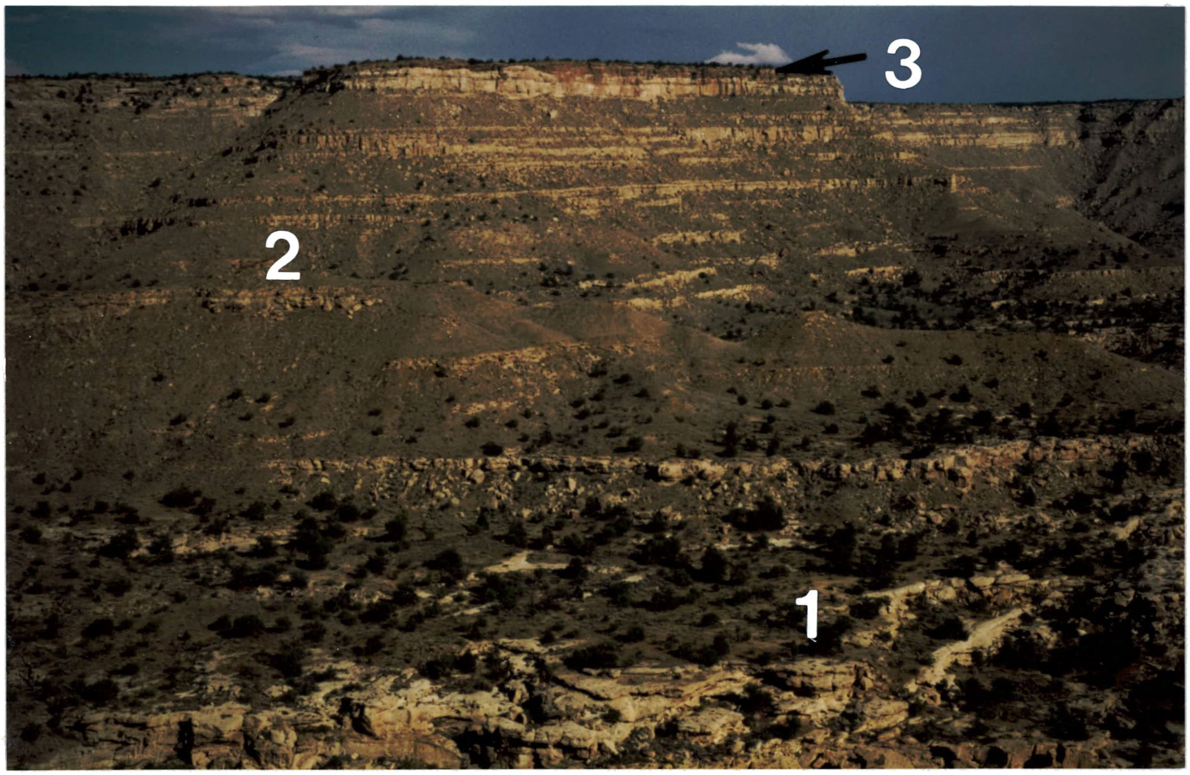


Figure 4. View to the east of Rock House Cove, an area dominated by alluvial strata. The stratigraphic position of this photograph is illustrated on Figure 3. The prominent sandstone in the foreground (#1) is the top of the amalgamated sandstone (A-sandstone) complex which forms the upper part of a transgressive systems tract. The majority of the photograph (#2) illustrates the highstand systems tract that comprises isolated sheet and ribbon-channel sandbodies within fine-grained overbank sediments. The skyline of the photograph shows the coarse-grained, slightly darker weathering, fluvial deposits of the Drip Tank Member which unconformably overlie finer-grained, isolated channels of the John Henry Member (#3). Approximately 165 m of section is shown between the top of the amalgamated sandstone and the Drip Tank Member. See Fig. 2 for location of photograph.

realistic reconstructions of channel morphology are difficult at best. Nevertheless, detailed facies models based on studies of both modern and ancient alluvial strata have been developed which suggest criteria to distinguish alluvial channel patterns (e.g.,Ethridge and Flores, 1981; Cant, 1982; Galloway and Hobday, 1983; Walker, 1984; Collinson, 1986). The continuum of alluvial processes and products led Collinson (1978), Friend (1983) and Bridge (1985) to critique various criteria commonly used to discern channel pattern. They determined that many criteria were either inconclusive or invalid. Although some end-member channel styles might be recognized with a certain measure of confidence, the vast majority are difficult to categorize. Friend (1983) and Bridge (1985) considered the following criteria useful in determination of paleochannel patterns: proportion of channel fill relative to lateral accretion deposits, the mean grain size of channel fills relative to lateral accretion deposits, paleocurrent variance, study of strata interpreted as bedload deposits, and quantitative reconstructions of channel hydraulics. The following interpretations are offered for the facies associations of the Kaiparowits Plateau using these criteria.

Pebbly and coarse-grained to medium-grained sheet sandstone facies

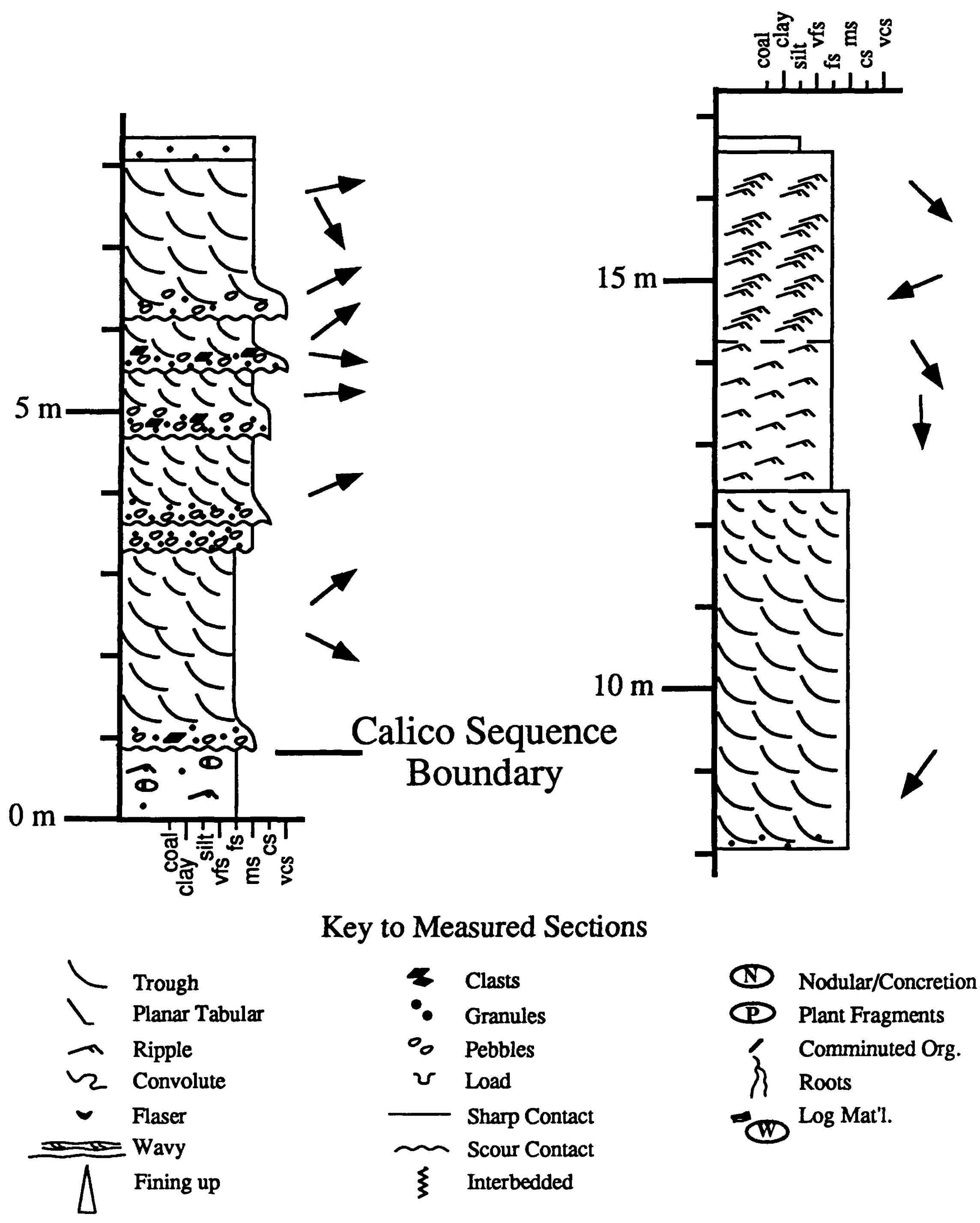
Description

Sandstones comprising this facies belong to both the Calico bed, an informal unit of the Smoky Hollow Member of the Straight Cliffs Formation and the lower portions of the Drip Tank Member of the Straight Cliffs Formation (Fig. 3). Because of the emphasis of this research program, we do not attempt to describe the entire Drip Tank Member. Our measured sections include the lowermost 5-15 m of Drip Tank strata and our comments, therefore, are limited to these strata. The Calico bed commonly has a bleached to light gray appearance on outcrop providing a superb visual marker throughout most of the plateau. In contrast, the Drip Tank Member commonly weathers a brown to brownish-orange color. It is also easily recognized throughout the plateau because it commonly forms the uppermost resistant sandstone ledge along the skyline of the plateau.

The Calico bed is characterized as a poorly sorted, friable, granule to medium-grained sandstone with interbedded pebble-conglomerate lenses. It erosionally overlies fine-grained channel sandstones, rooted mudrocks, carbonaceous shales and thin discontinuous coal beds of the Smoky Hollow Member; erosional relief locally exceeds 2 m (Fig. 5). Thickness of the Calico generally varies across the plateau from 0-15 m, although thicknesses as great as 40 m have been reported by Bobb and Ryer (1990) from the extreme northeastern part of the plateau. Conglomerate lenses are common, and generally occur along scour surfaces at the base of the Calico as well as along internal (storey) scour surfaces. These conglomerates are predominately composed of chert, quartz, and feldspar pebbles whose long axis rarely exceeds 2.5 cm. Conglomerates are both clast and matrix supported, range in thickness from a few centimeters to 0.4 m, and range in length from a few decimeters to 1-2 m (Fig. 6).

The Calico bed comprises several distinct sandstone bodies, or storeys (terminology after Friend et al., 1979), each of which has a scour base and which, in general, fines up from a coarse-grained and granule-bearing sandstone with scattered conglomerate lenses to a medium-grained sandstone with scattered granules and conglomerates (Fig. 5). Mud clasts up to a few centimeters long, finely comminuted plant material, and woody debris are commonly incorporated along scour surfaces, especially the basal scour of the Calico bed. At the base of the Calico, storeys range from decimeters to 1 m in thickness and are abbreviated in the sense that the upper portions of fining-upward units are removed by subsequent scour surfaces. Higher in the Calico, more complete fining-upward units are

Figure 5. Measured section of the Calico bed from Tibbet Canyon. The sequence boundary is interpreted where coarse-grained and pebbly sandstones overlie fine-grained, rooted alluvial plain strata. This surface marks a major basinward shift in facies tracts. Note the thin, multi-storey nature of the lower part of the Calico and the overall fining up character. These strata comprise a transgressive systems tract and are interpreted as low-sinuosity, possibly braided river deposits. The legend shown in this figure is also used in subsequent figures. See Fig. 2 for location of photograph.



coal
clay
silt
vfs
fs
ms
cs
vcs
15 m
10 m
5 m
0 m
Calico Sequence Boundary
Key to Measured Sections
Trough
Planar Tabular
Ripple
Convolute
Flaser
Wavy
Fining up
Clasts
Granules
Pebbles
Load
Sharp Contact
Scour Contact
Interbedded
N
Nodular/Concretion
P
Plant Fragments
Comminuted Org.
Roots
W
Log Mat'l.

Figure 5

Figure 6. Photograph of the Calico bed in Tibbet Canyon illustrating the intermixed pebble conglomerates and medium to coarse grain, trough cross-bedded sandstones that are common in the lower part of the Calico bed (3.3 m level in Fig. 5). The lens cap is 70 mm in diameter.

preserved ranging up to 5 m in thickness (Fig. 5). Sedimentary structures within the Calico bed consist primarily of trough cross-stratified and ripple-laminated sandstones, minor planar-tabular cross beds, and thin massive-bedded sandstones (Fig. 5). Trough sets vary from 0.1-0.5 m in thickness. Where preservation of fining-upward units is more complete, there is a systematic progression from 0.3-0.5 m thick trough sets near the basal scour to 0.1-0.15 m trough sets in the upper portions of fining-upward units. Planar-tabular cross bedded sandstones are not common but do occur as 0.5 m thick beds within sandstones that are otherwise trough cross-bedded. The upper part of fining-upward units are commonly fine-grained, ripple-laminated sandstones and interbedded ripple-laminated siltstones with cosets as thick as 2.5 m. The uppermost portions of these ripple-laminated sandstones are commonly massive .

Paleocurrents in the Calico bed are quite variable when viewed collectively (Fig. 7a), however, this variance decreases markedly when viewed in the context of individual outcrops. Nevertheless, these data suggest overall transport directions to the east. Similar paleocurrents were also reported by Peterson (1969a) and Bobb and Ryer (1990).

The Drip Tank Member of the Straight Cliffs Formation (Fig. 3) erosionally overlies fine-grained, rooted mudrocks, carbonaceous shales, thick coal-bearing strata, and fine-grained channel deposits of the John Henry Member (Fig. 8). Erosional relief at the base of the Drip Tank Member locally exceeds 5 m. Regional correlations across the Kaiparowits Plateau, however, suggest that the base of the Drip Tank Member has cut down towards the west by almost 60 m (Shanley and McCabe, 1990a-in review). The Drip Tank Member is a poorly sorted, granule to medium-grained, feldspathic/litharenite with interbedded pebble-conglomerate lenses. Conglomerates in the Drip Tank are principally composed of chert, quartz, and feldspar pebbles whose long axis rarely exceeds

Figure 7. Paleocurrent data for (a) Calico bed, (b) Drip Tank Member, (c) medium to fine-grained amalgamated sandstone facies, (d) medium to fine-grained amalgamated sandstone facies, and (e) tidally-influenced heterolithic facies. The azimuth of resultant vectors (R) was calculated according to the method outlined in Curray (1956). The number of readings used is shown in the center of each rose diagram.

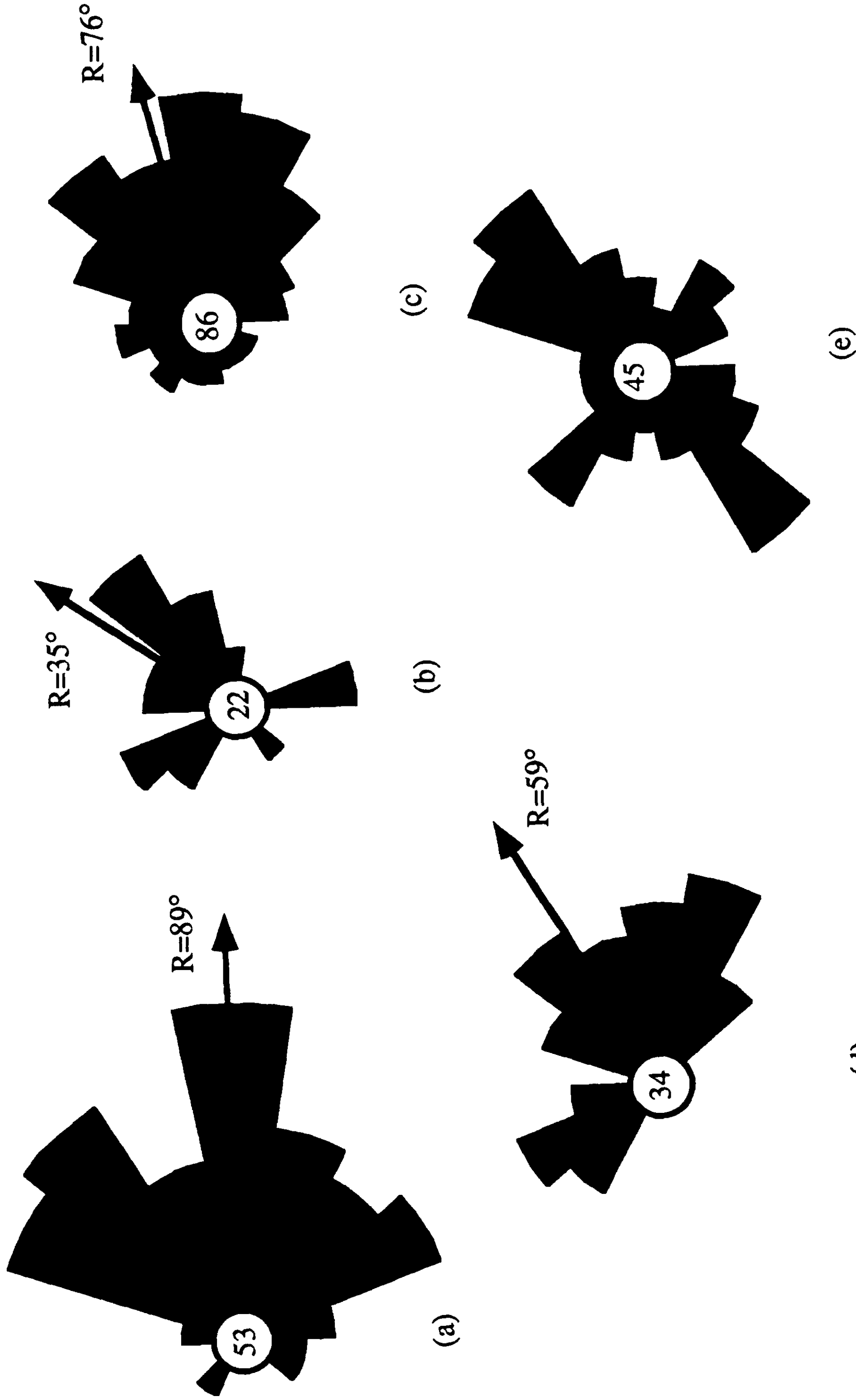


Figure 7

Figure 8. Photograph of coarse-grained, amalgamated fluvial sandstones of the Drip Tank Member unconformably overlying fine-grained fluvial sandstones and carbonaceous mudstones of the John Henry Member from Rock House Cove in the southwestern part of the plateau. This contact is interpreted as a widespread sequence boundary. See Fig. 2 for the location of this photograph.

4 cm. Both clast and sand-matrix supported pebble conglomerates are present and range in thickness from a few centimeters to 0.25 m.

Similar to the Calico bed, the Drip Tank Member sandstones are multi-storey in nature with individual storeys ranging from decimeters to a few meters in thickness. Each storey fines upward from coarse-grained sandstones and thin pebble conglomerates to medium-grained sandstones (Fig. 9). Within the lower 15 m of the Drip Tank Member the thickness of individual storeys progressively increases upwards from 0.3 m at the base to as much as 1.75 m near the top. Mud-clast conglomerates, woody fragments, and pebble-conglomerate lags outline the basal scour surface as well as internal storey-scour surfaces (Fig. 9). Sedimentary structures within the Drip Tank Member consist primarily of trough cross-stratified and planar-tabular cross-stratified rocks. Trough sets vary in thickness from 0.25 m to 1.5 m, whereas planar tabular sets are commonly 0.4-0.6 m in thickness. Paleocurrents in the Drip Tank Member suggest flow was primarily to the northeast (Fig. 7b) consistent with results reported by Peterson (1969a).

Sandstone thicknesses and areal extent, which indicate width/depth ratios in excess of 50:1, combined with the internal architecture, suggest the Calico bed and the lower portions of the Drip Tank Member may be characterized as sheet sandstones (Friend et al., 1979) or as multi-storey, lenticularly-bedded sheet sandstones (Puigdefabregas et al., 1989).

Interpretation

The sandstones comprising the Calico bed and the Drip Tank Member of the Straight Cliffs Formation are interpreted as bar and channel-fill deposits of aggrading, low-sinuosity, (terminology from Rust, 1978) perennial rivers. The multi-storey, sheet-like geometry of these sandstones make estimates of channel width and depth difficult;

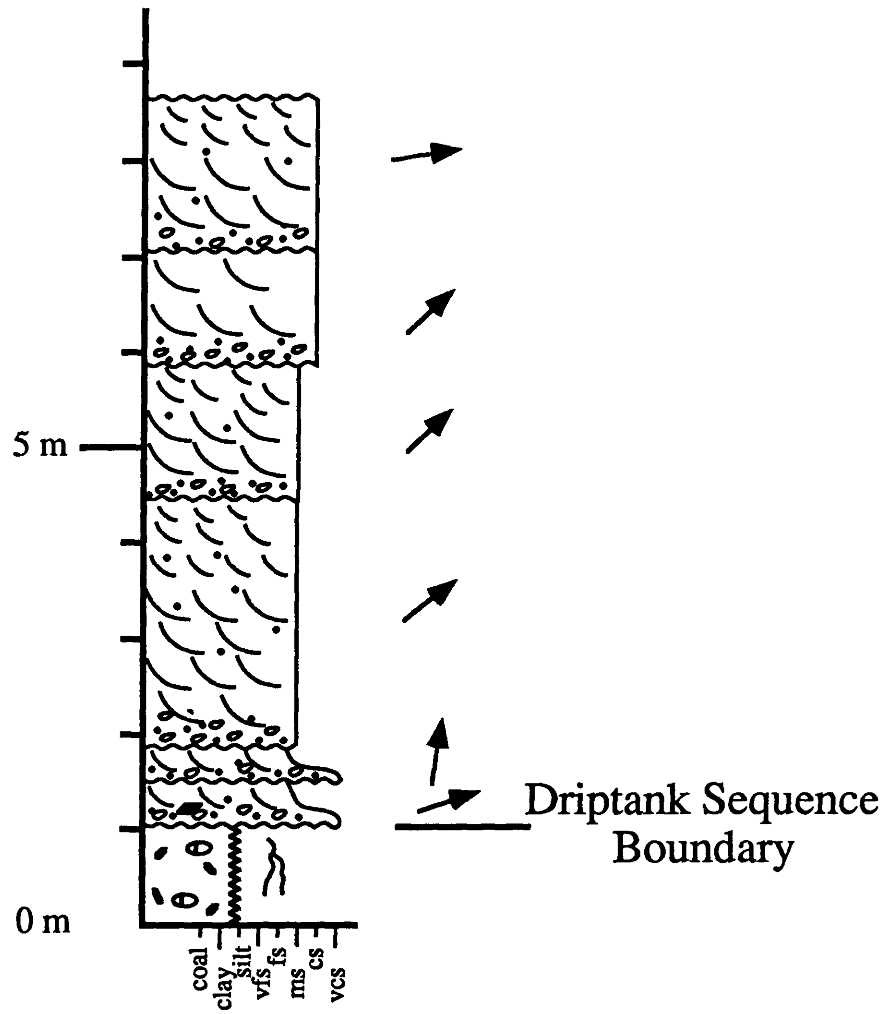


Figure 9. Measured section of the lower part of the Drip Tank Member from Tibbet Canyon. The sequence boundary interpreted at the base is placed where pebbly and coarse-grained sandstones erosionally overlie fine-grained and rooted alluvial plain strata. Similar to the base of the Calico bed, this contact marks a significant seaward shift in facies tracts. Note the thin, multi-storey nature of the lower part of the Drip Tank. This is interpreted to reflect low rates of base-level rise resulting in the slow creation of accommodation space. These strata comprise the basal part of a transgressive systems tract and are interpreted as low-sinuosity, possibly braided river deposits. See Fig. 5 for the legend to the measured section and Fig. 2 for the location of this section.

calculated sinuosity values (Schumm, 1963) are less than 1.2. The very low proportion of lateral accretion to channel fill deposits, combined with the relatively coarse-grain size of channel-fill deposits, the unidirectional paleocurrents with low variance, and sheet-sand geometry support the interpretation of low-sinuosity, probably multi-channel rivers. Peterson (1969a) and Bobb and Ryer (1990) made similar conclusions for the Calico bed. The predominance of trough cross-stratification suggests that during flood-stage the river bed was largely covered with three-dimensional dunes although the presence of planar-tabular cross-stratification suggests that straight-crested, two-dimensional dunes were also present. The lack of thick planar-tabular sets, with paleocurrent orientations divergent from adjacent trough cross-beds, however, may suggest that there were few braid bars migrating transverse to flow and may argue against an extensive multi-channel system. Ripple laminated, finer-grained sandstones were confined to the upper portions of bars in both the Calico and Drip Tank. The presence of both clast and matrix-supported pebble conglomerates along the basal scours and the internal storey scours suggests discharge variations leading to changes in shear stress. The abundant mud intraclasts, mud-clast conglomerates and woody debris, especially at the base of both the Calico bed and the Drip Tank Member indicate that these river systems were eroding fine-grained, mudrock-dominated, vegetated floodplains. The multistorey, sheet-like geometry of both sandstones further suggests that rates of aggradation were relatively low. These conclusions are consistent with quantitative-model experiments (e.g.,Bridge and Leeder, 1979) that suggest how fluvial architecture might vary due to changes in accommodation space .

It is worth speculating on the origin of the bleached appearance of the Calico bed not only for its importance as a visual marker but also for its role in sequence stratigraphic interpretations. Outcrop examination of the Calico bed suggests that both the friable nature and bleached appearance are in part due to preferential leaching of feldspar grains and the precipitation of kaolinite clays. Although it is difficult to constrain the timing of this alteration without conducting a paragenetic investigation (not part of this study), field relationships suggest this alteration may have occurred shortly after deposition during the late Turonian to early Coniacian; channel deposits of similar composition occur within the upper part of the Calico bed and are not bleached. We suggest this alteration may reflect periods of prolonged subaerial exposure. Such exposure may be explained by at least two mechanisms. Based on regional relationships as well as the local sedimentology, it is probable that the bleached part of the Calico bed was deposited and preserved, perhaps as a series of terrace deposits, during a period of base level lowering and before significant onlap (Shanley and McCabe, 1990b-in review). An alternative explanation suggests the Calico bed underwent prolonged subaerial exposure following/during a rapid base level rise but prior to significant fluvial aggradation of the John Henry Member of the Straight Cliffs Formation.

Medium to fine-grained amalgamated sandstone facies

Description

Sandstones comprising this facies occur near the base of the John Henry Member of the Straight Cliffs Formation (Fig. 3). These sandstones form a prominent cliff-face that can be correlated along the southwestern margin of the plateau from Rock House Cove to Blue Cove, a distance of approximately 12 km (Fig. 2). Thickness of the amalgamated sandstone facies varies from 0-30 m. The abrupt change in grain size that commonly marks the basal scour surface of the amalgamated sandstone facies combined with a marked change in alluvial stacking pattern facilitates the recognition of the lower part of this sandstone complex throughout the study area. The gradual but irregular increase in proportion of fine-grained strata in the upper part of this facies, however, renders the upper contact of this facies difficult to place (Fig. 10).

Sandstones of this facies are characterized as medium to locally coarse-grained feldspathic litharenites. These sandstones cut into fine-grained, rooted, carbonaceous mudrocks, and heterolithic facies. Erosional relief at the base of the amalgamated sandstone locally exceeds 2 m. The basal scour surface is covered with clay-clast conglomerates, with individual clay clasts up to 3 cm in length, scattered chert pebbles and granules, and woody debris. Coarse-grained sandstone lags also occur along the basal scour surface (Fig. 11).

This sandstone complex is composed of several distinct storeys that can be traced laterally for distances of 10's to 100 m. At the base, storeys range from less than 1 m up to 1.5 m thick with individual storey-scours marked by an increase in grain size and a thin granule or pebble lag (Fig. 11). Internal sedimentary structures of these lower storeys consist primarily of trough and planar tabular cross-bedding. In contrast to the lower part of this sandstone complex, upper storeys are thicker (3-8 m), have more complete fining upward units, and have greater variation in sedimentary structures (Fig. 11). The basal portions of upper storeys commonly contain clay clasts, scattered chert granules, and, rarely, bone material. Several sandstones within the upper portion of the amalgamated complex contain laterally inclined surfaces, some of which are clearly erosional. Where these surfaces are more completely preserved, they are low-angle in nature near the top of the sandstones, have maximum dips between 5°-15° within the middle of a sandstone, and become asymptotic at the base of the sandstone. Internal sedimentary structures consist of trough cross-beds that show a systematic decrease in thickness from 0.5 m near the storey-

Figure 10. View to the west of the amalgamated channel sandstone complex in Blue Cove. The sequence boundary at the base of the amalgamated sandstone complex is placed at the base of the thick sandstone cliff in the center of the photograph. This sequence boundary can be traced throughout the southwestern part of the plateau. The upper part of the amalgamated sandstone complex is gradational with isolated channel sandstones and fine-grained overbank strata. The increase in fine-grained strata towards the top of the amalgamated sandstone complex is clearly seen in this photograph. We interpret the upward increase in fine-grained strata to reflect increased accommodation space within a gradually aggrading valley complex. This particular valley sandstone can be traced from Rock House Cove to Blue Cove. See Fig. 2 for the location of this photograph.

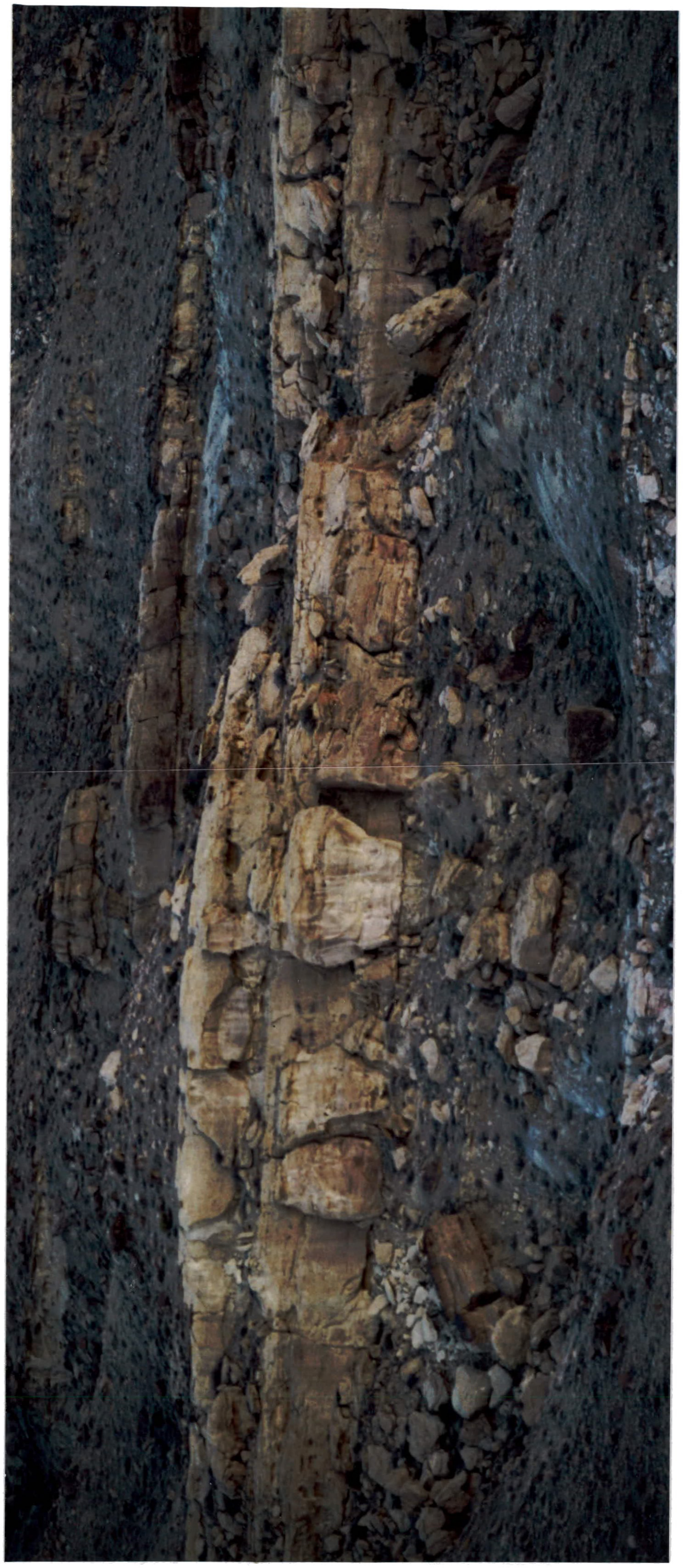


Figure 11. Measured section of the medium to fine-grained, amalgamated sandstone facies from Blue Cove. The sequence boundary is interpreted where coarser-grained, multi-storey, amalgamated sandstones erosionally overlie fine-grained and rooted alluvial plain strata. Note the numerous thin, fining-up sandstone complexes at the base of the measured section which become thicker towards the top of the section. This trend in preservation is interpreted to reflect the gradual filling of a broad incised valley complex. These strata comprise a transgressive systems tract and are interpreted as moderate to high-sinuosity river deposits. See Fig. 5 for the legend and Fig. 2 for the location of this section.

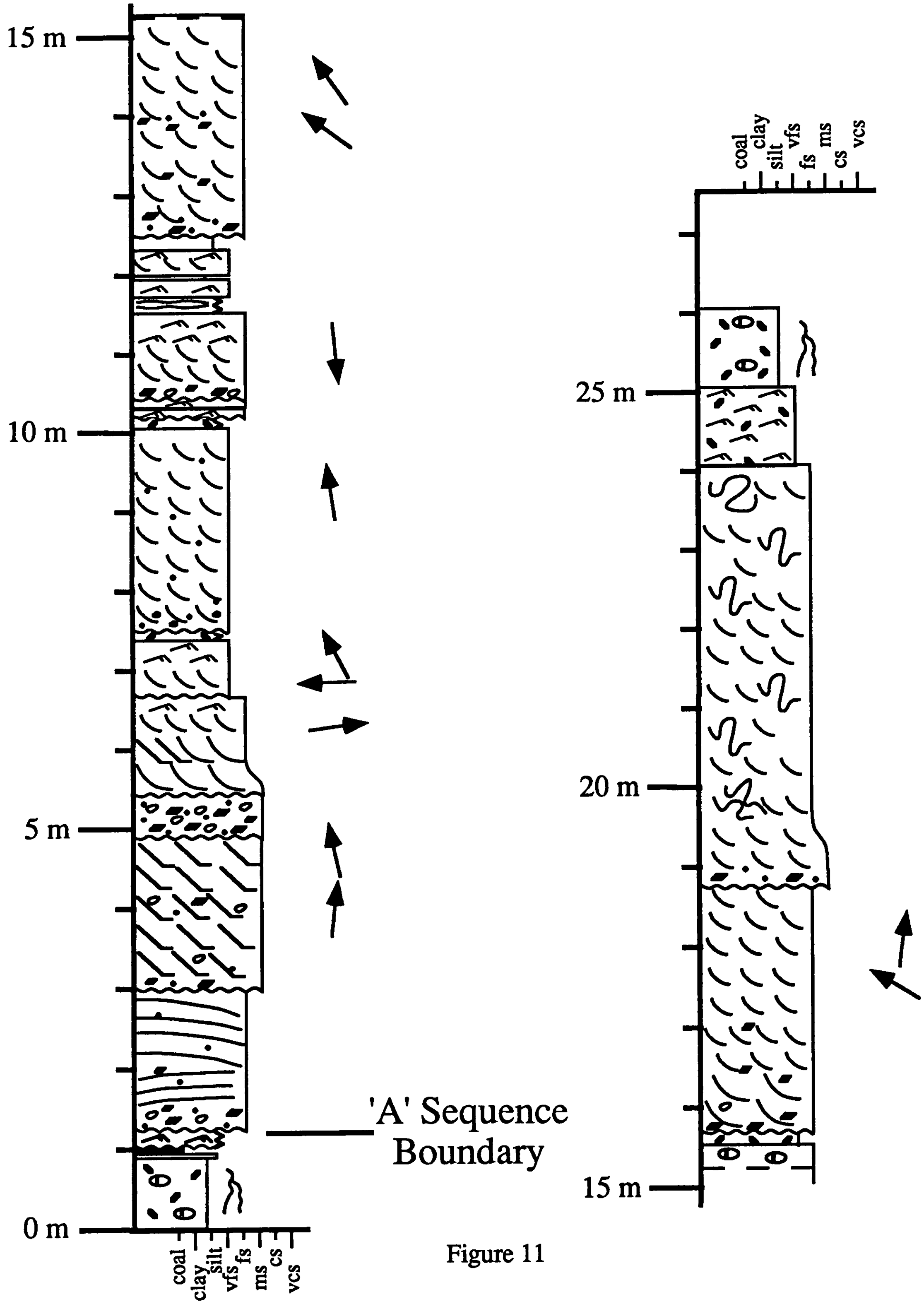

15 m
10 m
5 m
0 m
'A' Sequence Boundary
coal
clay
silt
vfs
fs
ms
cs
vcs
25 m
20 m
15 m
coal
clay
silt
vfs
fs
ms
cs
vcs

Figure 11

scour to 0.15 m at the top of a coset. Parallel with this decrease in the size of cross-beds is a decrease in grain size from medium to fine-grained sandstone (Fig. 11). Where more complete fining upward sandstones are preserved, trough cross-bedded sandstones commonly grade upward into ripple-laminated or massive sandstones and finally into ripple laminated siltstones or very fine-grained sandstones. Some trough and planar tabular cross-bedded sandstones have been convoluted into beds 0.5 m to 3 m thick.

Within the upper part of this facies association are thinly-bedded, ripple and climbing ripple-laminated sandstones that grade into ripple-laminated siltstones and very fine-grained sandstones. These sandstones contain finely comminuted organic material that is concentrated along laminae; they are interbedded with rooted mudrocks. Inclined beds of ripple-laminated sandstones, and thin mudrocks also occur within the upper part of this facies.

Paleocurrents in the amalgamated facies (Fig. 7c) suggest transport directions to the northeast through southeast. Although paleocurrents are clearly unidirectional, there is a spread of almost 140° in the data set. Paleocurrent orientations taken from planar-tabular sets that exceed 1 m in thickness diverge by almost 50-70° from the orientations taken from adjacent trough cross-beds. Paleocurrents from laterally inclined strata are approximately normal to the direction of inclination. Based on thickness and areal extent, width/depth ratios exceed 25:1, suggesting the amalgamated sandstone complex may be considered a sheet sandstone (Friend et al. 1979) or a multi-storey, lenticularly-bedded sheet sandstone (Puigdefabreas et al., 1989).

Interpretation

The amalgamated sandstone facies association of the John Henry Member is interpreted as channel fill deposits of aggrading, moderate- to high-sinuosity (Rust, 1978), perennial rivers. Although lateral-accretion deposits occur near the base of this facies, estimates of sinuosity are principally derived from exposures in the upper part, where both channel preservation and lateral accretion are better developed. At these localities, sinuosity estimates based on the method of Schumm (1963) range from 1.5 to 1.8. The relatively high proportion of lateral accretion to channel-fill deposits combined with the finer grain sizes of the lateral accretion deposits, the 140° variation in paleocurrents all support the interpretation of moderate to high sinuosity rivers. The presence of planar-tabular sets within the body of fining-upward units and paleocurrent orientations that significantly diverge from adjacent trough cross-beds may reflect the local preservation of straight-crested bars. Planar-tabular sets within the upper part of these fining upward sandstones may have formed as scroll bars. The preservation of discrete fining-upward units that grade from trough cross-beds to ripple and massive bedded sandstones and siltstones are interpreted as the preservation of the downstream portion of point-bar complexes. During flood stage, the channel base was likely covered with three-dimensional dunes that graded into current ripples on the margins of the point bar. Convolute lamination within trough cross-bedded sandstones is interpreted as partial liquifaction and deformation of water saturated sediment under the influence of lateral shear. Such conditions may be due to the migration of large bedforms over an unconsolidated substrate during conditions of high discharge (Plint, 1983). Channel sandstones that are completely dominated by convolute lamination more likely reflect catastrophic sediment liquefaction, perhaps via earthquakes. The abundant mud-clasts and woody debris incorporated along scour surfaces within this sandstone complex indicate that these river systems eroded fine-grained, mudrock-dominated, vegetated floodplains.

Based on vertical and lateral relationships, the amalgamated sandstone facies is interpreted to occur within an incised valley. The amalgamated sandstone facies, therefore, represents a valley-fill succession of strata. Within this valley, fine-grained strata, interpreted as overbank deposits and lateral accretion deposits, become increasingly common towards the top of the sandstone complex. As a result, the multi-storey, multi-lateral morphology grades vertically into smaller multi-lateral sandbodies more typical of sandstone bodies found in the isolated sandstone facies. We interpret this to reflect gradual aggradation within the valley complex. The increased preservation of discrete channel forms and higher proportion of fine-grained strata within the upper part of the valley is thought to reflect increased accommodation space combined with changes in rates of aggradation similar to ideas advanced by Bridge and Leeder (1979). Alternatively, this vertical change in preservation may reflect an evolutionary change in the fluvial system itself, however, the presence of lateral accretion deposits and minor fine-grained intervals within the lower part of this facies association suggests that similar rivers are present throughout the amalgamated facies.

Medium to fine-grained isolated sandstone facies

Description

Sandstones comprising this facies association occur throughout the middle and upper portions of the John Henry Member of the Straight Cliffs Formation and locally within the Smoky Hollow Member of the Straight Cliffs Formation (Fig. 3). Unlike the previous two facies that form prominent cliffs, these sandstones are noted for their isolated exposures.

Individual sandstones range from 5-12 m in thickness and from 65 m to approximately 300 m in width (measured normal to paleoflow) and are encased in interbedded siltstones and very fine-grained sandstone facies (Fig. 12). To the east, in the vicinity of Tibbet Canyon, the isolated sandstone facies association interfingers with thick coal-bearing strata, crevasse-splay deposits, and thin, ribbon-like channel sandstone strata.

Sandstones of this facies are medium to fine-grained feldspathic litharenites. These sandstones erosionally overlie fine-grained, rooted, carbonaceous mudrocks of the floodbasin facies with erosional relief locally exceeding 3 m. The basal scour surface of these sandstones has tool and flute marks, and is commonly covered with woody debris, small clay clasts less than 3 cm long, scattered granules and thin coarse-grained sandstone lags between 0.1 and 0.2 m thick. Clay-clast conglomerates between 0.2 and 0.65 m thick are present at the base of some sandstones (Fig. 13). Internal storey scours are marked by an increase in grain size from fine to medium-grained sandstones and the occurrence of scattered granule lags (Fig. 13).

These sandstones have the geometric arrangement of both multi-storey, multi-lateral ribbon sands, as well as sheet sandstones (Friend et al., 1979); they are classified as composite, tabular sandbodies (Puigdefabregas et al , 1989). In the case of multistorey sandbody exposures, two to three storeys are normally present. Complete single storeys are approximately 9 m thick and grade upward from medium to fine-grained sandstone and interbedded very fine-grained sandstone and siltstone. Internal sedimentary structures within these sandstones consists of trough cross-beds, ripple-lamination, massive bedding, and convolute lamination (Fig. 13). Trough cross-beds occur in the lower portion of sandstone storeys and decrease systematically from approximately 0.4 m at the base to 0.15 m near the top. Trough cross-beds may be interbedded with convolute lamination in beds

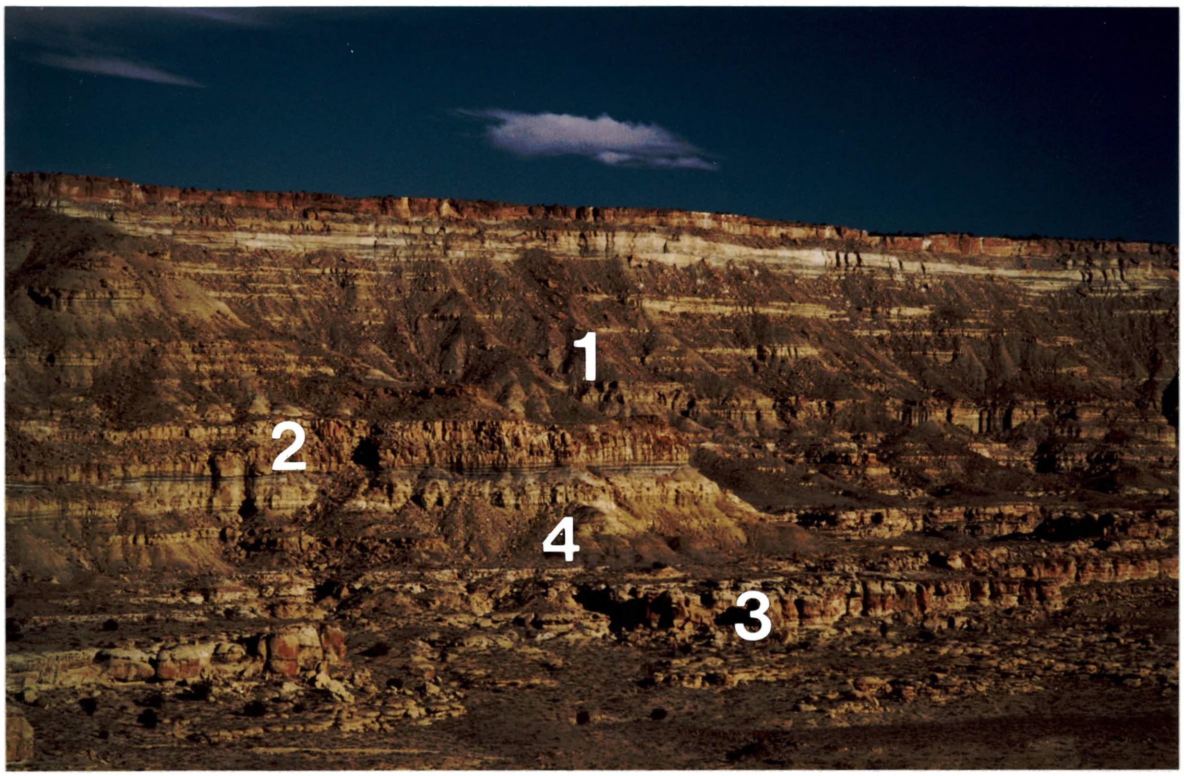


Figure 12. View to the east at Blue Cove of medium to fine-grained isolated channel-belt sandstones encased in overbank siltstones and sandstones. Note the laterally discontinuous nature of the sheet and ribbon sandbodies (#1). This photograph also illustrates the change in connectedness (net/gross sandstone) between channel sandstones of the amalgamated facies (high net/gross) (#2) versus those of the isolated facies (low net/gross) (#1). The amalgamated sandstones are part of a transgressive systems tract whereas the isolated channels comprise a highstand systems tract. In the foreground are shoreface sandstones of the Tibbet Canyon Member (#3) and alluvial deposits of the Smoky Hollow Member (#4). The skyline of the photograph illustrates the sharp contact at the base of the coarse-grained and pebbly sandstones of the Drip Tank Member. See Fig. 2 for the location of this photograph.

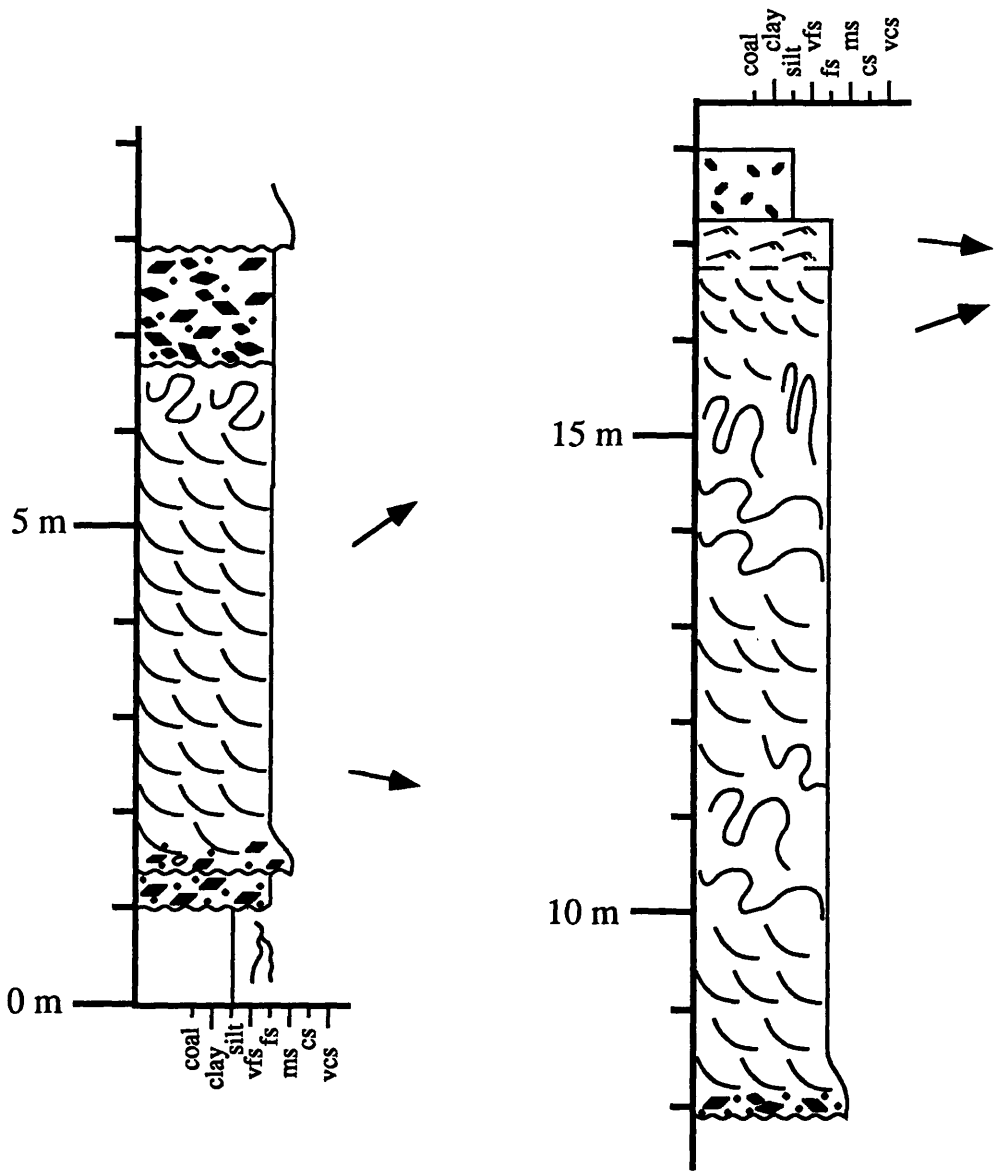


Figure 13. Measured section of the medium to fine-grained, isolated sandstone facies from Rock House Cove. These sandstones are typically comprised of two storeys and form sheet-like deposits. Individual storeys are more complete in this facies than in the amalgamated sandstone facies shown in Fig. 11. These strata comprise a high-stand systems tract and are interpreted as sinuous river deposits. See Fig. 2 for the location of this section.

up to 1 m thick (Fig. 13). In a single case an entire storey, approximately 9 m thick, consists of convolute lamination. Towards the top of sandstone storeys, trough cross-beds decrease in set thickness and are replaced by current ripple lamination that occurs in 0.25 m to 2 m thick sets (Fig. 13). Near the margins of these sandstones where they can be observed to scour into fine grained floodbasin strata, the sandstones are dominated by ripple- and climbing-ripple stratification. The uppermost part of these sandbodies are often characterized by massive and mottled sandstones approximately 0.3 m thick.

Paleocurrents in this facies association are consistent within a single storey, but may show as much as 90° variation between storeys. These paleocurrent data indicate a range in transport directions varying from northwest to east with a strong northeast component (Fig. 7d). The primary distinction between sandstones belonging to this facies versus the amalgamated-sandstone facies is the degree of sandstone amalgamation. Consequently, the upper contact of the amalgamated sandstone facies in some locations is difficult to place because of the gradational change to the more isolated sandstone facies.

Interpretation

The isolated sandstone facies association of the John Henry Member is interpreted as channel deposits of aggrading moderate to high sinuosity, perennial rivers. This interpretation is consistent with available paleocurrent data that suggest rivers were flowing to the northeast. Lateral accretion deposits are not well developed in many of these sandstones and estimates of sinuosity are largely based on storey thicknesses. These estimates suggest a sinuosity of approximately 1.5 (based on the method of Schumm, 1963). Because of the nature of the outcrop, fine-grained, abandoned-channel plugs are generally poorly exposed. The high proportion of fine-grained sediment adjacent to these sandstones combined with the internal architecture of these sandstones support the interpretation of a single-channel, sinuous fluvial system. Where complete abandoned-channel strata can be observed, estimates of channel depth and width are possible. Such exposures, although rare, indicate channel depths of 5 to 8 m and channel widths of 75 to 125 m. The erosional bases, abundant clay intraclasts, clay-clast conglomerates, and woody debris suggest that these channels cut into vegetated, fine-grained floodplain sediments. Minor variations in discharge are suggested by the presence of thin, coarse-grained sandstone lags and scattered granules that are interpreted to represent the traction load under flood discharge. The channel sandstones are dominated by fining-upward units that grade from trough cross-stratified sandstones to ripple-laminated sandstones and finally to thin rooted mudstones and massive-bedded sandstones. These units are interpreted as the deposits of the down-stream side of point bars. The rooted mudstones and massive-bedded sandstones that cap these units suggest the upper point-bar surfaces had established vegetation.

We interpret the isolated channel architecture to reflect high rates of creation of accommodation space similar to the model developed by Bridge and Leeder (1979).

Heterolithic facies

Description

Strata comprising this facies association occur in the lower one-third of the John Henry Member of the Straight Cliffs Formation (Fig. 3). A variety of sedimentary rocks are present in this facies association such that any outcrop may contain some or all of the characteristics described here. A detailed description of this particular facies assemblage is to be found in Shanley et al. (1990-in review).

In general, there is an overall fining trend in grain size from the eastern side of the plateau at Left Hand Collet Canyon to the western side of the plateau at Rock House Cove (Fig. 2). These strata erosionally overlie a variety of facies ranging from fine-grained, rooted carbonaceous mudrocks to medium-grained trough cross-bedded sandstones. The basal contact of the heterolithic facies is erosional with maximum depth of scour approaching 10 m. Despite the depth of scour, the overlying strata are dominated by interbedded ripple-laminated sandstones and thin mudrocks. The internal geometry of these heterolithic strata is complex. Inclined strata with paleocurrents normal to the direction of stratal inclination are common as are large internal scour surfaces (Fig. 14). Although the internal sedimentary structures are dominated by ripple-laminated sandstones and thin mudrocks, there is a variety of other sedimentary features (Fig. 15). These include wavy and lenticular-bedded sandstones, in sets approximately 0.2 to 0.5 m thick, pseudo-planar laminated sandstones (Smith, 1971; or transcurrent lamination of Allen 1984) sigmoidal beds that are outlined by thin mud drapes, ripple-laminated sandstones with shrinkage-crack casts on the base, trough and planar tabular-bedded sandstones containing multiple reactivation surfaces, and compound cross-stratification (Fig. 15). Of particular significance are the thin mudrocks that commonly drape ripple-laminated sandstones and which can be traced from the upper part of a sandstone complex along inclined surfaces into the basal part of the sandstone (Fig. 14).

Trace fossils within this facies association are the most diverse of all the strata described in this paper and include *Teredolites, Arenicola, and Diplocriterion. Teredolites* is commonly found in the basal portions of this facies association, whereas *Arenicola and Diplocriterion* are more commonly found in the upper portions of sandstones. Body fossils may include whole or broken inoceramid shells. Paleocurrents in these sandstones are

Figure 14. Photograph of inclined heterolithic strata (#1) in the lower part of the John Henry Member at Rock House Cove in the southwestern part of the plateau. The unit of inclined strata is approximately 10 m thick. The section illustrated in Fig. 15 was measured at this locality. These strata are interpreted as lateral accretion deposits within a tidally influenced river. Note the persistent mud drapes that can be traced into the lower part of the channel deposits. The top of the photograph (#2) records amalgamated fluvial deposits associated with the lower transgressive portion of the A-sequence. See Fig. 2 for the location of this photograph.

Figure 15. Measured section of the inclined heterolithic strata shown in Fig. 14 from Rock House Cove. Note the alternations of thin, ripple laminated and flaser bedded sandstones with thin, yet persistent mud drapes that can be traced into the base of the channel deposits. These strata are interpreted as lateral accretion deposits of a tidally influenced meandering river located approximately 65 km from a coeval shoreline. These heterolithic strata are temporally equivalent to condensed section deposits located on the eastern margin of the plateau. See Fig. 2 for the location of this section.

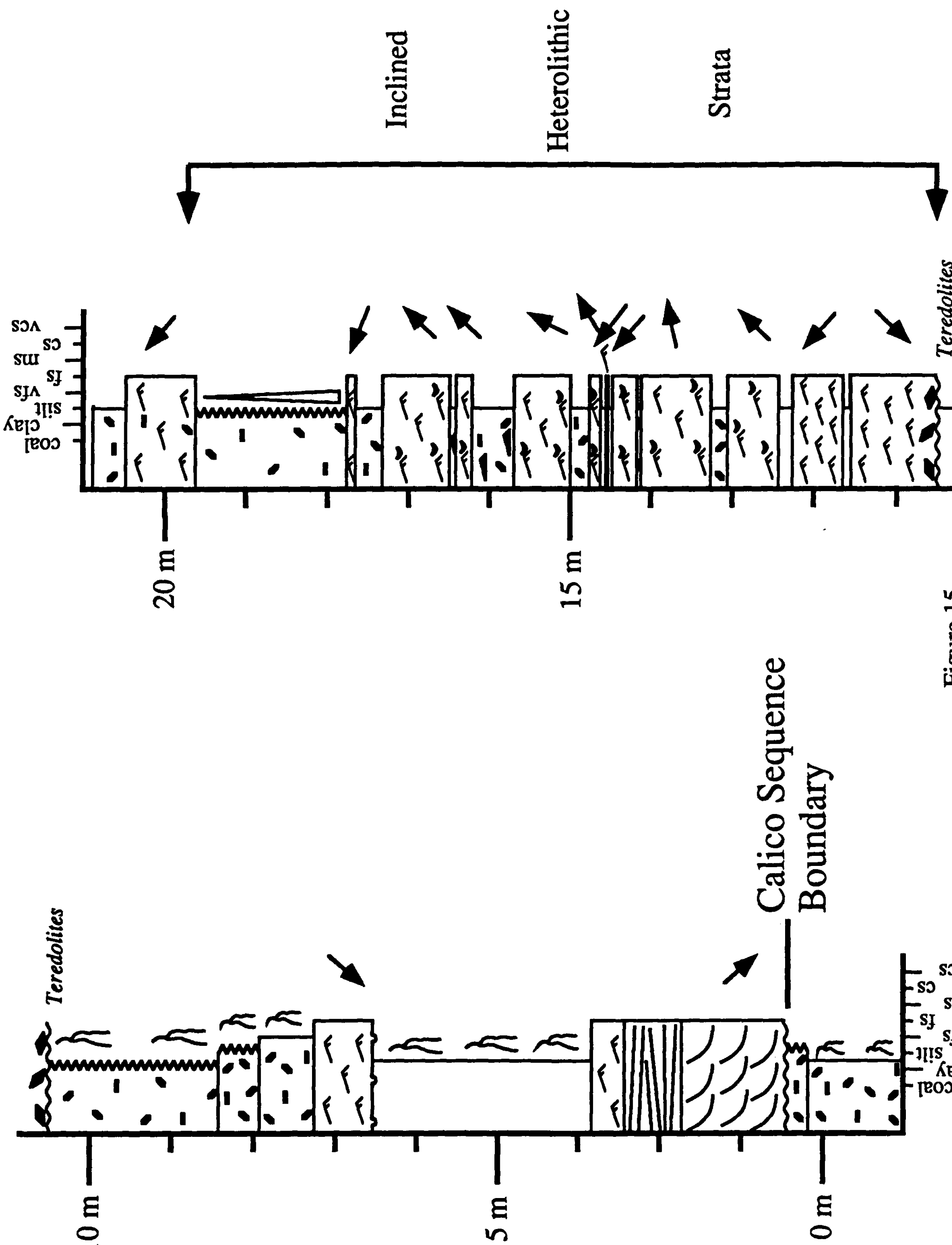

Inclined Heterolithic Strata
Teredolites
coal
clay
silt
vfs
fs
ms
cs
vcs
20 m
15 m
Calico Sequence Boundary
Teredolites
10 m
5 m
0 m

Figure 15

taken primarily from ripple-laminated sandstones and show a pronounced bidirectional paleocurrent orientation (Fig. 7e).

Interpretation

The heterolithic facies assemblage occurs at discrete horizons within the John Henry Member of the Straight Cliffs Formation. Along the northeastern margin of the plateau where these strata are overlain by a transgressive lag deposit, they are interpreted to reflect sedimentation in open to restricted estuaries. Across the vast majority of the plateau, however, these strata are entirely contained within nonmarine strata and were previously interpreted as fluvial deposits (Peterson, 1969a, b; Vaninetti, 1978). We interpret these strata as tidally-influenced river deposits; they represent maximum flooding into the alluvial plain (Shanley and McCabe, 1990, Shanley et al., 1990-in review). An examination of lateral accretion surfaces and the associated mud drapes suggest that many of the tidally-influenced rivers were of moderate to high sinuosity (Rust, 1978) with a sinuosity index of approximately 1.5 (Schumm, 1963). The overall westward fining trend in grain sizes and reduction in hydraulic energy as indicated by the sedimentary structures, is interpreted to reflect increasing distance inland from an open estuary or coeval shoreline. The presence of sigmoidal bedding geometries, double-mud drapes, wavy and lenticular bedding, multiple reactivation surfaces, and shrinkage cracks, interpreted as synaeresis cracks, all support the interpretation of fluvial deposits with a strong tidal influence. The paleocurrent data suggest fluvial processes modified by ebb and flood oriented currents that are normal to the regional trend of the paleoshoreline. The trace fossil assemblage suggests at least brackish water conditions (e.g., Ekdale et al., 1984).

While these complex channel deposits are interpreted as the product of tidally-influenced rivers, they almost certainly do not reflect the result of daily tidal processes or even spring-neap cycles. Rather, we interpret these channels to reflect the interaction of tidal processes, channel and valley morphology, variations in seasonal runoff conditions and development of turbidity maxima within the fluvial system (Shanley et al., 1990-in review). Rahmanni (1988) came to similar conclusions for heterolithic channel-fill deposits in Upper Cretaceous strata in Alberta, and Allen (George Allen, personal communication 1990), and Gelfenbaum (1983) reported similar observations and interpretations from Holocene studies along the Gironde River in France and the Columbia River, in Washington, respectively.

Interbedded siltstone-sandstone facies

Description

Strata comprising this facies association are the principal component of the Smoky Hollow Member and the John Henry Member of the Straight Cliffs Formation throughout the western and west-central portions of the Kaiparowits Plateau (Fig. 3). Cumulative thickness is approximately 150 m. Because of the fine-grained nature of this facies association, exposures are generally poor and the geometric relationships between the various fine-grained lithologies that comprise this facies association are difficult to evaluate. These strata are best exposed where they interfinger with the upper part of the amalgamated sandstone facies. Interbedded siltstones and sandstones have gradational contacts with the upper part of the amalgamated sandstone facies association, and an erosional relationship with sandstones of the isolated sandstone facies association.

This facies association is primarily composed of siltstones, interbedded very fine-grained sandstones and siltstones, and thin, laterally discontinuous very fine-grained sandstones; claystones and thin coals, although present, are rare. The siltstones and interbedded very fine-grained sandstones contain scattered carbonaceous material, have well developed root traces, contain slickensides, and scattered plant material. Several siltstone beds have a fractured texture and contain purple-colored siderite concretions. Rooted siltstones and fine-siltstones varying from 0.5 m to 4 m in thickness are interbedded throughout this facies association. The thin, very fine-grained sandstones that occur throughout this interval have sharp bases, are ripple laminated, and grade into mottled and massive sandstone in the uppermost 0.1 to 0.6 m. These sandstones vary in thickness from 0.2 m to 1.2 m. Sandstones that are less than 0.2 m thick contain massive and mottled bedding textures. Claystones in this facies association are up to 3.7 m thick and contain no discernable sedimentary structures. The coals in this facies are less than 0.1 m thick and are laterally discontinuous.

Interpretation

These strata are interpreted as fine-grained floodbasin deposits that accumulated on broad alluvial plains predominantly during periods of overbank sedimentation. These strata were deposited from suspension following floods. Discontinuous thin, fining upward sandstones capped with mottled and massive sandstones are interpreted as the distal portions of crevasse splays that have subsequently become vegetated and root penetrated. Thin claystone intervals with little or no comminuted plant material are interpreted as local lacustrine deposits that were scattered on the alluvial floodplain. The large volume of clastic overbank sedimentation from adjacent rivers likely prevented organic rich peat deposits from forming (McCabe, 1984). Soil horizons were locally well developed as indicated by the abundant root traces, sideritic nodules, and concretions within some of the siltstone intervals. The quality of the exposures, however, has prevented a detailed correlation of these soil horizons.

FLUVIAL ARCHITECTURE AND SEQUENCE STRATIGRAPHY

Introduction

The geometric arrangement of the facies associations provides the basis for developing a sequence-stratigraphic model for alluvial strata. We are fortunate in the Kaiparowits Plateau in that the geometry of alluvial strata can be compared with coeval coal-bearing strata in the central and eastern part of the plateau, as well as coeval nearshore strata that are exposed along the eastern margin of the plateau (Fig. 2, 3). Such comparisons place needed constraints on our models of alluvial sedimentation and offers insights into how significant stratal surfaces in the shallow marine are expressed in alluvial strata. Shanley and McCabe (1990b-in review) described how sequence boundaries, maximum flooding surfaces in marine strata, parasequence-stacking patterns of nearshore strata, and relative thicknesses of strata along the Straight Cliffs escarpment can be correlated to the southwestern part of the Kaiparowits Plateau. Prominent sequence boundaries related to the Drip Tank Member and the Calico bed can be visually traced across the entire plateau. Within this framework, Shanley and McCabe (1990b-in review) recognized progradational and aggradational shoreface parasequence sets (terminology from Van Wagoner, 1985) punctuated by additional sequence-boundary unconformities. In addition, upward-deepening successions that record a transition from alluvial to offshore and condensed section deposits were described in the Smoky Hollow and lower part of the John Henry Members along the Straight Cliffs escarpment (Shanley and McCabe, 1990b-in review; Shanley et al., 1990-in review). These criteria combined with detailed facies analysis allowed recognition of five unconformity-bounded sequences and their associated systems tracts in nearshore strata and the construction of a base-level curve for Turonian through Campanian strata along the northeastern margin of the plateau (Shanley and McCabe, 1990b-in review). Application of these concepts in alluvial strata in the central and southwestern plateau, within the framework provided by visually-correlatable surfaces, is the subject of the remainder of this paper.

Sequence boundaries in alluvial strata

Recognition of sequence boundaries in alluvial strata is difficult because basinward shifts in facies tracts and related incision can be difficult to distinguish from more localized channel scour. Both the Calico and Drip Tank sequence boundaries are associated with major basinward shifts in facies tracts, can be traced throughout the plateau, and are recognized in adjacent outcrop belts (Fig. 3) (Shanley and McCabe, 1990b-in review). These basinward shifts are interpreted on the basis of an abrupt contrast in facies tracts above and below the sequence boundary as well as a change in the degree of fluvial sandstone amalgamation. It is emphasized that these changes are observed not only in vertical section, but can also be traced along the outcrop belt. Coarse-grained and pebbly, laterally amalgamated fluvial deposits (Figs. 5 & 9) directly overlie finer-grained fluvial and alluvial-plain strata, carbonaceous shales, and to the east, shoreface strata. The regional extent of these erosional surfaces coupled with the lack of coarse-grained sandstone and pebble-conglomerates in underlying channel and overbank strata suggest these coarse, bedload rivers are not coeval with underlying deposits. In addition to the abrupt change in facies development across the sequence boundary unconformities, there is a concomitant change in fluvial architecture. Alluvial deposits that underlie both the Calico and Drip Tank sequence boundary unconformites are multistorey sandbodies that contain complete fining-upward units in the uppermost storey (i.e. Fig. 13). These strata belong to the isolated channel-sandstone facies and the fine-grained floodbasin facies associations. The abrupt change from isolated meanderbelt sandstones and fine-grained alluvial plain strata to amalgamated, coarse-grained and pebbly deposits of the Calico bed and Drip Tank Member in which preservation of fining-upward storeys is incomplete signifies a change in the rate of fluvial aggradation and/or a change in accommodation potential (after Bridge and Leeder, 1979). Abrupt changes in composition and degree of amalgamation (or fluvial stacking pattern) across erosional surfaces that have regional extent suggest a pronounced change in hydraulic character as well as rates of alluvial aggradation and together support the interpretation of sequence-boundary unconformities.

A sequence boundary unconformity has also been identified at the base of the medium to fine-grained amalgamated-sandstone facies (Shanley and McCabe, 1990b-in review) near the base of the John Henry Member of the Straight Cliffs Formation (Fig. 3). Criteria that allow identification of this sequence boundary, however, are significantly more subtle than those used for the Calico and Drip Tank sequence boundaries. To the east, along the Straight Cliffs, fluvial and tidally-influenced fluvial strata overlie a sequence boundary (A-sequence boundary) that truncates shoreface parasequences and which has been identified as an incised valley (Hettinger et al., 1990) (Fig. 3). The incised valley fill is overlain by a widespread marine-flooding surface (Hettinger et al., 1990; Shanley and McCabe, 1990b-in review). The A-sequence boundary itself, is slightly younger than a maximum flooding surface observed in somewhat older marine strata (Shanley and McCabe, 1990b-in review). Within the alluvial-dominated portion of the western and southwestern plateau, amalgamated fluvial sandstones erosionally overlie tidally-influenced fluvial strata that are coeval with this maximum marine flooding surface (Shanley et al., 1990), and fine-grained alluvial-plain strata containing well developed paleosols. Lateral relationships indicate these amalgamated sandstones comprise a broad, incised valley, portions of which can be traced from Rock House Cove to Blue Cove (Fig. 2). Although there is a significant change in alluvial stacking patterns from isolated meanderbelt and tidally-influenced fluvial deposits below the A-sequence boundary to coarser-grained, amalgamated sandstones above, the degree of facies tract dislocation is not as severe as with the Calico bed and Drip Tank Member. It is the change in fluvial amalgamation over a broad area that signifies an abrupt change in aggradation rate and accommodation space and serves to identify the sequence boundary.

Figure 3 illustrates a sequence boundary within the Tibbet Canyon Member of the Straight Cliffs Formation. Because this unconformity erodes into marine strata and juxtaposes channel deposits on offshore and shoreface strata, we do not emphasize this surface in a discussion of alluvial deposits. Descriptions of this unconformity are contained in Shanley and McCabe (1990b-in review).

Valley fill and alluvial-transgressive deposits

Laterally amalgamated, fluvial sheet-sand deposits with a high relative proportion of interconnected, coarser-grained channel-fill sandstone (referred to as high net/gross reservoir sandstone) are characteristic of three distinct stratigraphic levels in the Kaiparowits Plateau. These are the Calico bed, the amalgamated sandstone complex (A-sandstone) in the lower part of the John Henry Member of the Straight Cliffs Formation, and the basal portion of the Drip Tank Member of the Straight Cliffs Formation (Fig. 3). These three sandstone intervals overlie previously described sequence boundaries that have been traced throughout the plateau (Shanley and McCabe, 1990b-in review).

Throughout the western and southern margins of the plateau, amalgamated sandstones of the Calico bed and A-sandstone grade vertically into isolated channel deposits that are interbedded with fine-grained alluvial plain strata, and heterolithic, tidally influenced channel fill deposits. Because this research did not study the entire Drip Tank Member, we are not able to comment on the facies transitions very much above the Drip Tank sequence boundary. The transition from coarse-grained, pebbly deposits of the Calico bed to tidally-influenced heterolithic river deposits suggests a vertical progression from low-sinuosity, coarser-grained river deposits to more sinuous, fine-grained channel fill sandstones deposited within tidally influenced rivers. This "upward-deepening" facies succession reflects coastal transgression, and maximum marine incursion into alluvial environments (Shanley et al., 1990-in review). These alluvial strata are correlated with retrogradational shoreface parasequences, such as those at the top of the Ferron Sandstone Member of the Mancos Shale, that pass upward to a widespread condensed section deposit within the Mancos Shale (Shanley and McCabe, 1990b-in review) (Fig. 3). Tidally-influenced fluvial deposits, therefore, are temporally equivalent with the maximum flooding surface in marine strata that is represented by a condensed section that can be traced throughout the eastern margin of the plateau (Shanley and McCabe, 1990b-in review; Shanley et al., 1990-in review).

A similar set of upward-deepening fluvial deposits occur in association with the A-sandstone. Sinuous river deposits that have a high degree of lateral amalgamation grade upward into more isolated channel sandstones and finally into tidally-influenced heterolithic strata. This succession is interpreted to reflect filling of the incised valley associated with the A sequence boundary, coastal transgression and maximum marine flooding into alluvial depositional environments (Fig. 3). Tidally-influenced fluvial deposits that cap the A sandstone in the western and southwestern plateau, therefore, are coeval with development of maximum marine flooding surface to the east (Shanley and McCabe, 1990b-in review; Shanley et al.,1990-in review).

Readers will note that the fluvial deposits immediately overlying sequence boundaries in the Kaiparowits Plateau comprise an alluvial transgressive systems tract and that there are no lowstand deposits. The reasons for this are more a matter of nomenclature than one of depositional processes. Posamentier and Vail (1988), Posamentier et al. (1988) and Van Wagoner et al.(1990) suggest that the term transgressive systems tract be restricted to strata that are bounded by the maximum marine flooding surface above, and the first major marine-flooding surface (or transgressive surface) below. Lowstand deposits, on the other hand, are located below the transgressive surface. Within the western and southwestern part of the Kaiparowits Plateau, there are no marine strata intercalated with fluvial strata. This suggests that any lowstand-fluvial deposits, as defined above, are located to the east of the Kaiparowits Plateau and that the fluvial deposits in the plateau belong to the transgressive systems tract.

Highstand deposits

Tidally-influenced fluvial strata associated with transgression over the Tibbet Canyon, Calico, and A-sequence boundary are overlain by fine-grained floodbasin strata, isolated fluvial sandstones, and thin, discontinuous coals and carbonaceous shales. In the case of the strata overlying the A-sandstone complex, these deposits account for the vast majority of strata exposed in the John Henry Member of the Straight Cliffs Formation (Fig. 3). This thick succession of isolated channels and overbank siltstones and sandstones have been physically correlated into the central portion of the plateau where they interfinger with thick crevasse-splay deposits and thick, laterally continuous coal seams. The coal measures have been physically traced into thick, aggradational nearshore deposits along the Straight Cliffs escarpment (Shanley and McCabe, 1990b-in review). This architectural style of aggradational shoreface parasequences, isolated fluvial channel belts, and thick fine-grained overbank deposits is interpreted to reflect increased rates of accommodation that are balanced by rates of deposition. Our work in shoreface strata along the eastern margin of the plateau suggests that additional high frequency sequence boundaries may be present within these strata, however, we have yet to recognize these stratal surfaces within the alluvial deposits (Shanley and McCabe, 1990b-in review).

CONTROLS ON FLUVIAL STACKING PATTERNS

Background

The emphasis on geometric arrangement through geologic time, has advanced alluvial-architecture studies beyond facies studies (Walker, 1990). Efforts to describe alluvial architecture have proceeded along two somewhat parallel fronts -- those based on modeling of fluvial systems, either numerical or purely conceptual models, and those based on outcrop observations. Some of the earliest models for fluvial architecture were those of Allen (1965) who portrayed the three-dimensional architecture of alluvial strata through time in a number of different geologic settings through the use of block diagrams.

Although these models did not attempt to portray the effects of any particular allocyclic or autocyclic variable, they clearly illustrate how changes in fluvial stacking might occur. More rigorously constrained numerical models (e.g.,Allen, 1978, 1979; Leeder, 1978; Bridge and Leeder, 1979; Alexander and Leeder, 1987) allow the changes in alluvial architecture to be studied as specific variables are adjusted. Numerical models such as these share a common theme by emphasizing the role of tectonic subsidence in creating accommodation space for alluvial sedimentation. By changing rates of subsidence, avulsion, and aggradation, varying degrees of sandstone amalgamation and sand-body interconnectedness can be mathematically created. Although these early models were not tested against outcrop-based data sets, they are of paramount importance in our understanding of alluvial architecture because they demonstrate the sensitivity of alluvial sequences to changes in accommodation space. These models suggest that the degree of channel-sandstone amalgamation and interconnectedness vary inversely with respect to the rate at which accommodation space is created. This rather simple relationship is critical in relating fluvial architecture with sequence stratigraphy.

Lawrence et al. (1990) and Ross (1990) incorporated the relationship between alluvial architecture and subsidence rates predicted by Bridge and Leeder (1979) into their basin-scale stratigraphic models. As a result, these models predict specific architectural relationhips between alluvial and shoreface strata. These larger scale, stratigraphic models differ from previous models in their concern with changes in accommodation space due to changes in base level. The importance of accommodation space and base-level changes in studies of stratigraphic architecture has recently been re-emphasized (e.g.,Jervey, 1988; Posamentier et al., 1988; and Posamentier and Vail, 1988) and underpins sequence-stratigraphic concepts. In the context of sequence-stratigraphic studies, base level can be thought of as an"...equilibrium surface ... above which a particle can not come to rest and below which deposition and burial are possible" (Sloss, 1962, p. 1051). In more familiar terms, base level can be approximated by the concept of a graded fluvial profile in alluvial settings, sea level in nearshore regions, and the concept of a graded shelf in shallow-marine environments (Mackin, 1948; Swift, 1970). Placing stratigraphic models in terms of base-level change and accommodation space allows models to be applied in a variety of geologic settings regardless of whether the available space was created by tectonic subsidence, eustatic change, or some combination of the two (the most likely case!). Field verification of such models, however, requires outcrops that contain a sufficiently broad spectrum of facies tracts so that significant stratal surfaces can be traced between facies tracts and so that stacking patterns can be analyzed in these different facies tracts; the Kaiparowits Plateau presents this opportunity (Fig. 3).

Previous outcrop studies that seek to understand changes in sandstone amalgamation and alluvial architecture have invoked changes in base level, climate, subsidence, and sea level as well as changes in avulsion rates and other autocyclic processes (Table 1). Of these mechanisms, there is a preponderance of papers in which authors suggest changes in tectonic subsidence as the driving mechanism for changes in alluvial architecture. Close examination of many of these models, however, indicates that they often require dramatic changes in subsidence rate over short time periods to produce the observed stratal succession. The inability of many of these previous studies, however, to trace regionally significant stratal surface such as sequence boundaries and maximum flooding surfaces between alluvial and marine strata limit their use in evaluating changes in fluvial architecture due to changes in base level within the context of sequence stratigraphy.

Table 1. Outcrop studies of alluvial strata have invoked changes in base level, climate, lake level, and subsidence to account for changes in sandstone amalgamation and interconnectedness. Of these mechanisms, most authors favor changes in subsidence to account for the observed changes in architecture.

Table 1

Age and lithologic unit	Location	Author
<u>Subsidence controlled architecture</u>		
Holocene - alluvial fans	Death Valley, California, U. S. A.	Butler, 1984
Pliocene - Glenns Ferry Fm.	Idaho, U. S. A.	Kraus and Middleton, 1987
Oligocene - fluvial strata	Jaca Basin, Spanish Pyrenees	Turner, 1989
Late Cretaceous to Eocene - Chuckanut Fm.	Washington, U. S. A.	Johnson, 1984
Eocene - Capella Fm.	Tremp/Frauss Basin, Spanish Pyrenees	Atkinson, 1986
Paleocene and Eocene - Willwood Fm.	Wyoming, U. S. A.	Kraus and Middleton, 1987
Eocene - Castissent Sandstone	Tremp/Grauss Basin, Spanish Pyrenees	Marzo et al., 1988
Latest Cretaceous/Tertiary fluvial strata	Tremp/Ager Basin, Spanish Pyrenees	Puigdefabregas et et al., 1989
Campanian - lenticular sst. and shale	Green River Basin, Wyoming, U. S. A.	Schuster and Steidtmann, 1987
Aptian/Albian - Eumerala Fm.	Otway Basin, Australia	Felton, 1989
Aptian/Albian - Cloverly Fm.	Wyoming, U. S. A.	Meyers et al., 1989
Triassic - Otter Sandstone	Devon, England	Clarey and Tunbridge, 1989
Triassic - Chinle Fm.	Colorado Plateau, U. S. A.	Blakey and Gubitosa,1984
Frasnian - Catskill delta complex	New York, U. S. A.	Gordon and Bridge, 1987
Late Devonian - fluvial strata	Munster Basin, Ireland	Graham et al., 1989

Table 1-cont.

Sea-level, lake-level, and base-level controlled architecture		
Miocene - fluvial strata	Ridge Basin, California U. S. A.	Link, 1984
Jurassic - Scalby Fm.	Yorkshire, England	Nami and Leeder, 1978
Triassic - Ivishak Formation	Prudhoe Bay, north slope Alaska, U. S. A.	Atkinson et al. 1988
Devonian - Catskill delta complex	New York, U. S. A.	McCave, 1969
Climate controlled architecture		
Cenozoic - fluvial strata	South Africa	de Wit, 1989
Famennian - Kap Graah Group	eastern Greenland	Olsen, 1990

In a series of conceptual models, Posamentier (1988), Posamentier et al. (1988) and Posamentier and Vail (1988), suggested the timing of fluvial aggradation within the context of depositional sequences. These models incorporated concepts such as the equilibrium point (position on a depositional profile where the rate of eustatic change is equal to the rate of tectonic subsidence), the bayline (line containing points to which stream profiles are adjusted -- under certain circumstances may be equivalent to the shoreline), and stream equilibrium profiles. Although Posamentier et al. (1988) and Posamentier and Vail (1988) express their results in terms of eustasy, careful consideration of their variables allows the reader to view these same models in terms of base-level change. These models indicate that significant fluvial aggradation requires seaward migration of the bayline during a slow base-level rise. Furthermore, Posamentier et al. (1988) and Posamentier and Vail (1988) suggest that the rate at which alluvial accommodation space is created controls the degree of amalgamation and fluvial sandstone interconnectedness. Within late-highstand systems tract deposits, fluvial strata are thought to be laterally continuous whereas early-highstand systems tract deposits are more likely to be characterized by isolated channel deposits.

Insights into the timing of alluvial aggradation and the response of fluvial systems to base-level change can also be acquired by examining dam-engineering and reservoir siltation projects (e.g.,Eakin, 1936; Stevens, 1936, 1946; Strand, 1968; Lara and Sanders, 1970; Lara 1972, 1983; Condit et al., 1978; Ferrari, 1988; Lyons and Randle, 1988; Posamentier and Vail 1988; Orvis, 1989). Similar to the results proposed by Posamentier et al., (1988) and Posamentier and Vail (1988), these studies indicate that during rapid base-level rise, significant fluvial aggradation does not occur until the rate of rise decreases allowing fluvial systems to readjust to grade as the stream profile is translated in a basinward direction. Under conditions of more slowly rising base level, however, fluvial aggradation may occur depending on rates of sedimentation verus rates of base-level rise (Shanley et al., 1990-in review).

A model from the Kaiparowits Plateau

Alluvial strata in the Kaiparowits Plateau are characterized by regionally extensive sequence boundaries that are overlain by fluvial deposits that grade from laterally-amalgamated to more isolated channel deposits and heterolithic or tidally-influenced strata. When incorporated into the sequence-stratigraphic model developed for the Kaiparowits Plateau (Shanley and McCabe, 1990b-in review) a synergistic model emerges within which variations in fluvial architecture may be better understood.

Sequence boundary unconformities form as surfaces of sediment bypass during a time of base-level lowering. This has the effect of increasing fluvial gradients and causing headward erosion as far as the first nickpoint (Schumm et al., 1987; Butcher, 1990). Recent flume studies further suggest that incision resulting from base-level lowering results in increased sediment supply as drainage basins are progressively expanded (Schumm, 1977; Schumm et al.,1987; Koss et al., 1990). As a result of these increases in both fluvial gradients and sediment supply, sediment may bypass the alluvial realm and be redistributed in a more basinward position. In a chronostratigraphic sense, there is little sedimentation during the base-level lowering and the sequence boundary represents a time of erosion and sediment bypass. Although minor sediment aggradation may occur during a base-level fall, its preservation potential is thought to be somewhat limited; where these deposits are preserved, it is in the form of river-terrace deposits (Leopold et al., 1964). The result of sediment bypass is an abrupt facies tract dislocation across the sequence boundary. The severity of the facies dislocation may be used as a proxy for estimating the magnitude of base-level change in a qualitative fashion (i.e. braided-river deposits incised into marine shales might suggest a greater base-level change than if they were incised into meandering-river deposits). In the Kaiparowits Plateau, for example, we have interpreted three sequence boundaries within the alluvial succession of strata. The most dramatic facies dislocations are those associated with the Calico bed and the Drip Tank Member of the Straight Cliffs Formation. We refer to these two sequence boundaries as third-order boundaries and have correlated them to major base-level shifts suggested by Haq et al. (1988) (Shanley and McCabe, 1990b-in review). The sequence boundary associated with the A-sandstone has a less dramatic facies tract dislocation and is referred to as a fourth-order boundary. We have also correlated this sequence boundary to base-level shifts suggested by Haq et al. (1988).

Following a base-level lowering, significant fluvial aggradation initially takes place near the river mouth and progressively onlaps in a landward direction. Fluvial sedimentation during the base-level rise propagates in an upstream direction, dependant on the rate at which base-level rises and sediment supply. Our research suggests that significant fluvial sedimentation, requires equilibrium profiles to translate in a basinward direction similar to the models developed by Posamentier et al. (1988) and Posamentier and Vail (1988). We interpret alluvial strata in the Kaiparowits Plateau to have been deposited during a rise in base level; the degree of sandstone amalgamation and interconnectedness is interpreted to reflect changes in the overall rate of base-level rise.

Sequence boundaries in the Kaiparowits Plateau represent periods of widespread erosion and the development of broad incised valleys. During the initial phases of alluvial aggradation, while the rate of base-level rise was relatively low, rivers were confined to the lower portions of valleys and cannibalized much of their coeval flood plain strata resulting in amalgamated channel sandstones such as the Calico bed, A-sandstone, and lower part of the Drip Tank Member. Progressive infilling of incised valleys combined with increased rates of base-level rise (increased rate of base-level rise also enhanced by reduced topographic gradients) result in increased accommodation space. These effects, combined with a decrease in sediment supply, result in tidally-influenced fluvial deposits, an increasing proportion of preserved fine-grained floodplain strata and more isolated channel sandstone typical of the upper part of the John Henry Member of the Straight Cliffs Formation (Fig. 3).

The point of maximum marine transgression at the coastline is marked within alluvial strata by the most landward extent of tidally-influenced rivers. Within drowned river valleys tidal processes combine with fluvial processes to produce a complex, heterolithic facies assemblage (Shanley et al., 1990-in review). Tidally-influenced river deposits are, therefore, temporally equivalent with maximum flooding surfaces in marine strata (Shanley et al., 1990-in review). Alluvial strata bounded by an underlying sequence boundary and the top of the tidally-influenced deposits are placed in a trangressive systems tract.

With increased rates of base-level rise that are matched by sediment influx, or which slightly exceed sediment supply (Schumm et al., 1987), alluvial channels become increasingly isolated with an increasing proportion of preserved fine-grained sediment. These strata comprise the alluvial portion of the highstand systems tract and correspond with a period of shoreface aggradation.

DISCUSSION

The ability to predict fluvial architecture has important economic implications. Exploration and development of petroleum reservoirs, groundwater aquifers, and sediment hosted mineral deposits is greatly aided by an understanding of the controls on alluvial architecture. Previous models, invoked to explain changes in alluvial architecture, commonly resorted to facies changes that were interpreted to reflect abrupt changes in factors such as tectonic subsidence and sediment supply. As a result of this approach, lithofacies within alluvial successions are interpreted to broadly follow Walther's Law, and regionally extensive, time-significant unconformities are not recognized (Warme and May, 1990). Our work in the Kaiparowits Plateau, however, suggests that regionally extensive, time-significant sequence-boundary unconformities can be recognized in alluvial strata and that sediment architecture may be predicted. Furthermore, we suggest that these models can be successfully applied to subsurface studies where data consist of widespread cores and well-logs. Studies of many petroleum reservoirs, hosted in fluvial deposits, reveal that they are frequently composed of alternating amalgamated, persistent channel sandstones with a relatively high net /gross reservoir sandstone value, and more isolated, poorly connected, laterally discontinuous sandstones with a low net /gross sandstone value (e.g. Johnson and Krol, 1984; Ravenne et al., 1987; Atkinson et al., 1988; 1990; Ravenne and Beucher, 1988; Brown and Richards, 1989; Helland-Hansen et al., 1989; Livera, 1989; Miller et al., 1990; McPherson and Miller, 1990). We suggest that sequence boundary unconformities may underlie the laterally amalgamated sandstones and that these sequence boundaries correspond to a basinward shift in depositional environments that might be better observed in a nearshore position. The amalgamated sandstones themselves, likely comprise the lower and middle portion of a transgressive systems tract. The more isolated channel sandstones likely correspond to late transgressive and highstand systems tracts that are correlated to retrogradational and aggradational shoreface parasequences. Recognition of the sequence stratigraphic framework within an alluvial succession allows alluvial sandstone architecture to be predicted from somewhat limited data sets. These concepts are most readily applied to petroleum reservoir exploration where an appreciation of alluvial architecture allows for more efficient reservoir planning and management (e.g.,Budding, 1988). In the later stages of reservoir life, for example, an improved understanding of alluvial architecture can greatly improve the construction of detailed reservoir models allowing for more successful secondary and tertiary recovery methods (Weber, 1986; Weber and van Geuns, 1990).

CONCLUSIONS

1. Extensive, laterally amalgamated fluvial deposits overlie regionally significant sequence boundary unconformities. These sequence boundaries can be traced into shoreface strata and correspond to a basinward shift in depositional environments.
2. Amalgamated fluvial sandstones reflect aggradation during slowly rising base level and correspond to early transgressive systems tract deposits. The transition from amalgamated deposits to more fine-grained isolated ones with an increasing proportion of preserved fine-grained strata and finally tidally-influenced strata correspond to coastal transgression and the development of a maximum flooding surface. Together, these deposits comprise the transgressive systems tract.

3. Thick sequences of isolated channel-belt sandstones and abundant fine-grained floodbasin strata are equivalent to aggradational shoreface strata and comprise the early highstand systems tract.
4. Correlation of individual nearshore parasequences into thick alluvial deposits that are several kilometers inland of a coeval shoreline is not presently possible. Correlation of parasequence-sets (terminology from Van Wagoner et al., 1990), or systems tracts, however, is possible from nearshore strata to a position as much as 80 km inland of a coeval shoreline within an entirely alluvial succession.
5. The architecture of alluvial strata within a depositional sequence is largely controlled by changes in base level and accommodation space. This strongly suggests that detailed, quantitative studies of alluvial architecture should be placed within a sequence-stratigraphic framework if they are to be of maximum utility. Failure to do so, may reduce the effectiveness with which these studies can be applied to areas outside of where the study was conducted.
6. Consideration of fluvial architecture in terms of base level and changes in accommodation space allows these models to be applied to a variety tectonic settings throughout geologic time.

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Sequence stratigraphic relationships and facies architecture of Turonian-Campanian strata, Kaiparowits Plateau, south-central Utah

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by

Keith W. Shanley

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Chapter 6

RECOGNITION OF TIDAL INFLUENCE IN FLUVIAL DEPOSITS-A KEY ELEMENT IN HIGH RESOLUTION SEQUENCE STRATIGRAPHY: AN EXAMPLE FROM THE MID-CRETACEOUS OF SOUTHERN UTAH, U. S. A.

ABSTRACT

Detailed models already exist that outline physical and temporal relationships in marine and marginal-marine strata. Such models are still in their infancy in alluvial deposits. Recognition of tidal and estuarine influence in fluvial strata is critical to the development of high resolution sequence-stratigraphic correlations between marine and nonmarine strata. Strata that have previously been interpreted as low-energy meandering river deposits contain a variety of sedimentary and biogenic structures that suggest a tidal influence. These structures include sigmoidal bedding, double-mud/silt drapes, wavy and lenticular bedding, shrinkage cracks, multiple reactivation surfaces, inclined heterolithic strata, complex-compound cross beds, bidirectional cross beds, and a variety of trace fossils including *Teredolites, Arenicolites*. and *Skolithos*. Although any one of these structures is not unique to tidal processes, the preponderance of data suggests that fluvial systems have been affected by tidal processes well inland of coeval shoreline deposits. These deposits rarely form a significant proportion of a depositional sequence, however, their occurrence allows time-significant surfaces to be extended for tens or even hundreds of kilometers inland from coeval shoreline deposits.

In Turonian through Campanian strata exposed in the Kaiparowits Plateau of southern Utah, tidally-influenced facies are recognized within at least two distinct

stratigraphic levels that were deposited during periods of relatively rapid base-level rise. These strata form part of an alluvial transgressive systems tracts. Landward of each of the marine transgressive maxima, tidal facies are present in fluvial channels that are completely encased in nonmarine strata at distances up to 65 km inland from a coeval paleoshoreline. Our work suggests that these deposits may have gone unrecognized in the past, yet they form a significant component of alluvial strata in many depositional sequences. Although these tidally-influenced fluvial deposits may be difficult to recognize, they are temporally equivalent to marine-maximum flooding surfaces and provide a chronostratigraphic correlation between alluvial and nearshore marine deposits.

INTRODUCTION

Chronostratigraphic correlation between marine and alluvial strata in subsurface sections or discontinuous outcrop is particularily difficult. The lack of fossils that span both sedimentary environments and the poor preservation potential of iso-chronous deposits such as ash beds conspire against the sedimentologist trying to relate alluvial plain sedimentation with coeval marine deposits. In an innovative paper, however, McCave (1969) suggested that a causal connection should exist between alluvial aggradation and sea-level rise. He further suggested that sedimentologic changes in nonmarine strata caused by changes in the marine realm provide a basis for chronostratigraphic correlation. These ideas (McCave, 1969) were not accorded widespread acceptance and lay dormant for many years. The rediscovery of sequence stratigraphic concepts (e.g., Vail et al. 1977; Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al. 1990) and an understanding of base-level control on stratal patterns (e.g., Jervey, 1988) provide a unifying framework for the analysis of depositional facies and suggest that McCave's ideas bear consideration. Recognition of depositional systems tracts (e.g., Vail et al., 1977; Posamentier et al., 1988) within unconformity-bounded sequences suggests the position of depositional facies may be predicted with respect to sequence boundaries and maximum-flooding surfaces. Facies tracts, therefore, are selectively partitioned within a depositional sequence and may be used to extend chronostratigraphic correlations between alluvial and nearshore deposits.

Sequence-stratigraphic models developed in nearshore strata are quite sophisticated and can be used to develop chronostratigraphic correlations that far exceed the resolution of existing radiometric or biostratigraphic methods. Similar models, however, are still in their infancy in alluvial strata and considerable debate exists concerning the expression of maximum flooding surfaces and sequence boundaries within alluvial strata (e.g., Posamentier and Vail, 1988; Shanley and McCabe, 1990b-in review) . Our research in the Kaiparowits Plateau of southern Utah indicates that tidally-influenced river deposits are a key element in high resolution, sequence stratigraphic correlation. Although these deposits are commonly fine-grained or heterolithic and may not form economic reservoirs for oil, gas or water, their recognition is of paramount importance in terms of accurate chronostratigraphy. These deposits provide the basis for detailed correlations between marine and coeval alluvial deposits as much as 60 km inland of contemporaneous shoreface strata. In this paper we describe variations in alluvial strata along depositional dip that may be used to recognize tidally-influenced deposits in other stratal successions. Comparisons are offered between these Cretaceous strata in the Kaiparowits Plateau and more fully understood Holocene examples.

THE MIDDLE CRETACEOUS OF THE KAIPAROWITS PLATEAU

The Kaiparowits Plateau covers some 3600 km^2 in the southwestern part of the Colorado Plateau structural and physiographic province (Fig. 1). The structural configuration of the Kaiparowits plateau itself is one of gentle, north to northwest trending asymmetrical folds (Peterson, 1969) that plunge slightly to the northwest; structural dip within the plateau is generally less than 3°. While several high angle normal faults cut Cretaceous strata, displacement is minimal and they do not interfere with detailed stratigraphic and sedimentological investigations.

During the mid-Cretaceous, flexural loading of the lithosphere by successive thrust plates and synorogenic sediment derived from the Sevier orogenic belt to the west (e.g., Armstrong, 1968; Jordan, 1981; Cross, 1986) resulted in the development of an active

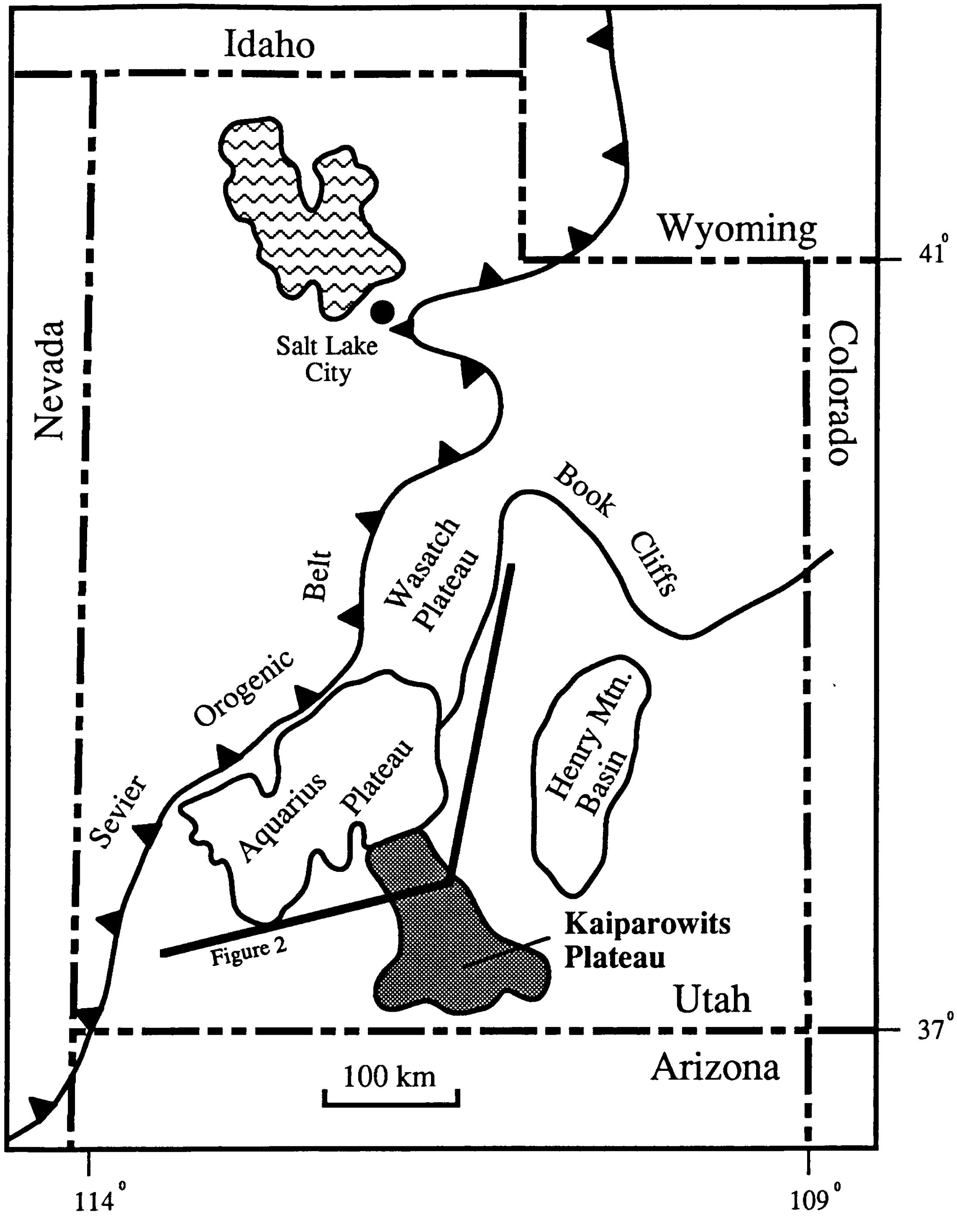
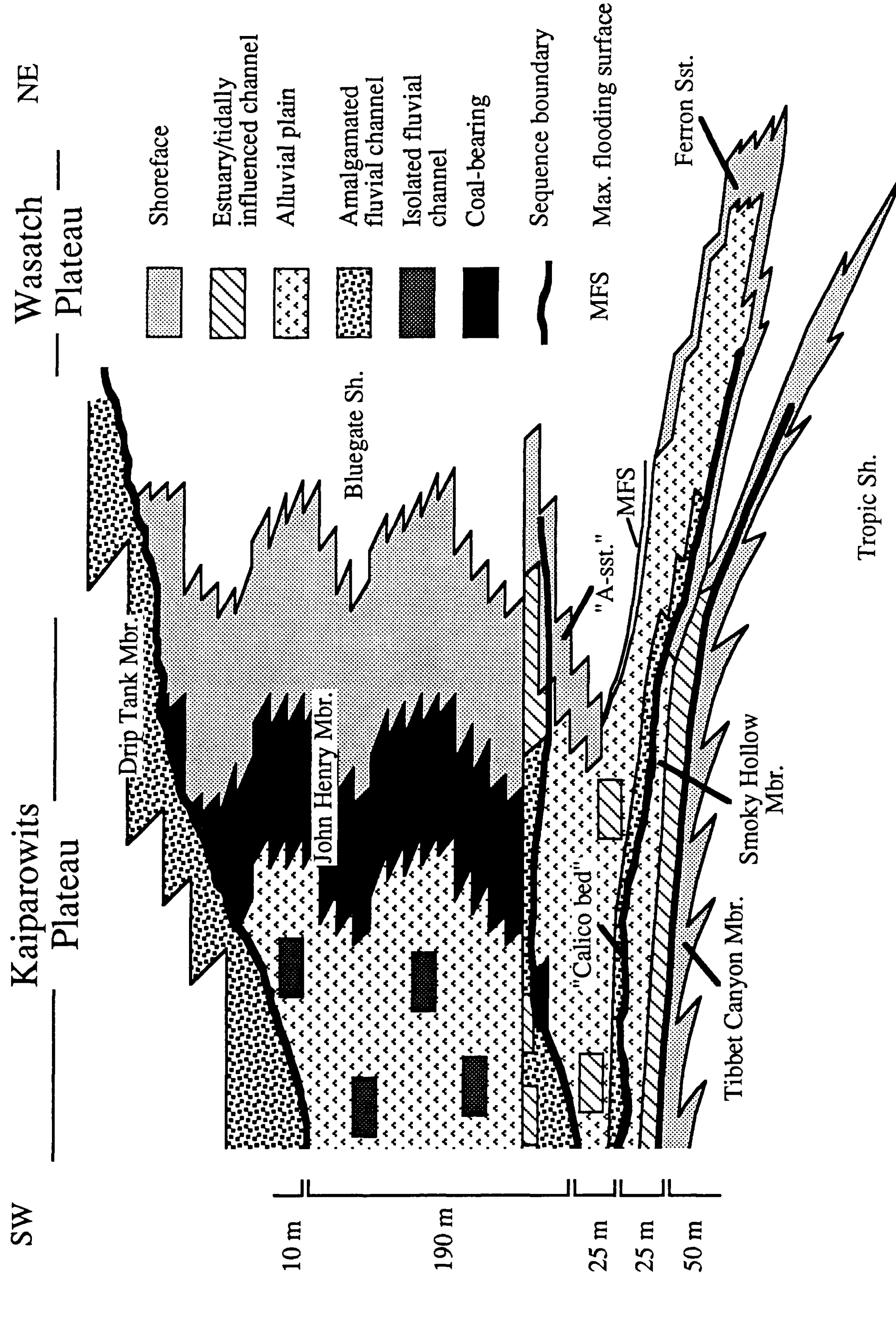


Figure 1. Regional map illustrating the location of the Kaiparowits Plateau within the state of Utah. Also shown are the trend of the leading edge of the Sevier orogenic belt, and locations of the Aquarius Plateau, Wasatch Plateau, Henry Mountains Basin, and the Book Cliffs. The line of section shown is illustrated in Fig. 2.

foreland basin. The Kaiparowits Plateau was located along the western margin of this actively subsiding basin, 120 to 180 km east of the leading edge of the thrust front. Between the early Turonian and Campanian, the foreland basin was inundated by an epicontinental sea. During maximum eustatic highstand, the seaway extended from present-day Arctic Canada to the present Gulf of Mexico, a distance of some 5000 km, and from western Utah to Iowa, a distance of some 1500 km (Williams and Stelck, 1975).

Exposures within the study interval belong to the Straight Cliffs Formation which ranges from Middle Turonian to Campanian in age and from 300-370 m in thickness. Within the Straight Cliffs Formation, we recognize five unconformity-bounded depositional sequences and their associated highstand and transgressive systems tracts (Shanley and McCabe, 1990c-in review) (Fig. 2). These depositional sequences are recognized throughout the plateau, are compatible with existing paleontologic and radiometric data sets, and provide a framework within which variations in facies architecture can be compared to stratal position. This sequence-stratigraphic framework is based on visual correlation of prominent sequence boundaries, changes in the stacking patterns of nearshore, coal-bearing, and alluvial strata, and detailed sedimentological studies, particularly within the alluvial successions (Shanley and McCabe, 1990b-in review, 1990c-in review). The northeastern escarpment of the plateau, known as the Straight Cliffs, provides approximately 80 km of depositional strike oriented exposure, while the southern margin of the plateau provides almost 80 km of depositional dip oriented exposure (Fig. 3). Age determinations of the marine strata are well constrained on the basis of ammonite and inoceramid collections (e.g., Peterson, 1969a, b). Similar assessments of alluvial and coal-bearing strata, however, are poorly constrained and rely on physical stratigraphic relationships (Shanley and McCabe, 1990c-in review). As a

Figure 2. Sequence stratigraphic cross section of Turonian through Lower Campanian strata from the Kaiparowits Plateau (southwest) to the Wasatch Plateau (northeast). The line of section is shown in Figure 1. Sequence boundary unconformities, or their correlative conformities, are shown. These allow the strata to be subdivided into chronostratigraphic units across at least 65 km of depositional dip from alluvial to shoreface deposits. The construction of this figure is outlined in chapter 4.



SW
NE
Kaiparowits Plateau
Wasatch Plateau
10 m
190 m
25 m
25 m
50 m
Shoreface
Estuary/tidally influenced channel
Alluvial plain
Amalgamated fluvial channel
Isolated fluvial channel
Coal-bearing
Sequence boundary
MFS
Max. flooding surface
Drip Tank Mbr.
John Henry Mbr.
Bluegate Sh.
"Calico bed"
"A-sst."
MFS
Smoky Hollow Mbr.
Tibbet Canyon Mbr.
Tropic Sh.
Ferron Sst.

Figure 2

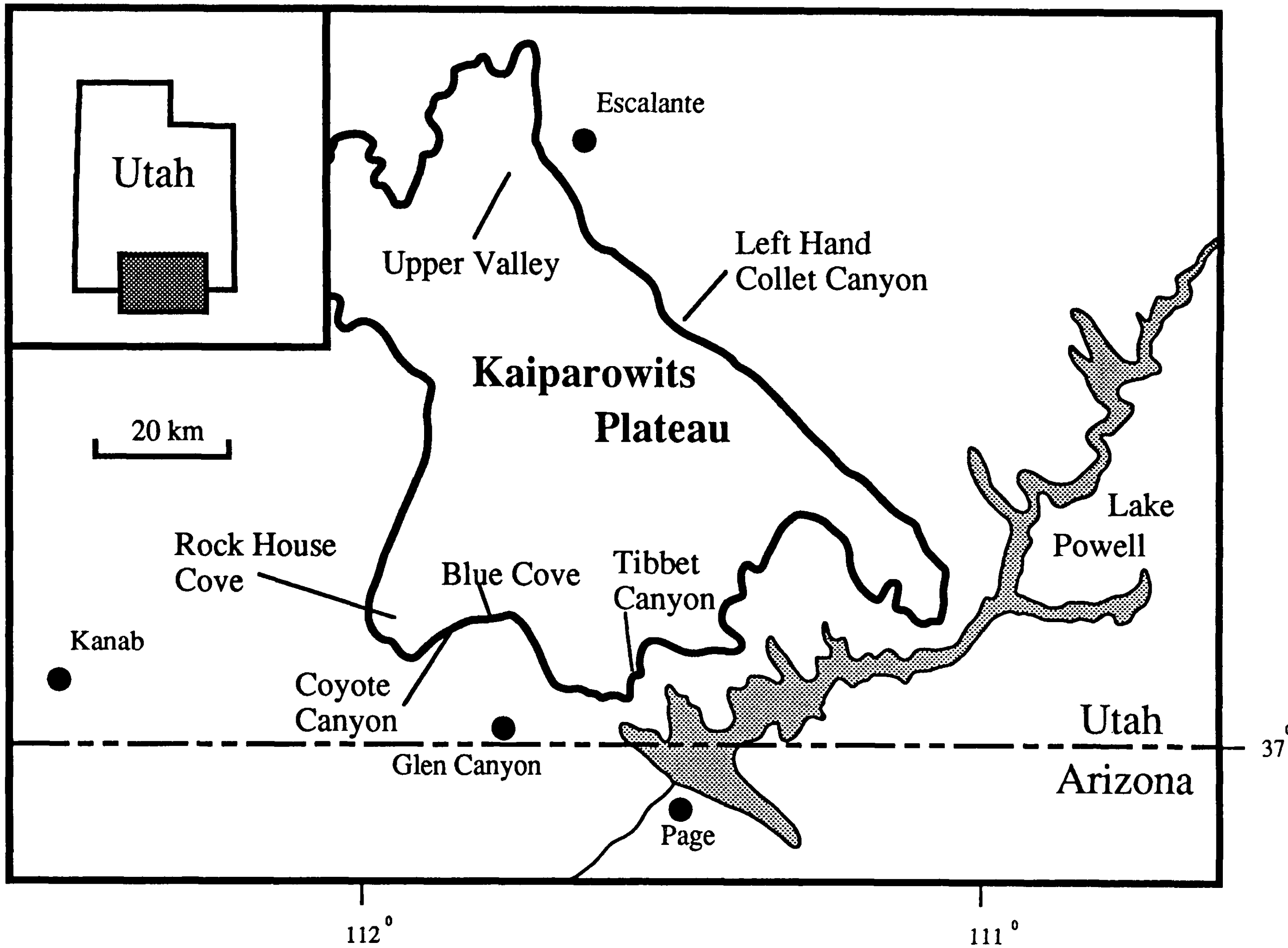


Figure 3. Map showing the locations of Rock House Cove, Blue Cove, Coyote Canyon, Tibbet Canyon, and Left Hand Collet Canyon. In general, tidally influenced alluvial deposits are sandstone dominated in the northeastern part of the plateau and become increasingly fine-grained towards the southwest and western portions of the plateau.

result of the poor age control within the nonmarine strata, our research has relied on stratal relationships defined by sediment stacking patterns, visual correlation of sequence-boundary unconformities, and regional flooding surfaces for chronostratigraphic correlation. The chronostratigraphic significance of such stratal surfaces has been previously discussed (e.g., Vail et al., 1977; Wilgus et al., 1988; Van Wagoner et al., (1990) and will not be repeated here.

This paper focuses on a portion of the fluvial deposits that occur within the upper transgressive systems tracts associated with the Calico and A-sequence boundaries (Shanley and McCabe, 1990b-in review) (Fig. 2). These strata form a relatively minor proportion of the alluvial deposits and occur in channel-form sandstones, 5 - 12 m thick that have erosional bases and fining-upwards successions. Clay clasts, carbonaceous debris, and coarse-grained material often form lag deposits along the base of these channels. The channels are encased in fine-grained strata that is rooted, contains carbonaceous shales, thin claystones that are interpreted as lacustrine deposits and coal seams. Intercalated fine-grained sandstones are generally a few decimeters thick, and contain root traces in the upper few centimeters. These sandstones have been interpreted as crevasse-splay deposits. Detailed descriptions of the alluvial strata are contained in Shanley and McCabe (1990b-in review) and their relationship to coeval nearshore deposits along the Straight Cliffs escarpment are found in Shanley and McCabe (1990c-in review). Along the northeastern escarpment, tidally-influenced fluvial deposits overlie strata interpreted as braided-river deposits (Calico transgressive systems tract) as well as strata associated with nearshore marine processes (A-transgressive systems tract). With the exception of the deposits found along the northeastern escarpment of the plateau, these strata have been previously interpreted as meandering-river deposits (Peterson, 1969a, b; Vaninetti, 1978).

Although the criteria is often subtle, recognition of tidal-influence within these alluvial facies provides greatly improved chronostratigraphic resolution.

FIELD CRITERIA TO DISTINGUISH TIDAL PROCESSES IN ALLUVIAL STRATA - KAIPAROWITS PLATEAU

Introduction

Recognition of tidal influence in strata dominated by fluvial processes requires careful examination of sedimentary structures and a weighing of the preponderance of data; there are, unfortunately, few sedimentary structures which unequivocally confirm the existence of tidal processes within fluvial settings (e.g., Frey and Howard, 1986). This lack of diagnostic criteria almost certainly reflects the mixing of sedimentary environments that occurs within drowned river valleys as marine processes are progressively replaced in a landward direction by nonmarine processes. This mixing of sedimentary processes can occur over distances of several tens to hundreds of kilometers and can significantly effect strata that are otherwise interpreted as entirely fluvial in origin. The nearly continuous exposure and lack of vegetation in the Kaiparowits Plateau make this region an ideal field laboratory in which to study the variations in fluvial and tidally-influenced strata within alluvial transgressive systems tracts.

Eight discrete sedimentary structures, including both biological and physical structures, reflecting tidally-influenced conditions have been recognized in fluvial strata of Turonian though Santonian age in the Kaiparowits Plateau. These structures are a relatively minor component within strata otherwise thought to be of fluvial origin. Recognition of these structures is based on a series of detailed measured sections (Fig. 3).

The first six structures are 'simple sedimentary structures', whereas the last two are 'composite structures'. Composite structures "... generally involve more than one type of lithology and type of simple sedimentary structure" (Allen and Friend, 1968, p. 43) and occur within channel-form sandstones.

Sigmoidal bedding

Description

Cross stratified sandstones (Fig. 4) form sigmoidal shaped bedsets approximately 1.5 m thick which cap trough cross-bedded, fluvial sandstones. These structures are most commonly observed along the northeastern part of the plateau; their occurrence is sporadic in the central and southwestern plateau. Individual sigmoidal beds range from 0.06 to 0.2 m in thickness, and from 2 to 8 m in length. Form sets of asymmetric ripples are commonly preserved at the top of individual sigmoidal beds. Sigmoidal beds are separated from each other by millimeter to centimeter thick mudstones and siltstones. Examination of the internal geometry of these sigmoidal beds reveals two distinct types of lamination (Fig. 4). The first type of internal lamination consists of gently dipping foreset laminae which gradually steepen and are overlain by millimeter thick mud drapes. Within an individual sigmoidal bed, the mud drapes subdivide the bed into several packages of foresets that vary substantially in their width. The second type of internal lamination is characterized by a transition from low-angle, poorly developed cross-stratification near the beginning of the sigmoid to more steeply dipping cross-stratification, at or near the angle of repose near the center of the sigmoid. These steeply dipping cross beds grade into more gently dipping laminations near the toe of an individual sigmoid. Mudstone drapes are noticeably absent in this type of internal lamination.

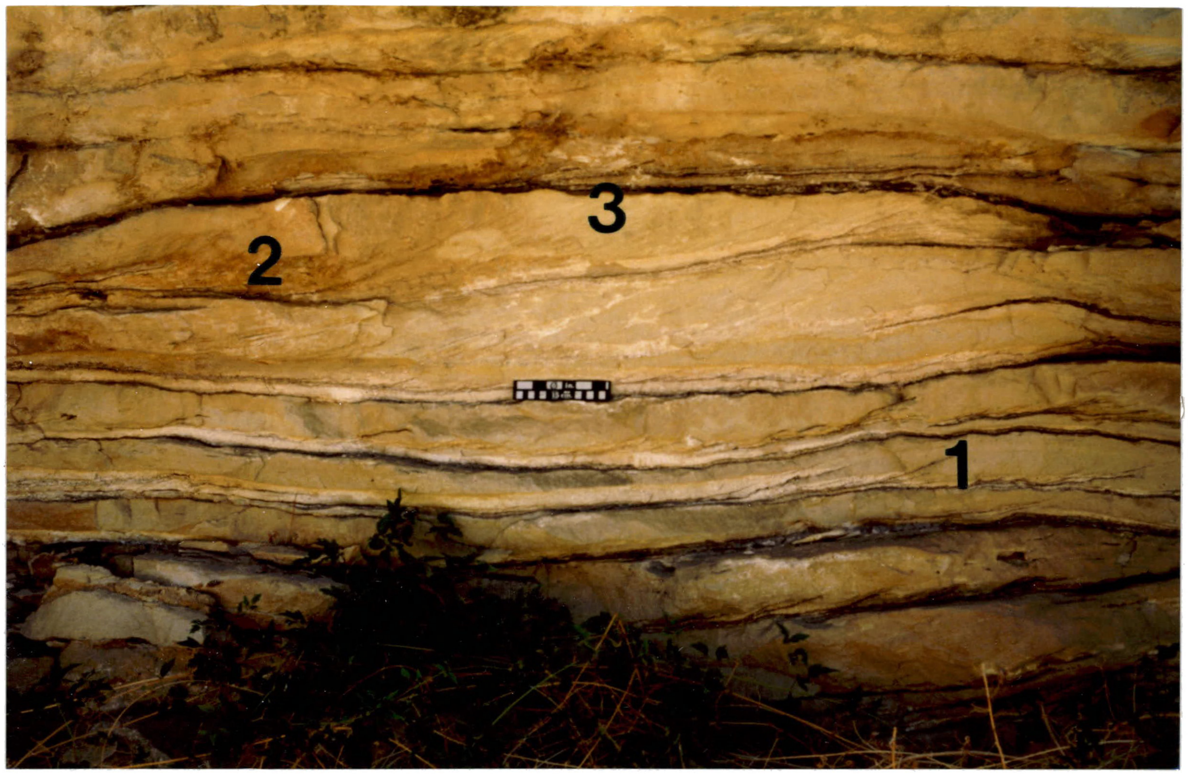


Figure 4. Photograph of sigmoidal shaped, cross stratified sandstones from Left Hand Collet Canyon (Fig. 14, 19 m level). These deposits cap fluvial deposits and are interpreted as ebb dominated tidal bundles, deposited and modified in response to neap-spring-neap tide fluctuations. Within some tidal bundles (#1) bedform migration may have occurred in response to several tidal cycles over the course of a single neap-spring-neap period. In other tidal bundles (#2), however, migration may have occurred in response to a single tidal cycle at or near spring tide. Note the transition from low-angle, poorly developed cross stratification to more steeply dipping cross stratification at or near the angle of repose. This is interpreted to represent flow acceleration within a single ebb tide. Subordinate, flood oriented ripples are preserved at the top of the tidal bundle (#3).

Current orientations indicated by the cross-beds within the sigmoidal facies suggest that transport was primarily to the east-northeast. Subordinate flow indicated by combined flow and current ripples that cap the sigmoidal beds was to the west-southwest.

Interpretation

Sigmoidal-shaped, cross-stratified sandstones are interpreted as ebb dominated tidal bundles, deposited and modified in response to neap-spring-neap tide fluctuations (e.g., Boersma and Terwindt, 1981a,b; Mutti et al., 1984a). They are principally located in the more open, sand-dominated portions of estuaries. The mud drapes that highlight the sigmoidal beds are interpreted to have been deposited during relatively slack water periods when the tidal bedforms were not active. Those tidal bundles that are characterized by several internal mud drapes and internal reactivation surfaces may have been produced by migration of the tidal bedform in response to several tidal cycles over the course of a single neap-spring-neap period. This is consistent with studies of Holocene tidal bedforms which suggest that many bedforms are only active during a few tidal cycles near spring tide conditions (Boersma andTerwindt, 1981a,b). Other tidal bundles, however, may have occurred in response to migration during a single tidal cycle at or near spring tide. The downcurrent transition in foreset angle from gently dipping to more steeply dipping and finally back to gently dipping cross stratification is interpreted to represent acceleration changing to full-vortex flow conditions within a single ebb tide. Similar observations and interpretations have been made in both Holocene tidal sediments (e.g., de Raaf and Boersma, 1971; Visser, 1980; Boersma and Terwindt, 1981b) as well as ancient rock sequences (e.g., Allen and Homewood, 1984; Mutti et al., 1984b; Cuevas-Gozalo, 1985a, b; Kreisa and Moiola, 1986; Mutti et al., 1988; Uhlir et al., 1988). Modification of these tidal bedforms by subordinate, flood-oriented currents is supported by reactivation surfaces and the presence of combined flow and current ripples along the upper parts of several sigmoidal beds.

Double-mud/silt drapes

Description

This facies comprises trough cross-stratified sandstones containing alternating thick-thin foreset and toeset laminae that are separated by finely comminuted organic material ("coffee grounds"), siltstone and mudstone (Fig. 5). The thicker sandstone laminae are approximately 8-10 mm thick, while the thinner laminae are approximately 3-4 mm thick; the interbedded drapes are approximately 1 mm thick. As a result of the alternations in foreset laminae thickness, the finely comminuted material appears as couplets. These structures often occur in association with sigmoidal bedded sandstones and within trough cross-bedded fluvial deposits.

Interpretation

These mud/silt drapes are interpreted as the product of alternating current and slack-water conditions in response to semi-diurnal tidal fluctuations. Finely comminuted plant material, mud and silt are deposited along the foreset of three-dimensional dunes during slack water conditions. The alternation of thick and thin sandstone laminae reflects the preferential migration of the three-dimensional bedform during the dominant current stage. These sedimentary structures are similar in process-response to the more commonly described double-mud drapes that have been documented in Holocene strata (e.g., Visser, 1980; de Boer et al., 1989). While similar comminuted plant material may be deposited

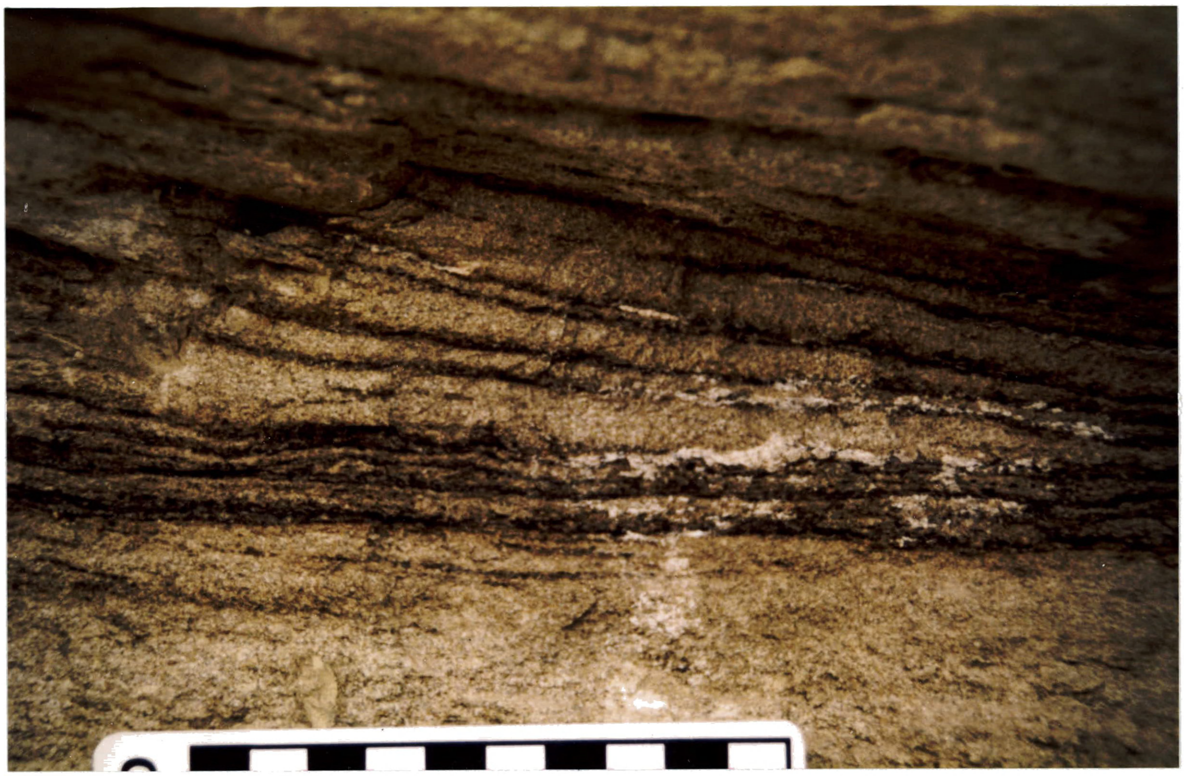


Figure 5. Photograph of finely comminuted organic debris and siltstone laminae separate alternating thick-thin foreset and toeset laminae. These are interpreted similarly to double-mud drapes and represent alternating current and slack water conditions in response to semi-diurnal tidal fluctuations.

along the lee side of slightly sinuous, three-dimensional bedforms due to entrapment within countercurrent eddy currents, the regular alternation of thick-thin sandstone laminae and "coffee ground" couplets serve to identify these deposits as the product of tidal influence. Smith (1988b) and Wheeler et al., (1990) suggested a similar interpretation for mud-carbonaceous drapes in the McMurray Formation of Alberta, and the Muddy Sandstone of Wyoming, respectively.

Wavy and lenticular bedding

Description

Wavy and lenticular bedded (Reineck and Wunderlich, 1968) sandstones and mudstones (Fig. 6) are common in heterolithic channel deposits. These heterolithic channels consist of alternating 0.50 to 1.0 m thick sandstones and mudstones. Wavy and lenticular bedded strata occur in beds as much as 0.5 m thick, and are interbedded with current ripple laminated sandstones. In wavy bedding, sandstone comprises approximately 75% of the rock volume, and mudstone and sandstone layers alternate to form layers that can be traced for several meters. Individual ripple laminated sand layers vary from less than 0.5 to 2.0 cm in thickness, and have ripple indices of approximately 10-14. Ripple laminated sandstone layers that exceed 1.0 cm in thickness commonly have load structures along their base creating an irregular contact with underlying mudstones.

Interpretation

Wavy and lenticular bedding are interpreted to reflect alternating current and slack water conditions associated with tidal cycles. Considerable controversy surrounds the temporal formation of wavy, lenticular and flaser bedding. Many have cited Holocene

Figure 6. Wavy and lenticular bedding are common throughout the heterolithic channel deposits and are interbedded with current ripple-laminated sandstones. The lens cap is 70 mm in diameter. Photograph is from Tibbet Canyon, (Fig. 17, 12 m level.).

depositional systems to suggest that the alternations of sand and mud layers reflect daily tidal cycles (e.g., Reineck and Wunderlich, 1968; Reineck and Singh, 1980), others (e.g., Terwindt, 1971; Terwindt and Breusers, 1972), citing flume and Holocene studies, have concluded that the mud laminations must reflect accumulation during several slack-water periods representing several tidal cycles. Such arguments suggest that the wavy and lenticular beds more properly reflect deposition associated with neap-spring cycles or are perhaps influenced by seasonal cycles (de Mowbray, 1983). While debate exists as to whether wavy and lenticular beds reflect daily or neap-spring tidal cycles, there is agreement that wavy and lenticular beds, though not diagnostic, are most common in tidally-influenced deposits. Within fluvial strata, the occurrence of extensive wavy and lenticular deposits might suggest the interaction of tidal processes and discharge variations causing the migration of a turbidity maxima within the upper reaches of an estuary.

Shrinkage-cracks

Description

Cracks developed in mudrocks are preserved as sandstone casts on the base of ripple bedded sandstones within the heterolithic fill of channel deposits (Fig. 7). The casts generally are between 1 and 2 cm in length, 2-4 mm in width, and occur as isolated, poorly aligned spindles. Less commonly, the sandstone casts occur as branching, spindle shaped, poorly aligned casts up to 8 cm in length. These deformation structures occur in thin-bedded heterolithic strata that are ripple laminated; scattered bivalve shells, and *Teredolites* trace fossils are also present in this heterolithic facies assemblage.

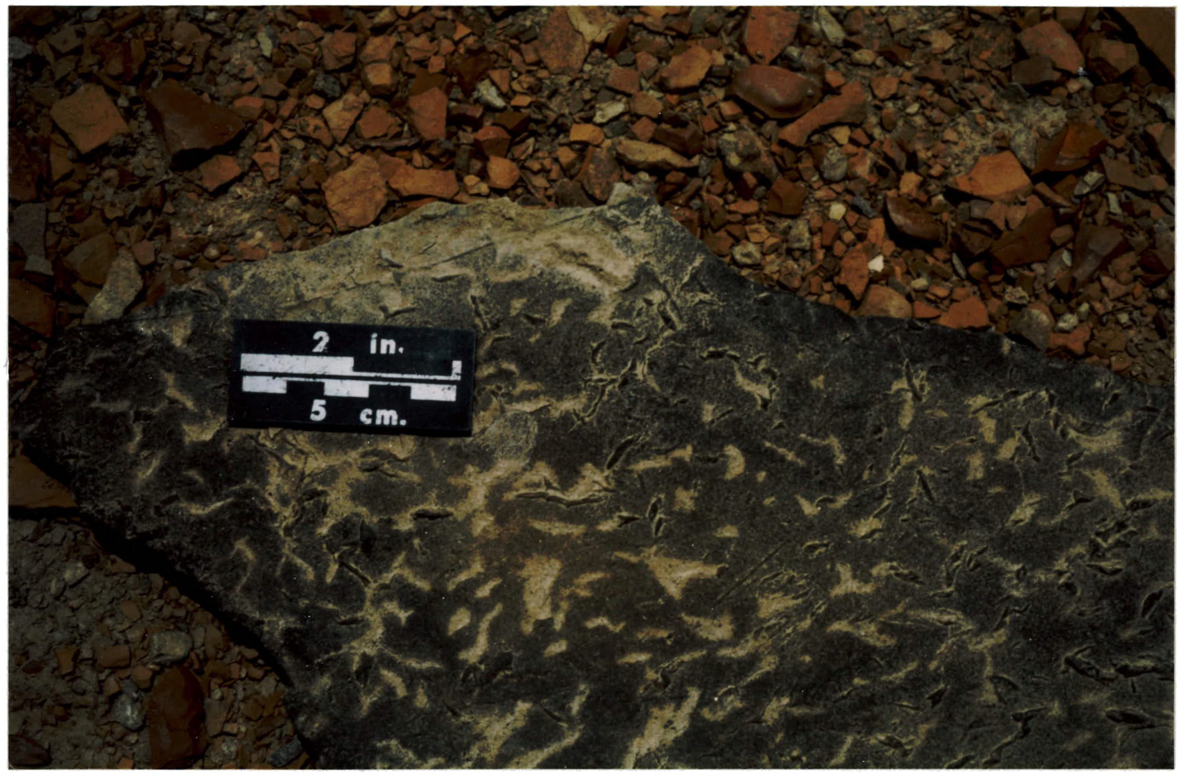


Figure 7. Synaeresis cracks developed in mudrocks are preserved as sandstone casts on the base of ripple bedded sandstones within heterolithic fill of tidally influenced river deposits. This particular example was collected within the fill of a channel in Tibbet Canyon shown in Fig. 23. These structures are interpreted to reflect compaction and development of subaqueous shrinkage cracks under conditions of varying salinity and are illustrated in Fig. 22 between 8.5 and 10 m.

Interpretation

These cracks are interpreted to reflect compaction and development of subaqueous shrinkage cracks or synaeresis cracks, within muddy sediments under conditions of varying salinity. The origin of these deformation features is in response to tension as muddy, water saturated sediment loses water to an overlying aqueous layer causing an increase in the strength of inter-particle forces within the clays (e.g., Picard and High, 1973; Plummer and Gostin, 1981; Allen, 1982; Collinson and Thompson, 1989; Kidder, 1990). The controls on the development of synaeresis are poorly understood but are thought to be promoted by changes in fluid salinity. Both Plummer and Gostin (1981) and Allen (1982) cite previous work where salinity variations present during either sedimentation or immediately following sedimentation of muddy sediments induced the formation of shrinkage cracks under carefully controlled experimental conditions. Despite this work in controlled environments, there are few reported cases where synaeresis cracks have been observed to form in natural settings. The presence of these shrinkage cracks in heterolithic strata containing additional evidence of salinity variations such as *Teredolites*, and escape burrows leads us to interpret these features as being due to synaeresis processes rather than compaction, and being indicative of brackish water conditions within tidally-influenced rivers.

Multiple reactivation surfaces

Description

Reactivation surfaces are characterized by gently dipping erosion surfaces that become slightly convex-upward in an upstream direction within a single cross-bed set. These structures are common in many trough cross-bedded sandstones encountered in this study. The amplitude of these surfaces varies between 0.1-0.5 m. The horizontal spacing of these erosion surfaces is quite variable but generally is of a few decimeters. Reactivation surfaces are common in sandstones that overlie the Calico bed throughout much of the plateau but they are especially common along the northeastern margin of the plateau where they occur in both the Calico bed and the A sandtone (Fig. 2).

Interpretation

Reactivation surfaces have been recognized in a variety of depositional settings and have been interpreted to occur by at least three distinct mechanisms (McCabe and Jones, 1977; Allen, 1982). In fluvial deposits, reactivation surfaces have most commonly been interpreted to reflect stage fluctuations and subsequent modification of bedforms (e.g., Collinson, 1970; Cant and Walker, 1978; Jones and McCabe, 1980). In tidal deposits, reactivation surfaces have been attributed to reversals in flow direction such that a bedform's leeside is changed into the stoss side resulting in substantial bedform modification (e.g., Boersma, 1969; Klein, 1970; de Raaf and Boersma, 1971; Boersma and Terwindt, 1981a, b; Allen and Homewood, 1984). Finally, reactivation surfaces have been attributed to the migration of superimposed bedforms on both experimental grounds (McCabe and Jones, 1977) and examination of modern sedimentary environments, such as the tidal sandwaves of the Bay of Fundy (e.g., Dalrymple, 1984).

Although reactivation surfaces may be attributed to several processes that occur in many sedimentary environments, multiple, close spaced reactivation surfaces are most common in tidal environments. Within modern tidal sandbodies, multiple reactivation surfaces likely reflect both the migration of superimposed bedforms and current reversals associated with tidal cycles and are cited as a common component of tidal facies models particularly in open estuaries (e.g., Reineck and Singh, 1980; Nio et al., 1981; Allen, 1982; Walker, 1984; Cuevas-Gozalo, 1985a, b; Reading 1986). Although reactivation surfaces do occur in fluvial deposits they are less common and do not form a common component of fluvial facies models (e.g., Reineck and Singh, 1980; Allen, 1982; Cant, 1982; Collinson and Lewin, 1983; Walker, 1984; Reading 1986).

Trace and body fossils

Description

In addition to simple vertical escape traces, identified trace fossils found in the alluvial strata discussed in this paper include *Arenicolites*, *Skolithos*, and *Teredolites*. Escape traces are generally vertical structures, approximately 1-4 cm in diameter and 2-6 cm long with retrusive internal laminae. *Arenicolites* burrows are simple, vertical, U-shaped burrows with a structureless fill measuring approximately 0.5 cm across and 3-4 cm in length. *Skolithos* burrows are simple, vertical burrows with a structureless fill measuring approximately 0.5 cm in diameter and 3 cm in length. *Teredolites* trace fossils (Fig. 8) are preserved as very fine-grained sandstone molds of borings that penetrated a woody log. Borings are club-shaped, range from 0.5-1.2 cm in diameter and 2-6 cm in length; in general, an increase in diameter is observed as they penetrate the log. The borings are generally straight to slightly curved and do not intersect one another, however, they may be intertwined as shown in Figure 8. The sandstone molds are commonly ornamented with sub-parallel striations that conform to small grooves and ridges which can be traced continuously across several boring molds. These grooves are interpreted as growth rings within the log acting as substrate. No body fossils were found associated with any of these trace fossils.

Figure 8. *Teredolites* are commonly preserved as sandstone casts within compacted logs along the base of many tidally-influenced fluvial channels. Note the growth ring imprints and the increase in diameter of the borings towards the center of the log.

Body fossils have been found in these strata along the eastern margins of the Kaiparowits Plateau, particularly within the A sandstone, and decrease rapidly towards the west and southwest. The principal fossils are broken and whole inoceramid and oyster shells which occur in channel sandstone lags (Fig. 9). Scattered thin-walled mollusc shells have been found along the base of ripple-laminated sandstones in heterolithic strata in Tibbet Canyon in the southern part of the plateau.

Interpretation

The trace fossils are interpreted to represent the boring and burrowing activity of organisms. The size of the escape traces suggest that they likely reflect the upward burrowing activity of small bivalves or polychaete worms following rapid sedimentation of the enclosing sandstone bed (Ekdale et al., 1984). Characteristics that allow these trace fossils to be distinguished from soft sediment deformation structures are provided by Kamola (1984). Both *Skolithos* and *Arenicolites* burrows are interpreted as dwelling structures, perhaps of small bivalves or polychaete worms (e.g., Elders, 1975; Ekdale et al., 1984) that penetrated relatively stable sediment substrates. While both *Skolithos* and *Arenicolites* have been previously described from strata ranging from nonmarine to marine (e.g., Chamberlain, 1975; Ekdale et al., 1984),they are significantly more abundant in marine and marginal marine strata.

Teredolites is interpreted as the dwelling structure of a pholadid bivalve, similar to *Martesia*, which extensively bored into logs that have since undergone compaction and coalification. Bromley et al., (1984) provided a similar description and interpretation of this trace fossil from estuarine strata in the Horseshoe Canyon Fm. of Late Cretaceous age in Alberta. Although pholadid bivalves are largely of marine or brackish water affinities,

Figure 9. Inoceramid debris and oyster shells are commonly found in channel lag deposits within the open estuary portions of tidally-influenced river deposits. This particular example is from the transgressive systems tract associated with the A-sandstone in Upper Valley.

some species have been recorded in fresh waters (Cox et al., 1969), however, their occurrence is rare. The abundance of *Teredolites* and other trace fossils in these strata suggest brackish to marine salinity conditions are likely.

The whole and broken inoceramid shells that have been recovered in channel lags along the eastern margin of the plateau suggest that marine salinities were common when these channels were active.

Inclined heterolithic strata

Description:

This composite structure occurs within channel-form sandstones. It is characterized by, a complex internal geometry of alternating ripple, lenticular and wavy-bedded, or locally trough cross-bedded, fine-grained sandstones and persistent mudstone drapes (Fig. 10). Both sandstones and mudstone drapes can typically be traced from the upper part of inclined surfaces into the basal portions of channel sandstones and dip at angles between 10° and 15°. Multiple erosion surfaces within the inclined heterolithic strata generally dip at steeper angles than the adjacent strata. Individual sandstones average 0.45 m in thickness with a range of 0.08-0.85 m, while mudstones average 0.2 m in thickness with a range of 0.08-0.45 m. These strata combine into heterolithic strata and form cosets 6-12 m thick. The contacts between sandstones and mudstones are sharp, with loading along the base of several sandstone units. Many inclined beds of sandstone have erosional bases that locally scour decimeters into underlying mudstones. Although there are a substantial variety of sedimentary structures within the inclined heterolithic strata, sandstones are commonly ripple-laminated or pseudo-planar laminated (Smith, 1971; transcurrent lamination of Allen, 1982) and can be traced from the base to top of the inclined strata. Shrinkage cracks

Figure 10. Photograph of inclined heterolithic strata (#1) in the lower part of the John Henry Member at Rock House Cove in the southwestern part of the plateau. The unit of inclined strata is approximately 10 m thick. These strata are interpreted as lateral-accretion deposits within a tidally influenced river. Note the persistent mud drapes which can be traced into the lower part of the channel deposits and the thickening of many ripple laminated sandstone towards the upper part of the point bar surface. The top of the photograph (#2) records amalgamated fluvial deposits associated with the lower transgressive portion of the 'A-sequence.

preserved as sandstone casts along the base of ripple laminated sandstones, sigmoidal bedding, double mud/silt drapes, as well as *Teredolites*, and escape traces are all common components within these inclined strata. Paleocurrent indicators within these strata are oriented in a direction normal to paleoflow with current reversals common between adjacent sandstone beds.

Interpretation:

The inclined heterolithic strata are interpreted as lateral accretion deposits on point-bar surfaces within tidally-influenced rivers. Alternations in fluvial discharge, in the lower stretches of a river, combined with tidal processes are thought to be capable of generating the abrupt changes in lithology and stratification. In addition, development of 'fluid mud' within a turbidity maximum zone (e.g., McCave, 1979; Jouanneau and Latouche, 1981) is likely to have enhanced deposition of mudstone drapes. Bidirectional currents suggest that under conditions of greatly reduced fluvial discharge, and perhaps spring tides, bedforms migrated predominantly under the influence of flood tidal currents. The persistent mud drapes that can be traced from the upper part of point bar surfaces into the deepest parts of the channel, combined with inclined sandstones that are ripple-laminated throughout suggest a relatively even shear-velocity distribution within the channel. Such a velocity distribution is markedly different from that normally encountered in fluvial systems. These data are consistent with fluvial processes that have been significantly modified by tidal processes (e.g., Smith, 1987, 1988; Thomas et al., 1987; Rahmani, 1988).

Inclined heterolithic strata have been described from modern intertidal point bars, modern tidally-influenced rivers, and ancient channel-fill sequences (e.g., Thomas et al., 1987). Bridges and Leeder, (1976), Reineck and Singh, (1980), de Mowbray, (1983), and Howard and Frey (1985), for example, have described interlaminated fine-grained sandstones and mudstones forming accretion deposits on tidal flat point bars. The fine interlamination observed on these point bars is interpreted to reflect deposition during slack water (Bridges and Leeder, 1976) and to reflect seasonal fluctuations in discharge in concert with tidal cycles (de Mowbray, 1983).

The ability of discharge variations and tidal cycles to significantly affect sedimentation is also supported from studies of large estuaries where migration of a turbidity maximum and deposition of 'fluid mud' is influenced by fluvial discharge (Jouanneau and Latouche, 1981; Gelfenbaum, 1983; Nichols and Biggs, 1985). Deposition of fine-grained sediment may be due to abrupt changes in shear velocity due to either fluvial discharge or tidal-current variation as well as being promoted by floculation of clay particles due to salinity mixing of fluvial derived fresh water and marine waters (Nichols and Biggs, 1985).

In an attempt to understand thick inclined heterolithic strata from the Cretaceous McMurray Fm. of Alberta, Smith (1987, 1988a, 1989) studied modern tidally-influenced fluvial systems. Examination of cores from point bars of the Willapa River in Washington,U.S.A., the Ogeechee and Altamaha Rivers in Georgia, U.S.A., and the Babahovo and Daule Rivers in Ecuador revealed heterolithic channel fill complexes up to 8.5 m thick comprised of complex mudstone-sandstone couplets. Sandstones in these deposits were interpreted to have been deposited during fluvial flood stage coupled with ebb tides whereas the muds were deposited during low stage flow coupled with both ebb and flood tides. Examples of ancient tidally-influenced fluvial successions are few but include the Cretaceous McMurray and Horseshoe Canyon Formations in Alberta, Canada and the Eocene Bracklesham Fm. in southern England. Mossop and Flach (1983), Flach and Mossop (1985), and especially Smith, (1987, 1988a, b, 1989) suggest tidal or estuarine controls on the deposition of alternating sandstones and mudstones in the McMurray Fm. Rahmani (1988) also invoked tidal influence to explain heterolithic fluvial strata in the Horseshoe Canyon Fm. Plint (1983) interpreted inclined heterolithic strata in the Bracklesham Fm. to reflect migration of a point bar within an estuarine channel.

Although the evidence in support of tidally-influenced deposition is compelling, these deposits might initially be interpreted to reflect only variations discharge. Under these conditions, however, clays and muds deposited during low discharge would tend to be eroded from the deeper portions of the channel and placed in suspension unless allowed to compact during desiccation. Structures indicative of desiccation within both the channel deposits or the overbank sediments have not been found.

Complex-compound bedding

Description:

Fluvial strata containing complex-compound cross-stratification are characterized by broad, low-angle (5-10°) dipping surfaces with smaller sets of cross-bedding dipping up or down the 'master bedding surfaces' (Fig. 11). These broad, low-angle surfaces may be traced into near-horizontal or slightly convex upwards surfaces. These surfaces are erosional where they have observable dip and become disconformable where they are horizontal to slightly convex upwards. The smaller sets of cross-bedding that are defined by these broad, low-angle surfaces may be overlain by asymmetric current ripples and thin (millimeter thick) mudstone drapes. Sigmoidal shaped cross-beds, wavy and lenticular bedding, double mud/silt drapes and *Teredolites* are all common components of this composite sedimentary structure.

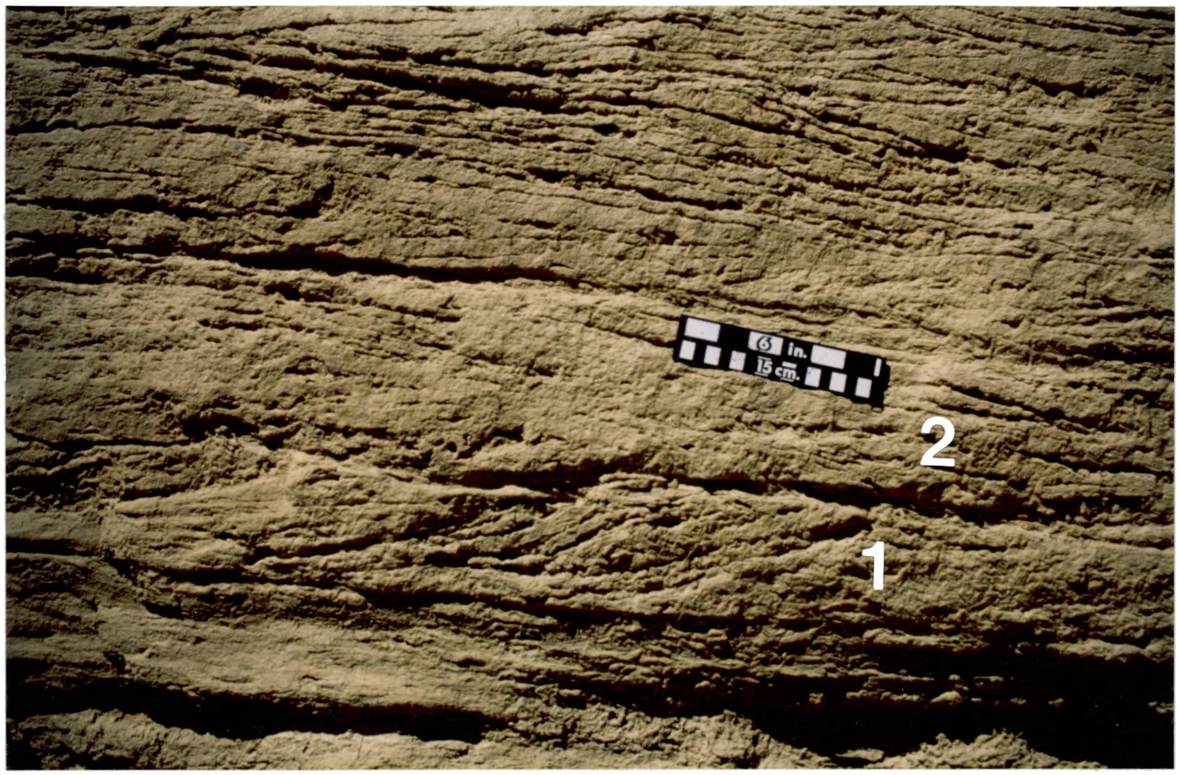


Figure 11. Compound cross-stratification showing bidirectional current flow is common in some heterolithic channel fill strata. This particular example is from Tibbet Canyon. Gently dipping erosional surfaces separate cross beds that are oriented both up (#1) and down (#2) the master bedding surfaces. These strata are interpreted to have been deposited within a tidally influenced river by currents possessing some degree of time-velocity asymmetry.

Interpretation:

The complex and compound cross-stratification are interpreted as sandwaves containing large-scale reactivation or erosion surfaces that formed in tidally-influenced rivers. The transition from cross-bedded sandstones to ripple laminated sandstones and thin mudstone drapes is interpreted to reflect a deceleration of current velocities related to an asymmetric time-velocity distribution (Allen, 1980). The time-velocity asymmetry is interpreted to have been further enhanced by variations in fluvial discharge such that the resulting sedimentary succession reflects velocity variations at a seasonal scale as opposed to the more common neap-spring cycles. Similar interpretations have been advanced for tidally-influenced fluvial deposits in the Gironde estuary, France (George Allen, personal communication 1990). While descriptions of similar structures are rare from alluvial strata, similar sedimentary features have been described from modern shelves (e.g., Boersma and Terwindt, 1981a, b; Dalrymple, 1984) and have been proposed for strata interpreted as open shelf tidal sand bodies (e.g., Allen, 1980; Levell, 1980; Walker, 1984). We interpret the structures in the Kaiparowits Plateau to have occurred within channel fill complexes in tidally-influenced rivers.

Paleocurrents

Description

Paleocurrents measured from fluvial strata within the transgressive systems tracts are summarized in Figure 12. These data are based on measurements of both trough cross-beds and ripple cross-lamination. While paleocurrent orientations at any one locality within the transgressive systems tract tend to be somewhat unidirectional, consideration of several localities suggest bidirectional sediment transport directions in a preferred northeast-

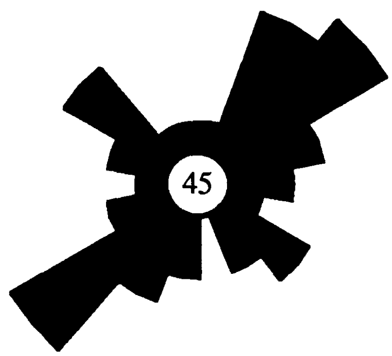


Fig. 12

Figure 12. Paleocurrent data for trough and ripple laminated sandstones in the alluvial transgressive systems tract clearly show a bidirectional current orientation. These currents are normal to estimated paleoshoreline orientations. The number of readings used is shown in the center of the rose diagram. Each reading represents a synthesis of many readings taken within a coset of strata.

southwest orientation; true herringbone stratification has rarely been observed. Although the overall number of data points in Figure 12 is somewhat, each data point summarizes a large number of cross beds examined within a coset of strata. In the case of trough cross-beds, readings are based on both plan view examination of rib and furrow patterns as well as determination of trough axes. Where ripple cross-lamination were used for paleocurrent analysis, measurements are based on plan view examination of rib and furrow structures as well as attempts to resolve the three-dimensional aspect of the ripple-form.

Interpretation

The preferred orientation of these paleocurrents are normal, or at high angle, to paleoshoreline orientations for both the underlying Tibbet Canyon Mbr. and the overlying John Henry Mbr. (this study; Peterson, 1969; Vaninetti, 1978) Although shoreline sandstones that are strictly coeval with these transgressive systems tracts are not found within the Kaiparowits Plateau, the paleocurrent data presented here are also normal or at high angle to paleoshoreline orientations suggested by Ryer (1981) and Ryer and McPhillips (1983) for the upper part of the Ferron Sandstone Mbr. which we suggest are temporally related to some of these transgressive fluvial deposits (Fig. 2). We interpret these paleocurrent data to reflect fluvial currents substantially influenced by both ebb and flood oriented tidal currents as well as discharge variations.

FACIES ASSOCIATIONS

Introduction

Exposures in the Kaiparowits Plateau region afford the opportunity to examine changes in depositional textures in tidally-influenced fluvial strata along a depositional dip oriented transect. Exposures near a coeval shoreline in an open estuary on the eastern margin of the plateau can be compared with exposures as much as 60 km inland of a coeval shoreline that crop out on the western margin of the plateau.

Figure 2 illustrates unconformity-bounded depositional sequences within the Kaiparowits Plateau. Within this framework, we recognize both third and fourth-order sequence boundaries (Shanley and McCabe, 1990c-in review). The major distinction between these third- and fourth-order sequences is the severity of the facies tract dislocation across the sequence boundary. Major facies tract dislocations accompany third-order sequences, such as the Calico sequence, which juxtaposes coarse-grained and pebbly, braided-river deposits over fine-grained floodplain strata (Fig. 2). This is in contrast to less dramatic facies dislocations associated with the A sequence boundary. The transgressive systems tracts associated with both these sequences allow a depositional dip-oriented transect to be reconstructed from open-estuary deposits on the eastern margin of the plateau. to tidally-influenced fluvials strata in the central and southwestern portions of the plateau. Figure 13 illustrates the stratigraphic position of measured sections that are used to reconstruct this depositional dip-oriented transect.

Figure 13. Detailed sequence stratigraphic cross section of the Tibbet Canyon Sandstone through the lower portions of the John Henry Member. The positions of measured sections discussed in the text relative to this depositional dip profile is shown.

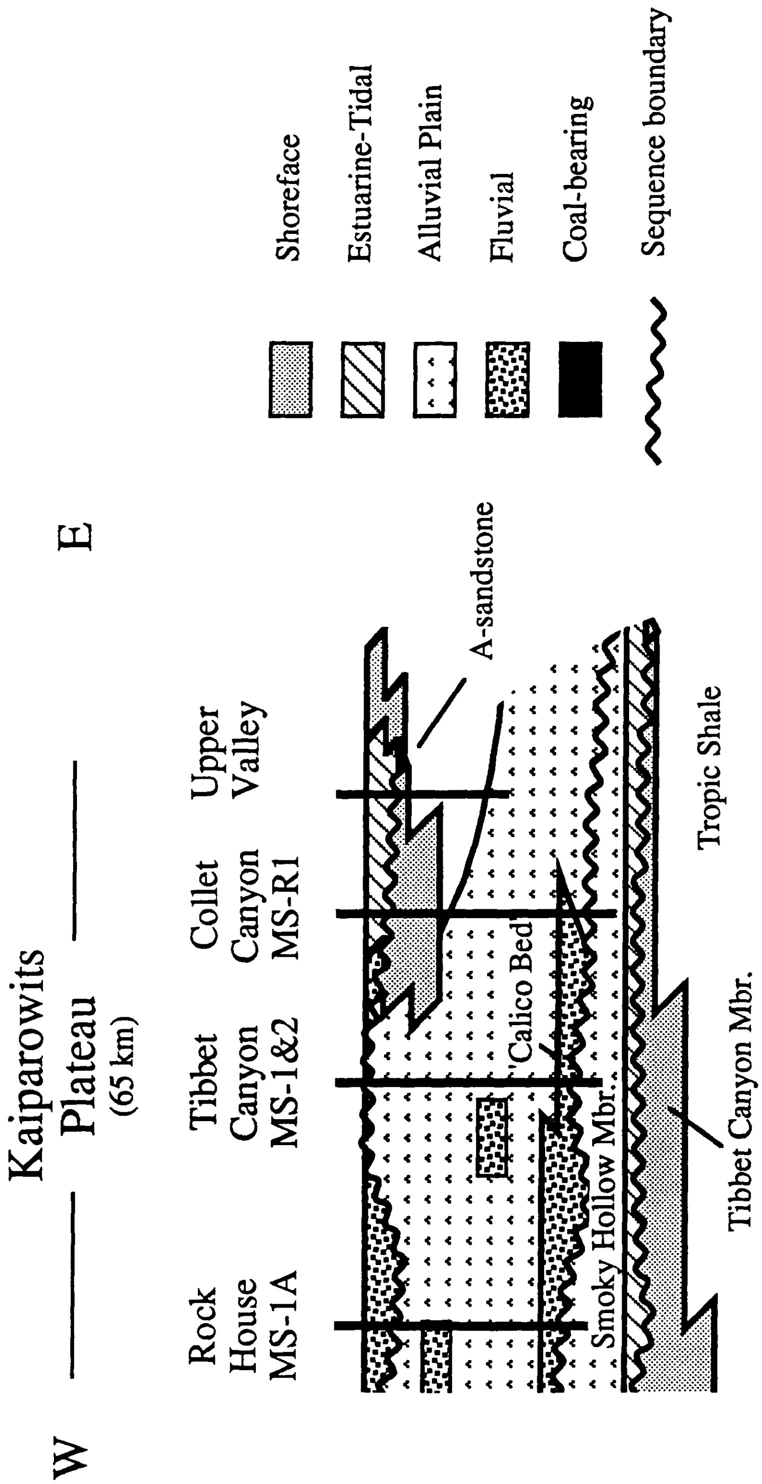

W
E
Kaiparowits Plateau
(65 km)
Rock House MS-1A
Tibbet Canyon MS-1&2
Collet Canyon MS-R1
Upper Valley
A-sandstone
Calico Bed
Smoky Hollow Mbr.
Tibbet Canyon Mbr.
Tropic Shale
Shoreface
Estuarine-Tidal
Alluvial Plain
Fluvial
Coal-bearing
Sequence boundary

Figure 13

Tidally-influenced deposits associated with the Calico transgressive systems tract

Facies associations near a coeval shoreline - Left Hand Collet Canyon

Tidally-influenced strata deposited near their coeval shoreline, such as those in Left Hand Collet Canyon (Figs. 3, 13), can be seen throughout the eastern margin of the plateau. A measured section from this area is shown in Figure 14. Coarse-grained and pebbly braided-river deposits unconformably overlie fine-grained and rooted floodplain shales (Fig. 14, 2.2 m level). These braided river deposits grade upwards into sandstone dominated, tidally-influenced channel deposits (Fig. 14, 18-19.5 m level). Sigmoidal bedding, multiple reactivation surfaces, and thin mudstone drapes are interpreted as the products of tidal current reversals perhaps related to neap-spring tidal cycles.

Erosionally overlying these tidally-influenced fluvial deposits is a pebble lag of variable thickness (Fig. 15) containing scattered inoceramid debris. The underlying erosion surface is interpreted as a ravinement surface that resulted from shoreface transgression across tidally reworked valley fill deposits. The pebble lag is interpreted as a transgressive lag. Continued coastal transgression resulted in a deepening upward facies succession (Fig. 16) culminating in a condensed interval (Fig. 14, 25.5 m level). This deposit can be traced throughout the eastern portion of the plateau, contains sharks teeth, inoceramid debris, and other molluscan debris and ammonites and is interpreted as a maximum flooding surface. We interpret this surface at Left Hand Collet Canyon to be temporally equivalent to tidally-influenced fluvial strata above the Calico sequence boundary at both Tibbet Canyon and Rock House Cove.

Figure 14. Measured section from Left Hand Collet Canyon illustrating the transition from coarse-grained fluvial sandstones of the Calico bed to tidally influenced sandstones near a coeval shoreline. The Calico sequence boundary marks a basinward shift in facies tracts. The transgressive systems tract is shown from 2.2-25.5 m. Tidally-influenced river deposits are sharply overlain by a transgressive lag deposit which separates shoreface deposits above from alluvial strata below. Continued transgression resulted in a deepening upward succession that culminated in deposition of a condensed interval interpreted as the maximum flooding surface. This surface is temporally equivalent to the tidally-influenced river deposits in the central and western portions of the plateau. The legend shown is also used for all subsequent measured section diagrams.

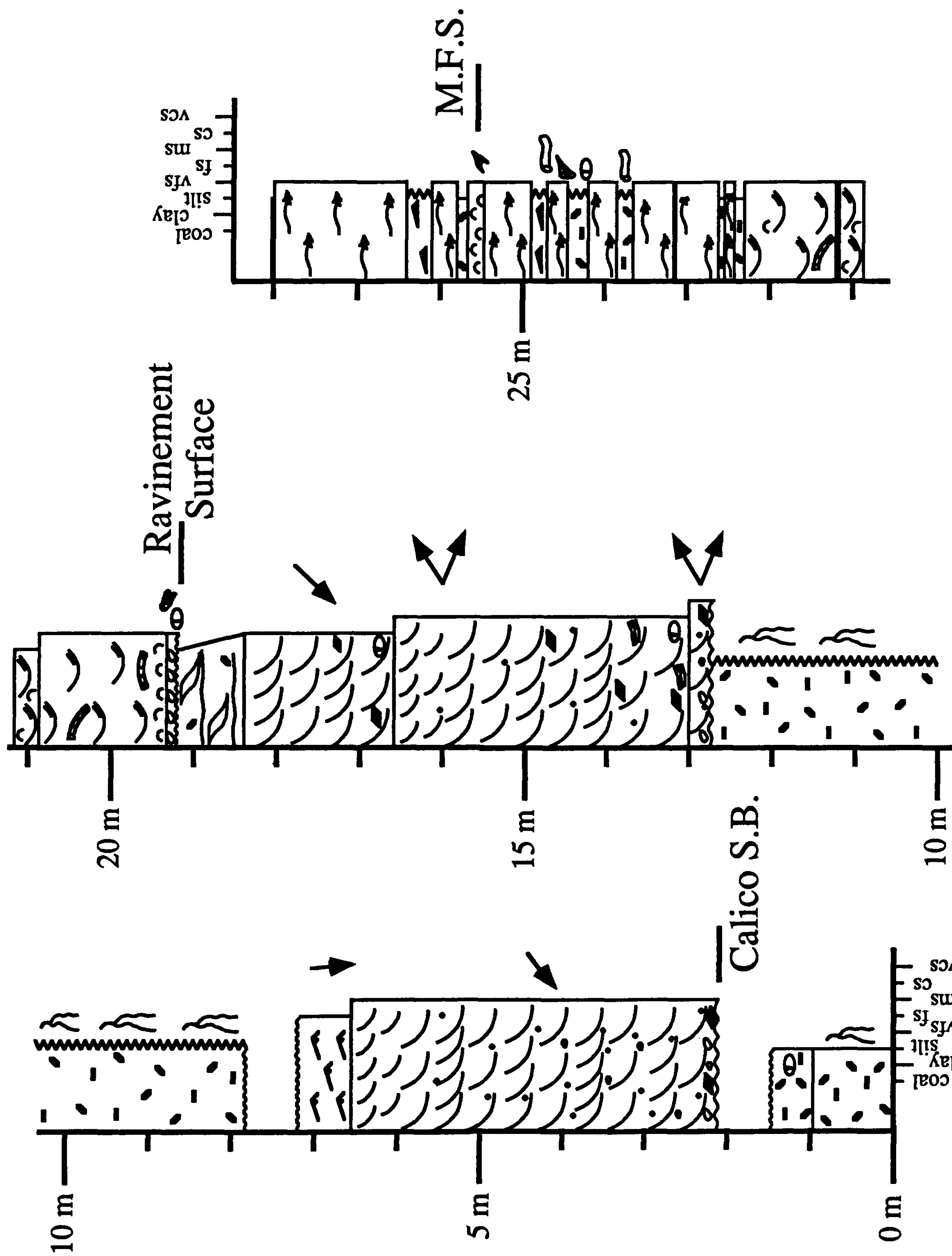

M.F.S.
25 m
coal
clay
silt
vfs
fs
ms
cs
vcs
Ravinement Surface
20 m
15 m
10 m
Calico S.B.
5 m
0 m

Figure 14

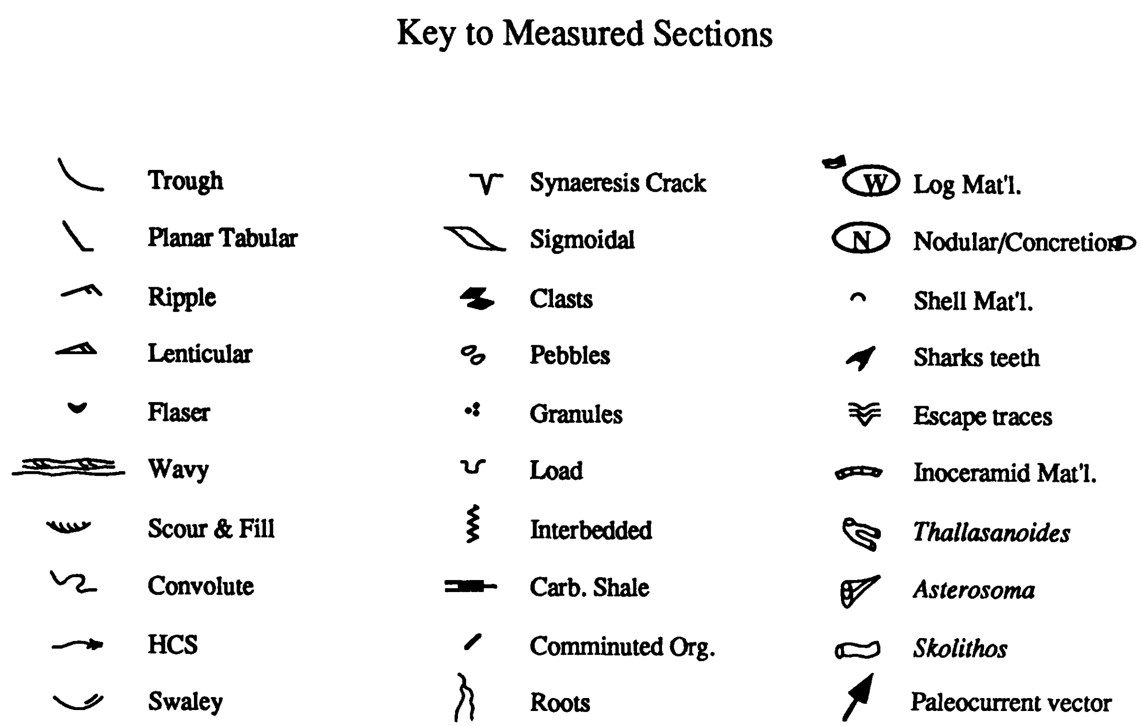


Figure 14-cont.

Figure 15. A quartzite pebble lag erosionally overlyies tidally-influenced river deposits and separating them from strata of clear marine origin. This lag is interpreted as a transgressive deposit. This clast supported conglomerate is well rounded and poorly sorted. Elsewhere in the plateau, the lag contains scattered inoceramid debris.

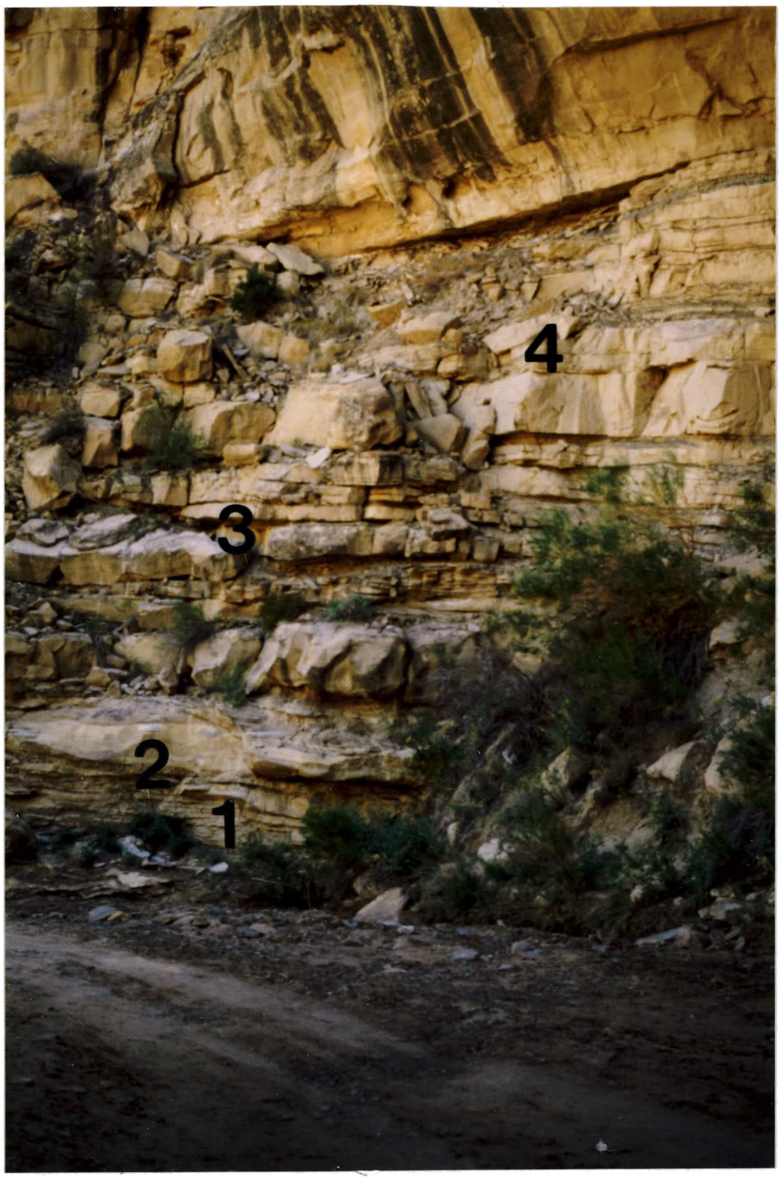


Figure 16. Tidally influenced fluvial deposits at Left Hand Collet Canyon (#1) are erosionally capped with a persistent pebble lag (#2) interpreted as a ravinement surface and transgressive lag. Continued coastal transgression resulted in thinning upward beds of swaley followed by hummocky cross-stratified sandstones. A condensed interval interpreted as a maximum flooding surface (#3) is recorded by a thin fossiliferous lag. The subsequent highstand systems tract is reflected by a shallowing upwards succession of hummocky and swaley cross-stratified sandstones (#4).

Facies associations 30 km inland - Tibbet Canyon

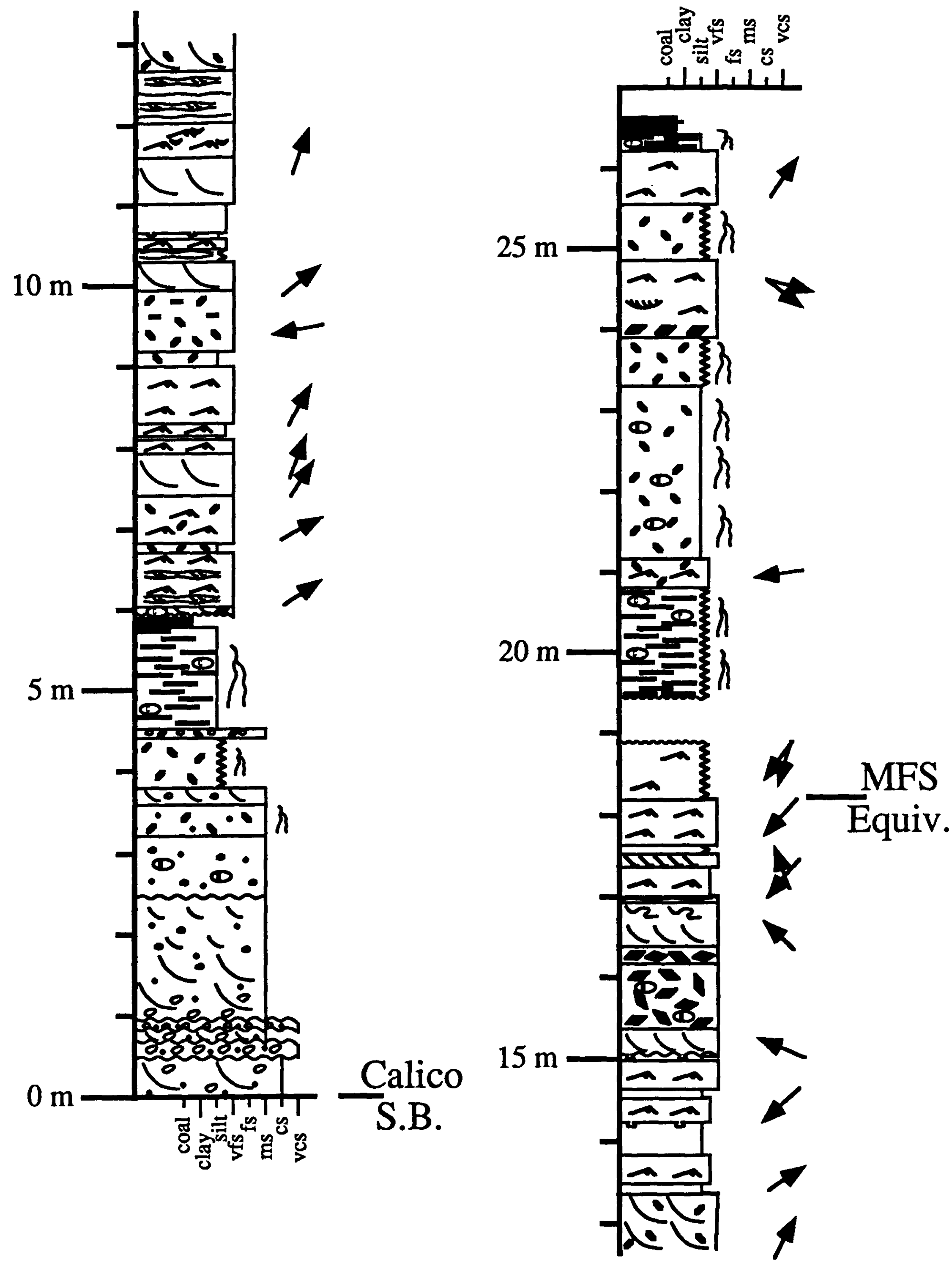
Tidally-influenced fluvial strata deposited some 30 km inland from their coeval shoreline are exposed in Tibbet Canyon (Fig. 3, 13) and are illustrated in Figure 17 (5.8 - 18.8 m level). Unlike the tidally-influenced fluvial strata along the eastern margin of the plateau which are sandstone dominated, these channel fill strata consist of alternations of fine and very-fine grained ripple laminated and wavy bedded sandstones separated by thin, laterally continuous mudstone and siltstone beds (Fig. 18). Complex and compound cross beds composed of very fine-grained sandstones and mudstones are common. *Teredolites* bored fossilized wood occurs along the base of channels, and escape traces have been noted within some of the ripple laminated sandstones.

The complex internal geometry of inclined scour surfaces, and wavy and ripple-laminated sandstone and siltstones overlain by mudstone drapes are interpreted to reflect episodic channel aggradation in tidally-influenced rivers. Annual discharge variations combined with neap-spring tidal cycles are interpreted to have produced the complex, heterolithic deposit. The wavy and ripple lamination within individual sandstones, combined with bidirectional current orientations may reflect migration of a turbidity maximum under neap-spring tidal cycles.

Facies associations 60 km inland - Rock House Cove

Tidally-influenced fluvial strata deposited approximately 60 km inland from a coeval shoreline are seen at Rock House Cove (Fig. 3, 13) and illustrated in Figure 19 (10.5 - 19.6 m level). These strata consist of inclined heterolithic strata (Fig. 10) composed of alternating fine-grained ripple laminated sandstones, thin siltstones, and mudstones. These strata form lateral accretion beds approximately 9.5 m thick that are interpreted as point-bar

Figure 17. Measured section from Tibbet Canyon illustrating the development of heterolithic channel fill strata approximately 30 km inland of a coeval shoreline deposit. The basinward shift in facies tracts is shown at the Calico sequence boundary with the transgressive alluvial deposits extending up to 18.8 m. Note the development of thin ripple-laminated, wavy-laminated, and trough cross-bedded sandstones that alternate with thin, persistent mudstone drapes. A photograph of this measured section is shown in Figure 18. Refer to Figure 14 for the legend for the measured section.



coal
clay
silt
vfs
fs
ms
cs
vcs
25 m
20 m
15 m
10 m
5 m
0 m
MFS
Equiv.
Calico
S.B.

Figure 17

Figure 18. Photograph of heterolithic channel fill sandstones from Tibbet Canyon. The coarse-grained fluvial deposits of the Calico bed are shown in the foreground (#1). These are overlain by thin carbonaceous shales (#2) that contain root and some horizontal burrows. Erosionally overlying these fine-grained deposits are heterolithic channel fill sandstones which comprise the majority of the photograph. Note the inclined erosional surfaces that are draped with mud- and siltstone (see arrows).

Figure 19. Measured section from Rock House Cove illustrating the development of an alluvial transgressive systems tract deposited approximately 60 km landward from a coeval shoreline deposit. Inclined heterolithic strata consisting of ripple, wavy, and flaser bedded sandstones alternate with persistent mudstone drapes that extend into the base of the channel. A photograph of these strata is shown in Figure 10. Refer to Fig. 14 for the legend for this measured section.

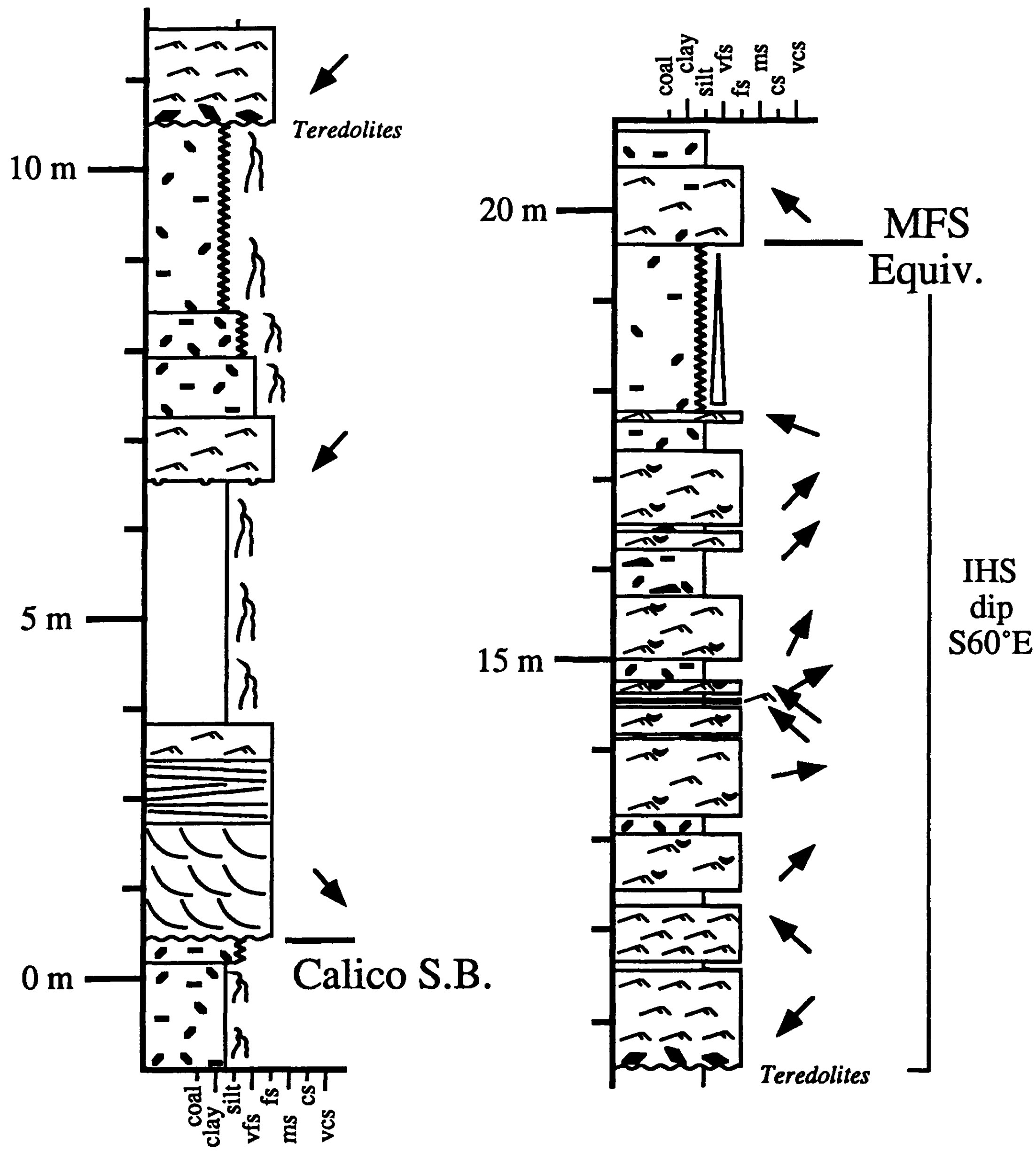

Teredolites
10 m
5 m
0 m
Calico S.B.
coal
clay
silt
vfs
fs
ms
cs
vcs
20 m
MFS
Equiv.
IHS
dip
S60°E
15 m
Teredolites

Figure 19

deposits within a tidally-influenced meandering river. Once again, discharge variations, perhaps on a seasonal basis, combined with tidal processes are invoked to explain the resulting sedimentological facies. *Teredolites* bored fossilized wood has also been found within the base of the channel fill complex providing corroborating biological data for this interpretation.

Tidally-influenced deposits associated with the A-sandstone transgressive systems tract

Facies associations near a coeval shoreline - Upper Valley

Tidally-influenced strata associated with the transgressive systems tract overlying the A-sequence boundary can be seen in exposures along Upper Valley (Figs. 3, 13). These strata were deposited in a mosaic of sedimentary environments associated with an open estuary setting near a coeval shoreline and are illustrated in Figure 20. Tidally-influenced strata (Fig. 20, 1.5-33.3 m) erosionally overlie swaley and hummocky cross-stratified shoreface sandstone (Fig. 20, 1.5 m). The facies juxtaposition of tidally reworked deposits overlying shoreface strata, the erosional relief, which locally exceeds 10 m, and the regional persistence of this erosional surface all support the interpretation of a sequence boundary. Wavy and lenticular-bedded sandstones interbedded with thin (0.5 m) fine-grained channel sandstones overlie the sequence boundary and are interpreted as mixed tidal flats and channel margin deposits (Fig. 20, 1.5-6.5 m). These strata, in turn, are erosionally overlain by amalgamated, tidally-influenced channel sandstones (Fig. 20, 6.5-33.3 m; Fig. 21). Individual channel fill strata are comprised of fining-upwards units that range in thickness from 1to 5 m. Channel lags containing inoceramid and oyster debris are common. Channel fill deposits contain complex-compound bedding, heterolitic strata, and

Figure 20. Measured section from Upper Valley illustrating the development of tidally-influenced strata deposited in an open estuary near a coeval shoreline (section courtesy of Robert D. Hettinger). These strata are within the transgressive systems tract associated with the A-sandstone. The sequence boundary at the base of the A-sandstone is shown at 1.5 m. The transgressive systems tract is shown from 1.5 to 33.3 m.

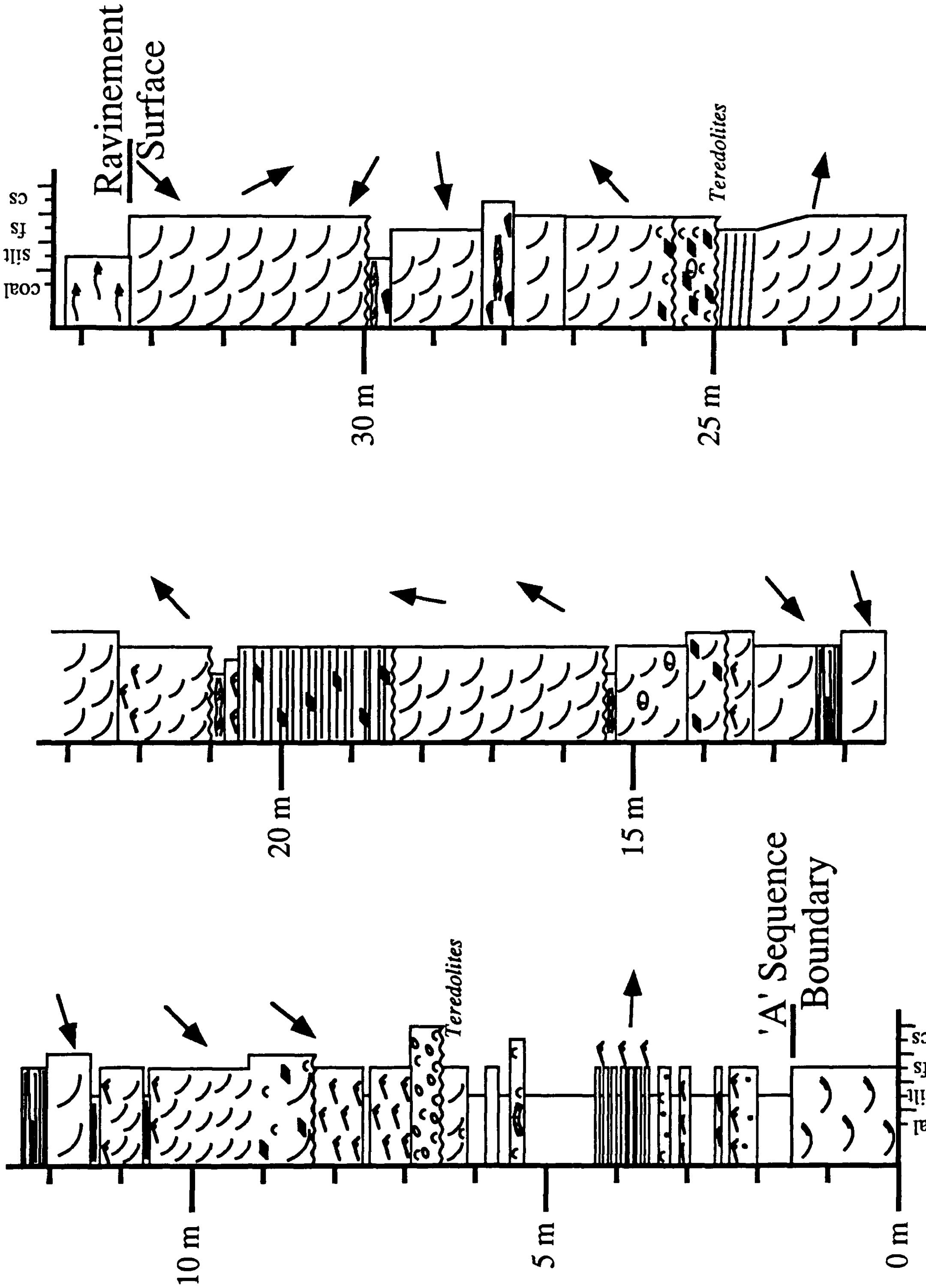

Ravinement Surface
Teredolites
30 m
25 m
20 m
15 m
'A' Sequence Boundary
Teredolites
10 m
5 m
0 m
coal
silt
fs
cs

Figure 20

Figure 21. Photograph of amalgamated tidally-influenced channel deposits from Upper Valley. The vegetated slope in the foreground is comprised of wavy and lenticular bedded sandstones interpreted as mixed tidal flat and channel overbank deposits. The alternation of heterolithic channel sandstones and more resistant weathering trough cross-bedded sandstones within the channel fill complex can be seen (photograph courtesy of Robert D. Hettinger).

trough and planar tabular cross-bedded sandstones containing multiple reactivation surfaces. The tidally-influenced channel deposits are abruptly overlain by offshore and lower-shoreface strata with the contact interpreted as a ravinement surface.

These strata are interpreted to be deposited within an open estuary during a rise in base level. Regional mapping in the Upper Valley area suggests that the incised valley, which was subsequently drowned, may have been as wide as 9 km.

Facies associations 40 km inland - Tibbet Canyon

Tidally-influenced fluvial strata deposited approximately 40 km inland from the open estuary setting of Upper Valley are exposed in Tibbet Canyon as part of the transgressive systems tract related to the A-sandstone complex (Fig. 3, 13). These deposits are described in Figure 22 (4.7 - 14.8 m level). These fluvial channel fill deposits consist of inclined heterolithic beds containing ripple-laminated and trough cross-bedded sandstones that alternate with persistent siltstone beds. Numerous internal scour surfaces can be followed within the channel fill complex (Fig. 23). Escape traces and synaeresis cracks are preserved in several of the ripple laminated sandstones within the channel fill and are thought to represent variations in salinity conditions. These strata are interpreted to represent episodic deposition within a tidally-influenced fluvial system. It is likely that the episodic deposition reflects a delicate interplay between variations in fluvial discharge and tidal processes within an estuarine setting.

Twenty kilometers further inland, evidence of tidal processes related to the transgressive systems tract of the A-sequence is limited to the occurrence of simple verical burrows and some U-shaped burrows at the top of isolated meandering river deposits.

Figure 22. Measured section illustrating the nature of heterolithic channel fill strata deposited approximately 40 km inland of a coeval shoreline. A photograph of this section is shown in Figure 23. Unlike previous sections, these strata are associated with the A-sandstone sequence (refer to Fig. 13). The sequence boundary at the base of the A-sandstone complex is shown at 0.6 m. The alluvial transgressive systems tract is shown from 4.7 - 14.8 m. This channel fill complex consists of alternating ripple and trough cross-bedded sandstones and thin persistent mudstone drapes. Note the occurrence of escape traces, *Teredolites*, and synaeresis cracks within this channel complex. Refer to Figure 14 for the legend for this measured section.

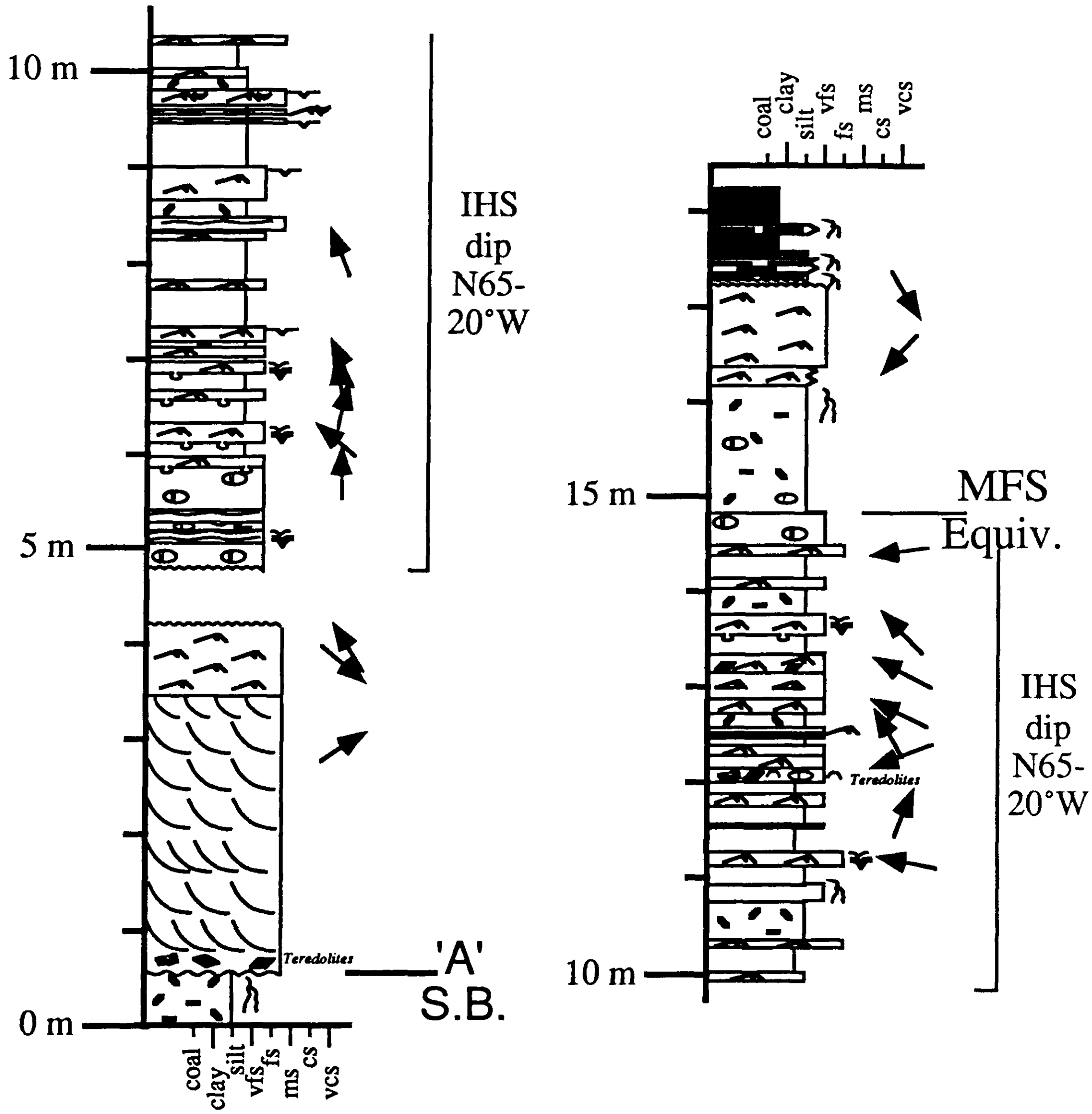

10 m
5 m
0 m
coal
clay
silt
vfs
fs
ms
cs
vcs
Teredolites
IHS
dip
N65-
20°W
'A'
S.B.
15 m
10 m
MFS
Equiv.
Teredolites
IHS
dip
N65-
20°W

Figure 22

Figure 23. Photograph of inclined heterolithic channel fill strata from Tibbet Canyon. These strata are interpreted as lateral accretion deposits within a tidally influenced river. The cliff face is approximately 10 m high. Note the persistent mud drapes that extend to the base of the channel sequence as well as the numerous internal erosion surfaces. The heterolithic strata and internal erosion surfaces likely reflect a complex interaction between discharge variations and tidal cycles.

DISCUSSION

The development of incised-river valleys and abrupt basinward shifts in facies tracts during periods of base-level lowering are an important phase in the development of many unconformity-bounded depositional sequences (e.g., Weimer, 1983; Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990). Fluctuations in sea level during the Pleistocene, for example, resulted in basinward shifts in facies tracts and widespread river valley incision across present day alluvial plains and many continental shelves (e.g., Fisk, 1944; Nelson and Bray, 1970; Pantin and Evans, 1984; Berryhill et al., 1986; Cameron et al., 1987; Demarest and Kraft, 1987; Suter et al., 1987; Thomas and Anderson, 1988, 1989; Zagwijn, 1989). The subsequent Holocene sea level rise over the last 15,000 years has resulted in the development of a transgressive systems tract (Posamentier et al., 1988) throughout many coastal regions. Similar to these recent examples, base-level lowering in the Turonian through Santonian resulted in basinward shifts in facies tracts and development of both the Calico and A-sequence boundaries. The subsequent base-level rises resulted in development of transgressive systems tracts

A significant component of these transgressive systems tract deposits, whether they be Cretaceous or Holocene in age, are the development of extensive estuaries within drowned river valleys and the preferential development of tidally-influenced facies (e.g., Campbell and Oaks, 1973; Nio, 1976; Roy et al., 1980; Nichols and Biggs, 1985; Colman et al., 1990; Fletcher et al., 1990). Fairbridge (1980) defined an estuary as "...an inlet of the sea, reaching into a river valley as far as the upper limit of tidal rise." This is a physically based definition which, Nichols and Biggs (1985) suggest, should be used for sedimentological purposes; this definition is less affected by short term, dynamic changes in the estuary than other definitions (e.g., Clifton, 1982; Reading, 1986).

The effect of tidal processes in fluvial strata

Although the effect of tides on sedimentary processes along coastlines may be somewhat predictible through an understanding of tidal range, wave strength, and coastline morphology (Hayes, 1975, 1979), their effect within drowned river valleys are highly variable and less well understood. Studies of drowned river-valley estuaries suggest that tides are the dominant energy source responsible for mixing fresh and saline waters and for controlling sediment distribution patterns. Furthermore, tidal effects can be pronounced well beyond the limit of saline water intrusion (e.g., Gelfenbaum, 1983; Allen, 1984; Nichols and Biggs, 1985) and hence well beyond those definitions of an estuary that are based on some degree of fresh-water mixing with seawater. Within estuaries, tidal waves are modified as a result of friction and estuary convergence (narrowing of the estuary). This results in pronounced tidal current asymmetry. The combination of frictional effects and convergence within an estuary generally results in hypersynchronous estuaries characterized by a gradual increase in tidal range and tidal current velocity towards the middle and landward reaches of the estuary (Salomon and Allen, 1983; Nichols and Biggs, 1985). Although hypersynchronous estuaries are the most common, examples of hyposynchronous estuaries, those in which frictional effects overcome convergence to produce a progressive decrease in tidal wave amplification, also exist. As a result, pronounced changes in tidal range, tidal asymmetry, and maximum current velocity can occur in a landward direction within the estuary that do not directly reflect the tidal range near the coastline (Table 1).

Although tidal processes are largely responsible for the distribution of sediment within estuaries, they are substantially modified by variations in fluvial discharge. During

Table 1

Estuary Location	**Tide range at estuary mouth**	**Tide range at distance upstream**	**Author**
Guayas Estuary, Ecuador	1.8m	3.3m, 20 km	Murray et al., 1975
Oosterschelde, Netherlands	1.8m	3.5m, upstream limit	Kohsiek at al., 1988
Westerschelde, Netherlands	2.4m	3.5m, 35km	Boersma and Terwindt, 1981
Gironde Estuary, France	2.5m	6m, 70-90km	Allen, 1984
Ord River, Australia	4.3m	2m, 42km	Wright et al., 1975

Table 1. Overview of some Holocene estuaries in which tidal effects have been observed at various distances upstream of an open coastline. Significantly, the tidal range at the coastline has only a minor effect on the tidal effects upstream.

periods of reduced discharge, saline incursions may extend many tens of kilometers up the fluvial system and tidal processes including slack water conditions may persist for distances of 10's to more than 300 km inland. Conversely, during periods of increased fluvial discharge, fresh waters may occur near or beyond the mouth of the estuary and tidal processes may be more restricted to the lower reaches of the estuarine complex (Allen, 1984; Nichols and Biggs, 1985). As a result, the turbidity maximum which develops within the estuary can translate tens of kilometers as a function of both discharge and tides. In the Gironde estuary of southwestern France, for example, salt water intrusion extends 30-70 km up river depending on fluvial discharge, and slack water conditions have been described 150-160 km up river (Allen, 1984; Nichols and Biggs, 1985). The Chesapeake estuary on the east coast of the United States is a microtidal system in which salt water intrusion extends 290 km upstream and in which slack water conditions have been recorded 330 km upstream. The Columbia River estuary on the west coast of North America is also a microtidal estuary where salt water intrusion extends only 37 km upriver, yet tidal flow reversals extend 85 km upriver, and tidal height fluctuations are observed as far as 225 km upriver at Bonneville Dam (Gelfenbaum, 1983). Although the tidal range at the estuary mouth is an important factor, it is clearly not the only factor that must be considered in the evolution of tidal processes within drowned river valley estuaries.

Fluvial strata within the transgressive systems tracts of the Calico and A-sandstone in the Kaiparowits Plateau suggest that tidal processes may significantly modify fluvial processes at least 65 km upstream from an open estuary or coeval shoreline. This is well within the scope of observations made in several Holocene estuarine complexes. In point of fact, we might expect tidal evidence within fluvial deposits of the Kaiparowits Plateau to have extended considerably further to the west. Furthermore, we should expect sedimentary structures indicative of tidal processes to be a common component in many ancient fluvial deposits.

Practical significance of tidally-influenced fluvial strata

Introduction:

While recognition of tidally-influenced fluvial deposits is of interest from a purely sedimentological viewpoint, it is also of considerable practical interest to those interested in chronostratigraphic correlation of strata. Understanding the significance of tidally-influenced alluvial strata requires consideration of the physical and temporal controls on alluvial aggradation.

As used in this paper, base level refers to an imaginary and dynamic "...equilibrium surface ... above which a particle can not come to rest and below which deposition and burial is possible" (Sloss, 1962, p. 1051). Changes in base level, whether they be driven by tectonic effects, eustatic changes, or some combination of the two result in changes in accommodation space which in turn governs sediment body geometry and distribution (e.g., Jervey, 1988). In nonmarine strata, base level may be approximated by the concept of the graded stream profile (Mackin, 1948; Leopold and Bull, 1979) whereas in nearshore environments it is represented by mean sea level. The rate at which base level changes, and the rate at which sedimentary systems are able to adjust to those changes govern the variations in facies architecture within a stratigraphic sequence. While quantitative data sufficient to describe these relationships are presently unavailable, examination of ancient depositional sequences offer considerable insight into the controls on depositional architecture.

Fluvial aggradation, base level changes, and temporal correlations:

The rate of base-level rise can have a profound effect on the timing and degree to which alluvial aggradation occurs, and the extent to which tidal effects are reflected upstream of contemporaneous shoreline deposits. Studies of dam engineering projects and reservoir siltation projects provide an opportunity to study the effects of a near instantaneous base-level rise on alluvial systems (e.g., Eakin, 1936; Stevens, 1936, 1946; Strand, 1968; Lara and Sanders, 1970; Lara, 1972, 1983; Chitchob and Cowley, 1973; Condit et al., 1978; Ferrari, 1988; Lyons and Randle, 1988; Posamentier and Vail, 1988; Orvis, 1989). These studies suggest that during rapid base-level rise, significant aggradation does not occur until the rate of base-level rise is reduced and the river begins to readjust to grade. Posamentier and Vail (1988) employed the concept of a bayline and its position relative to an equilibrium point to describe the readjustment to grade and its effect on fluvial aggradation; their conclusions are similar to ours. A rapid rise in base level will result in a significant landward translation of depositional environments, and deposition of a thin veneer of fluvial sediment. In vertical section, these sediments "deepen upwards" as tidal/estuarine conditions are rapidly emplaced over former fluvial deposits. This scenario is illustrated in schematic fashion in Figure 24a, which is a longitudinal profile of a fluvial valley during transgression, and Figure 24b which is the accompanying time-distance facies plot (Wheeler diagram). Because of the rapid rise in base level, tidally-influenced sediments may be deposited directly over braided river deposits and may be observed at a considerable distance inland of the transgressive maxima observed in marine strata. Fluvial strata overlying the Calico sequence boundary record the juxtaposition of tidally-influenced conditions directly on coarse-grained, braided river deposits. As the rate of base-level rise is reduced and the alluvial system begins to readjust to grade, the point to which the river is

Figure 24a. Longitudinal cross section through a fluvial system illustrating the stratal geometries resulting from a rapid rise in base level. Only a very thin veneer of sediment is deposited during the initial rise. Note that tidally-influenced strata may lie directly over braided river deposits.

Figure 24b. Wheeler diagram (vertical axis is geologic time, horizontal axis is distance) illustrating the chronostratigraphic relationships present in the cross section of Fig. 24a. Note that the upper portions of the tidally influenced fluvial strata are temporally equivalent with the maximum flooding surface in nearshore and marine strata.

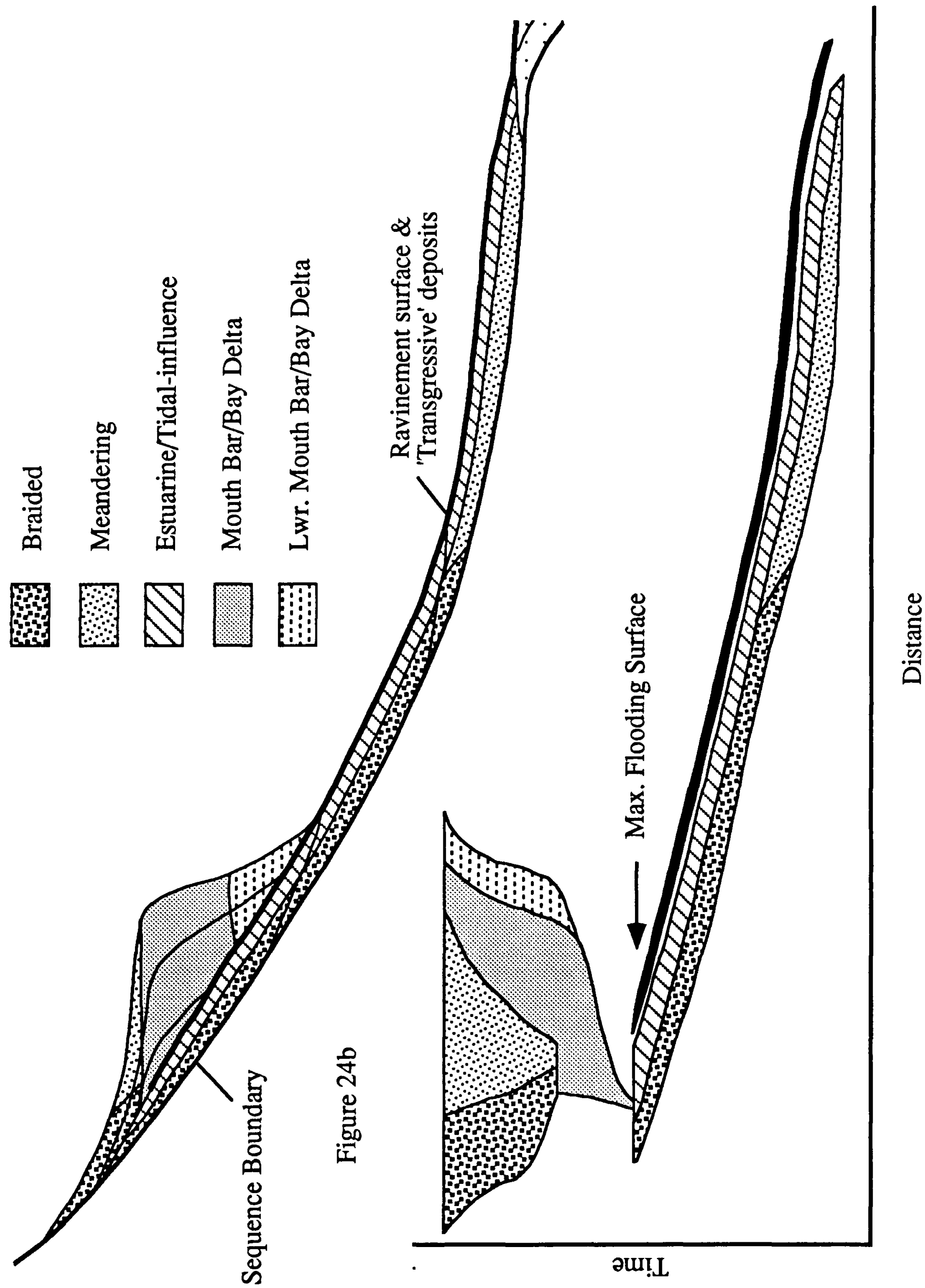


Figure 24a
Braided
Meandering
Estuarine/Tidal-influence
Mouth Bar/Bay Delta
Lwr. Mouth Bar/Bay Delta
Ravinement surface &
'Transgressive' deposits
Sequence Boundary
Figure 24b
Max. Flooding Surface
Time
Distance

graded will move seaward resulting in the creation of significant subaerial accommodation space and allowing substantial fluvial aggradation (Fig. 24).

Under conditions of more slowly rising base level, where sediment supply is more in balance with the rate of base-level rise, minor fluvial aggradation may actually accompany the rise in base level (Fig. 25). This is because the fluvial system maintains a profile somewhat similar to its graded profile. As a result, accommodation space created during the base-level rise may be partially filled with alluvial sediment (Fig. 25). This results in an early phase of aggradation that may extend a considerable distance inland before the marine transgressive maxima is reached (Fig. 25). Deposition of fluvial strata overlying the A-sequence boundary may be representative of a slow rate of base-level rise. As with the case of the rapid rise in base level, the majority of alluvial sedimentation, however, is more likely to occur as the rate of base-level rise is reduced allowing the point to which streams are graded to move significantly basinward.

CONCLUSION

1. Tidal processes can significantly affect fluvial sedimentation well inland of any coeval shoreline. Study of modern drowned-river valley estuaries suggests that tidal processes can persist many tens to hundreds of kilometers upstream, and may, in fact, be magnified relative to their effect along coeval shorelines. Our study of Turonian through Campanian strata from the Kaiparowits Plateau suggests that tidal processes can be recognized at least 65 km inland of a contemporaneous shoreline in strata that have previously been interpreted as simple meandering river deposits.

Figure 25a. Longitudinal cross section through a fluvial system illustrating the stratal geometries resulting from greatly reduced rates of base level rise relative to Figure 24. In contrast to Figure 24, an early phase of fluvial aggradation may accompany a slow rate of base level rise.

Figure 25b. Wheeler diagram (vertical axis is geologic time, horizontal axis is distance) illustrating the chronostratigraphic relationships present in the cross section of Fig. 25a. Note that the upper portions of the tidally influenced fluvial strata are temporally equivalent with the maximum flooding surface in nearshore and marine strata.

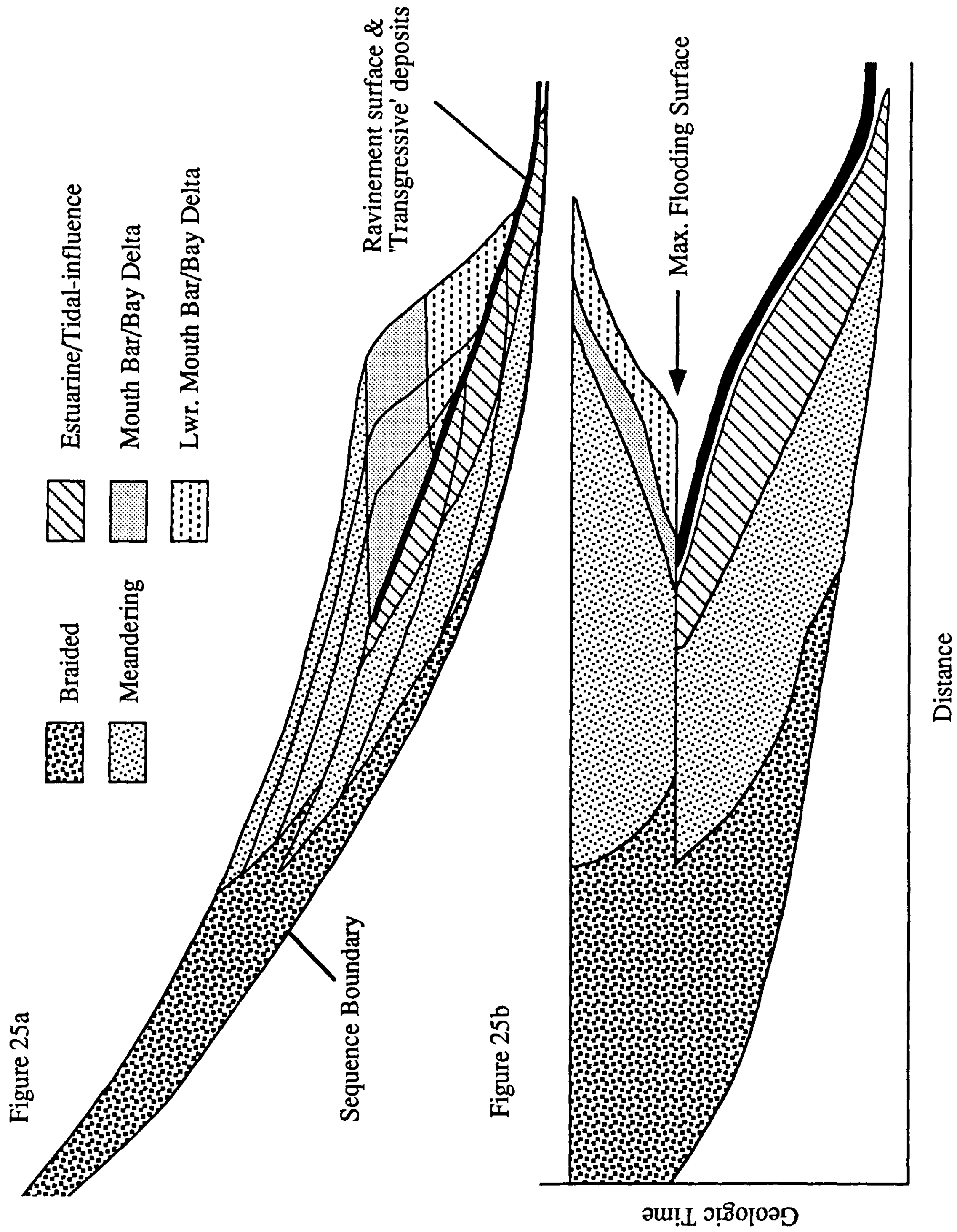


Figure 25a
Braided
Meandering
Estuarine/Tidal-influence
Mouth Bar/Bay Delta
Lwr. Mouth Bar/Bay Delta
Ravinement surface &
'Transgressive' deposits
Sequence Boundary
Figure 25b
Max. Flooding Surface
Distance
Geologic Time

2. When alluvial strata are viewed in the context of depositional sequences, recognition of tidal influence allows construction of a high-resolution chronostratigraphic framework within nonmarine deposits. As McCave (1969) suggested, there is a direct correlation between base-level rise and alluvial aggradation. Examination of coeval marine and nonmarine strata in the Kaiparowits Plateau suggests that tidally influenced fluvial deposits contained within an otherwise alluvial succession are temporally equivalent with maximum flooding surfaces in marine strata. When combined with sequence boundary unconformities, this correlation allows time-significant surfaces to be extended from marine into nonmarine strata.

3. Recognition of the alluvial portion of transgressive systems tracts requires identification and interpretation of subtle sedimentary features. With increasing distance upstream, the diagnostic features that suggest tidal influence become increasingly difficult to resolve. The Kaiparowits Plateau suggests that these features may be recognized as much as 65 km inland of a coeval shoreline. In subsurface studies that rely on core data or wireline logs, the necessary criteria would be quite difficult to recognize. Under these conditions, the interpretation of an alluvial transgressive systems tract might be better supported by changes in overall alluvial architecture from laterally amalgamated fluvial deposits to more isolated channel deposits that have an increasing amount of fine-grained overbank deposits preserved (Shanley and McCabe, 1990b).

Chapter 7

CONCLUSIONS

The goals of this research were: (a) to determine the variation in stratal architecture in fluvial, coastal plain, and nearshore strata within the context of unconformity-bounded stratigraphic sequences, and (b) to test the hypothesis that the observed geometry, internal stacking patterns, and style of a depositional environment are related to its position within an unconformity-bounded depositional sequence (see chapter 2). Examination of Turonian through Campanian strata in the Kaiparowits Plateau during the course of this research has accomplished these goals. The results of much of this research have been presented in the form of 'stand-alone papers'. This chapter summarizes the conclusions reached to date regarding this research effort in the Kaiparowits Plateau of Utah and discusses some problems that might be future areas of research.

1. Within the upper part of the Tropic Shale and the Straight Cliffs Formation, recognition of sequence boundary unconformities and major flooding surfaces in nearshore, coal-bearing, and alluvial strata has resulted in identification of at least five unconformity-bounded depositional sequences.

    (a) Sequence boundaries have been recognized in the Tibbet Sandstone Member, at the base of the Calico bed within the Smoky Hollow Member, within the A-sandstone near the base of the John Henry Member, and at the base of the Drip Tank Member. These surfaces are manifested by abrupt basinward shifts in facies tracts or abrupt changes in stratal stacking patterns related to erosional surfaces that can be traced throughout the plateau.

(b) Major flooding surfaces related to maximum-flooding surfaces within the depositional sequence have been recognized in nearshore and alluvial strata. Within nearshore strata, thin fossiliferous beds that separate deepening upwards from shallowing upwards strata are interpreted as condensed interval deposits. Tidally-influenced fluvial deposits are interpreted as the landward equivalents of marine maximum-flooding surfaces. Significantly, the effect of tidally-influenced conditions can be recognized many tens of kilometers inland of coeval shoreline deposits even in microtidal regimes.

2. Sequence boundaries and flooding surfaces allow systems tracts to be recognized in both nearshore and alluvial strata. Changes in alluvial architecture, shoreface parasequence stacking patterns, coal-seam development, and continental deposits are observed to occur in a predictible fashion.

(a) Early-highstand systems tract deposits consist of progradational shoreface parasequences such as the Tibbet Canyon Member and the lower part of the A-sandstone. Sequence boundary unconformities in alluvial strata erosionally overlie these shoreface parasequences and reflect a basinward shift in facies tracts. Coal seams are thin and laterally discontinuous. Continental deposits generally have well developed paleosol deposits.

(b) Late-highstand systems tract deposits consist of aggradational shoreface parasequences such as are seen in the majority of the John Henry Member. Alluvial deposits consist of thick, fine-grained overbank sediments and isolated meanderbelt sandstones. Coal seams are thick and laterally extensive. Continental deposits may have well developed paleosols and relatively thick lacustrine deposits.

(c) Strata within transgressive systems tracts consist of retrogradational shoreface parasequences that are capped with transgressive lags such as are seen at the top of the Calico bed within the Smoky Hollow Member and the top of the A-sandstone. Alluvial strata consist of laterally amalgamated channel sandstones that grade vertically into more isolated meanderbelts that were deposited under tidally-influenced conditions.

3. Sequence boundaries in the Kaiparowits Plateau can be correlated on the basis of stratal stacking patterns and biostratigraphic data with outcrops in Black Mesa, Arizona, the western and southwestern part of the San Juan Basin, New Mexico, and the Wasatch Plateau in central Utah.

(a) The Tibbet Canyon sequence boundary is interpreted to occur within the Upper Sandstone Member of the Toreva Sandstone in Black Mesa, within the Carthage Member of the Tres Hermanos Formation in the San Juan Basin, and is likely a correlative conformity related to emplacement of the Clawson and Washboard units of the Ferron Sandstone Member of the Mancos Shale in the Wasatch Plateau. The Tibbet Canyon sequence boundary is likely equivalent to the 90.5 ma sequence boundary of Haq et al. (1988).

(b) The Calico bed is interpreted to partially reflect the development of terrace deposits. Biostratigraphic data and stratal geometries suggest the Calico sequence boundary in the Kaiparowits Plateau was a surface of sediment bypass throughout much of the late Turonian and earliest Coniacian.

(c) The Calico sequence boundary is thought to separate the Middle Carbonaceous Member from the Upper Sandstone Member of the Toreva Sandstone in Black Mesa. In the San Juan Basin, this sequence boundary may well correspond to an abrupt basinward shift in parasequence stacking patterns within the Gallup Sandstone and in the Wasatch Plateau, this same sequence boundary is probably related to a basinward shift in parasequence patterns of the Ferron Sandstone Member of the Mancos Shale. The Calico sequence boundary represents a period of prolonged sediment bypass and is likely equivalent to the 90.0 ma sequence boundary of Haq et al. (1988).

(d) The A-sequence boundary is interpreted to occur within the Rough Rock Sandstone in Black Mesa. In the San Juan Basin this sequence boundary occurs within the Crevasse Canyon Formation. In the Wasatch Plateau, high subsidence rates may have prevented the formation of a sequence boundary unconformity. The A-sequence boundary is likely equivalent to the 88.5 ma sequence boundary of Haq et al. (1988).

(e) The Drip Tank sequence boundary has been interpreted within basal parasequences of the Emery Sandstone in the Wasatch Plateau as well as within an abrupt basinward shift in parasequence stacking patterns in the Point Lookout Sandstone in the San Juan Basin. The Drip Tank sequence boundary is likely equivalent to the 85 ma sequence boundary of Haq et al. (1988).

4. A lower Coniacian sequence boundary that is well developed in the San Juan and Denver Basins was developed during a period of continued sediment bypass in the Kaiparowits Plateau and Black Mesa regions (related to the Calico sequence boundary). High subsidence rates in the Wasatch Plateau prevented this surface from being developed as a subaerial unconformity. The suggestion of two significant sequence boundaries, one in the late Turonian and one in the early Coniacian differs from Haq et al. (1988). Although this research suggests that this may reflect an additional base-level cycle not observed by Haq et al. (1988) an alternative explanation may exist. Tectonic movement related to the uplift of basement blocks may lead to the development of significant unconformities that lack basinwide extent. Detailed sequence stratigraphic analysis of Turonian-Campanian age outcrops in the southern Colorado Plateau, San Juan, and Denver basins, combined with detailed subsurface analysis of both well log and seismic data may result in improved temporal and spatial understanding of the Turonian

and early Coniacian stratal boundaries. This work might then allow more definitive statements to be made regarding the tectonic control on these unconformities.

5. Detailed work in the Kaiparowits Plateau combined with stratal correlations to adjacent areas and comparison with the Haq et al. (1988) Mesozoic-Cenozoic Cycle Chart suggests that eustatic changes were an important control on the observed stratal geometries within third-order sedimentary cycles. Tectonic subsidence is interpreted to have a greater affect on accommodation space at the scale of second-order sedimentary cycles.

6. Consideration of sedimentary architecture in terms of changes in accommodation space and base level indicate that conceptual-based sequence stratigraphic models that were largely developed in passive margins are applicable in foreland basins with some modifications. It is expected, therefore, that the results of this research will have applicability in a variety of tectonic settings through a wide range of depositonal environments. The conclusions of this research regarding sedimentary architecture within a sequence stratigraphic framework should be tested in other tectonic settings as well as elsewhere in the Western Interior foreland basin.

7. This research identified two widely correlative pebble conglomerates that were interpreted as transgressive lag deposits. This interpretation was largely based on the vertical and lateral succession of depositional facies. An alternative

hypothesis would suggest that these pebble conglomerates are related to a base-level lowering, development of a sequence boundary, and superimposition of a flooding surface across the sequence boundary. This hypothesis was not favored because fluvial deposits with a similar grain size to the pebble conglomerates could not be identified at the appropriate stratigraphic horizon. A problem still remains, however, in that the pebble conglomerates, interpreted as transgressive deposits are more coarse grained than any adjacent fluvial or marine strata suggesting that the pebbles were likely not derived from underlying sediments. The question arises then as to the source of the pebbles. Although this research has suggested that they may have been transported along shore, there is little supporting evidence. Future research that places greater emphasis on provenance may be able to address the source of these enigmatic pebbles. The explanations offered thus far are often driven by an Occam's Razor solution, however, additional data is required.

8. This research has suggested that a sequence boundary may be associated with the abrupt progradation of the Ferron Sandstone Member of the Wasatch Plateau. Furthermore, this research has also suggested that increased subsidence rates in the Wasatch Plateau may have prevented the formation of an erosional unconformity. Subsidence rates in the Henry Mountain Basin were significantly less than those in the Wasatch Plateau and may offer the opportunity to carefully examine the Tununk Shale-Ferron Sandstone transition and the nature of the Ferron Sandstone. These outcrops have received only limited attention to date and have not received the detailed study that they deserve.

Chapter 8

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Appendix - A

LEGEND FOR DETAILED MEASURED SECTIONS

Physical Sedimentary Structures, Textures, and Constituents

Interbedded	Syneresis crack
Scour	Load cast
Trough cross bedded	Granules
Planar tabular cross-bed	Pebbles
Ripple cross-laminated	Clay clasts
Flaser-bedded	Wood debris
Wavy-bedded	Organic debris
Lenticular-bedded	Carbonaceous shale
Symmetrical ripple	Root traces
Scour & Fill	Massive
Sigmoid-geometry	Nodular/Concretion
Swaley cross-bedded	Coal spar
Hummocky cross-strat.	Plant material
Convolute lamination	

LEGEND-cont.

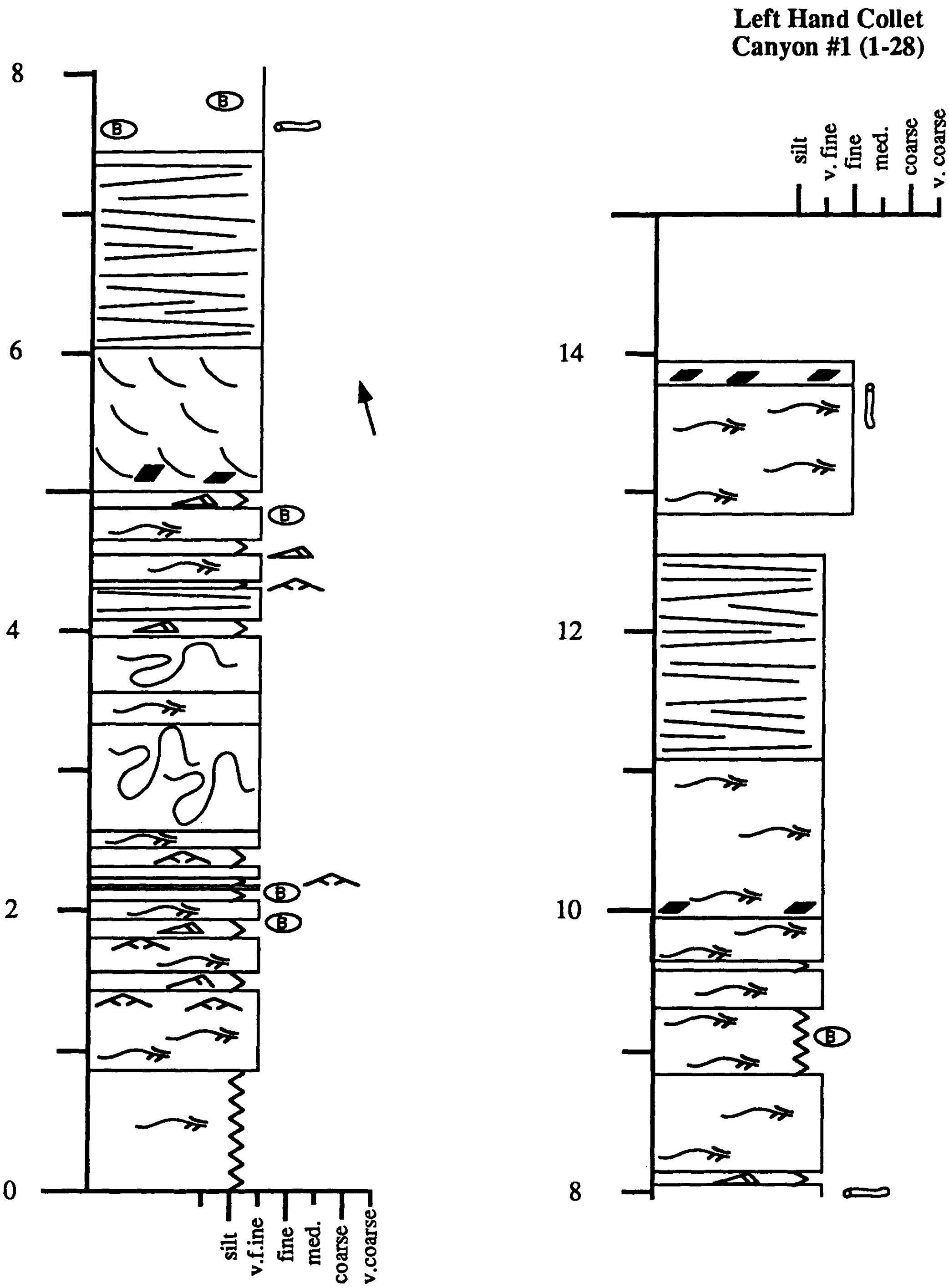
Biogenic Sedimentary Structures, Textures, and Constituents

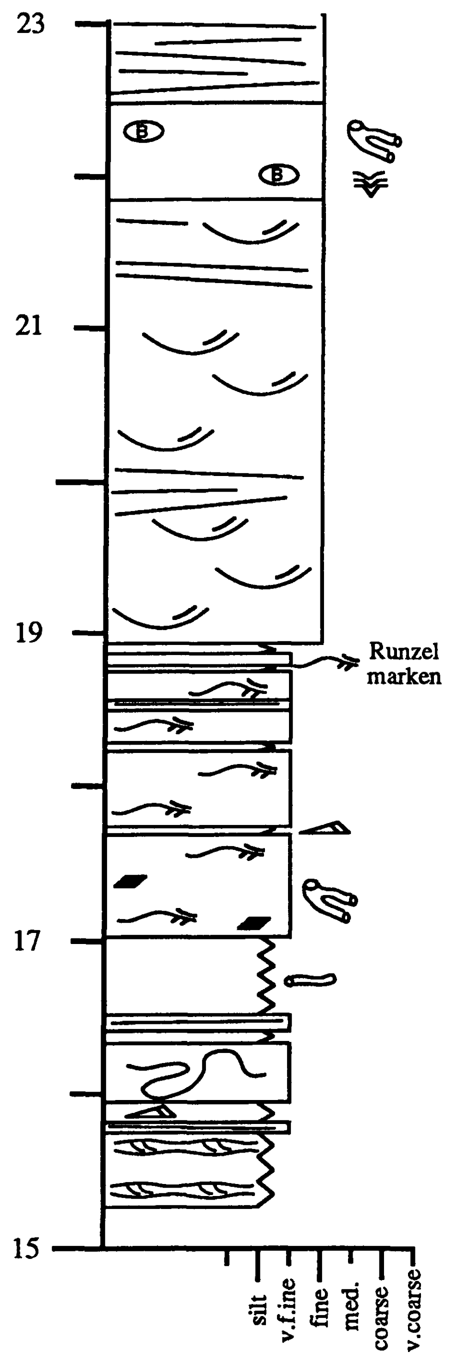
Inoceramid debris	Planolites
Mollusc shell debris	Ophiomorpha
Sharks teeth	Asterosoma
Thallasanoides	Escape Traces
Terebellina	Skolithos
Chondrites	Bioturbated

Appendix B

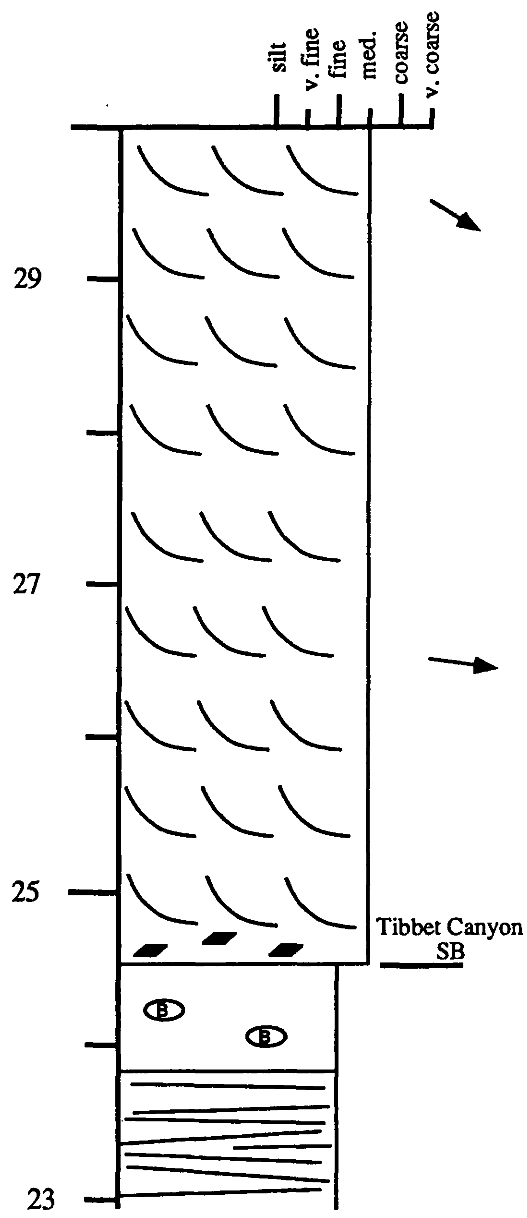
MEASURED SECTION, LEFT HAND COLLET CANYON

A detailed stratigraphic section was measured along the creek bed and the adjacent walls of Left Hand Collet Canyon, Township 38 south, Range 4 east, Kane County, Utah. The section extends from the upper part of the Tropic Shale to the lower part of the Drip Tank Member of the Straight Cliffs Formation. The canyon can be located on the U.S.G.S. Seep Flat Quadrangle - 7.5 minute topographic map. All measurements on the Left Hand Collet Canyon section are in meters.

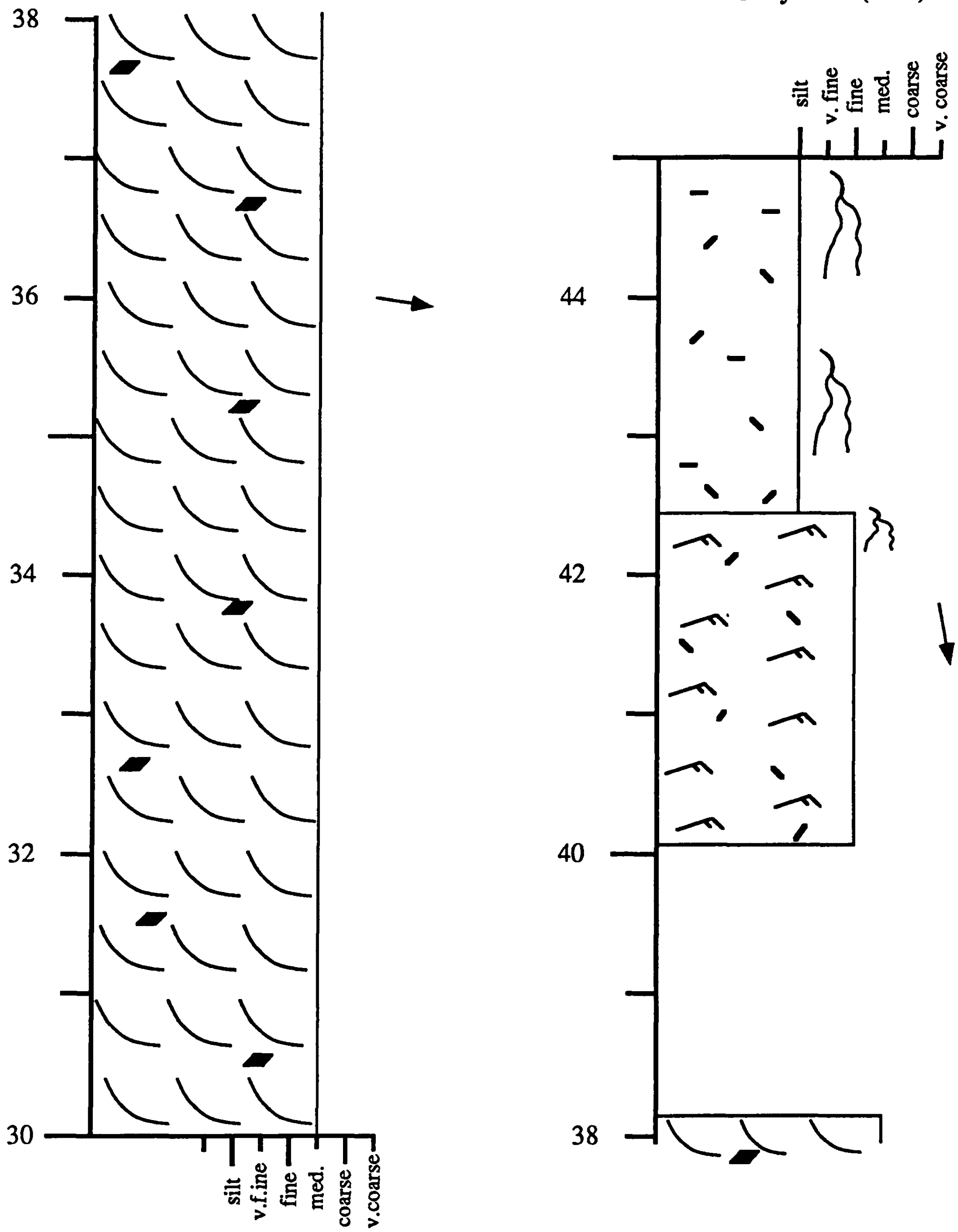

Left Hand Collet
Canyon #1 (1-28)
0
2
4
6
8
10
12
14
silt
v.f.ine
fine
med.
coarse
v.coarse
v. fine
v. coarse

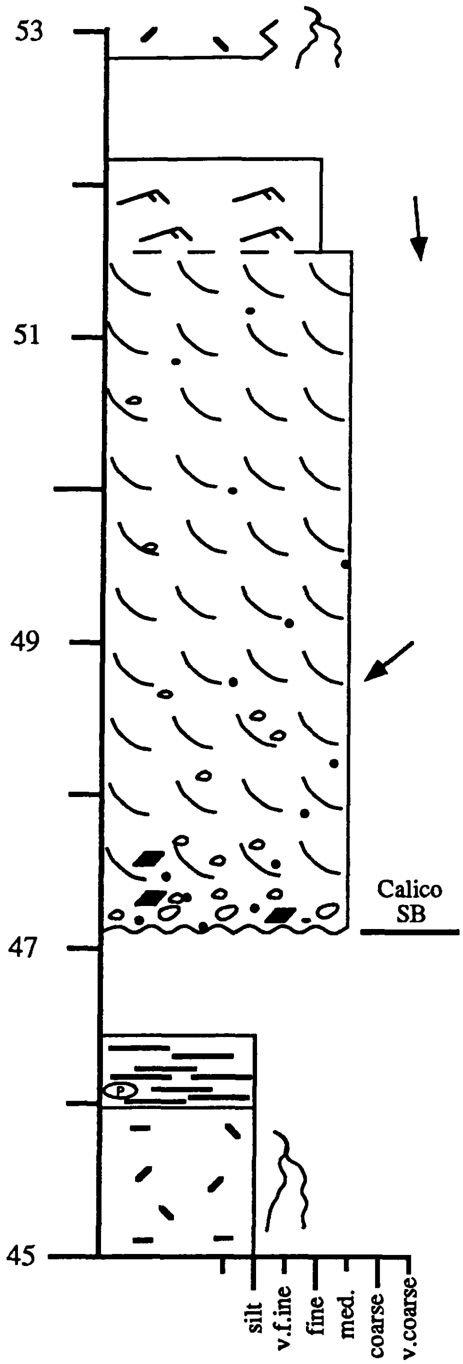


Left Hand Collet Canyon #1 (2-28)



Left Hand Collet Canyon #1 (3-28)

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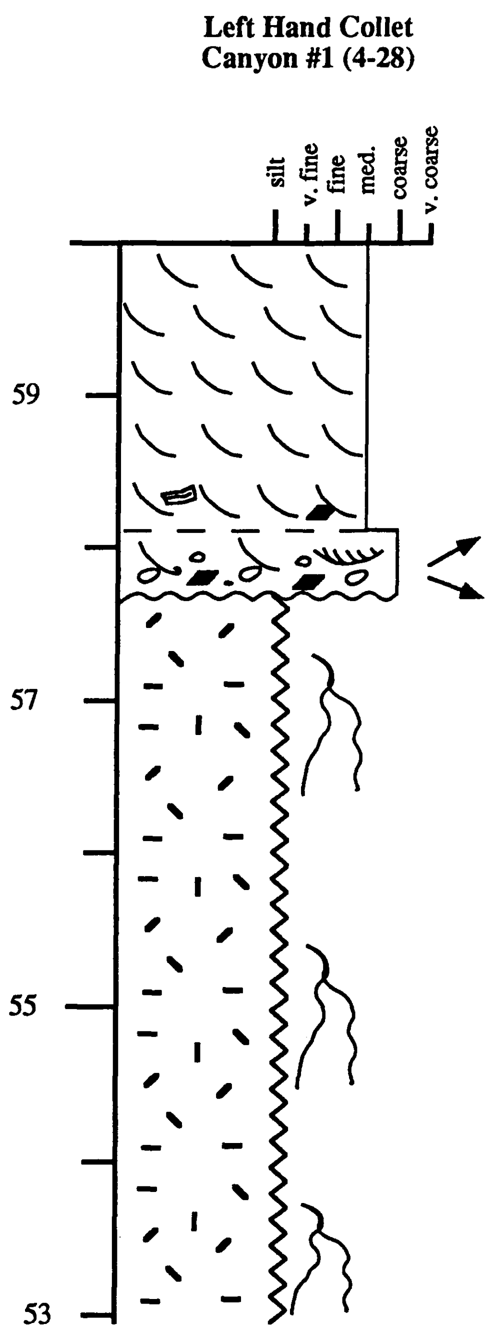
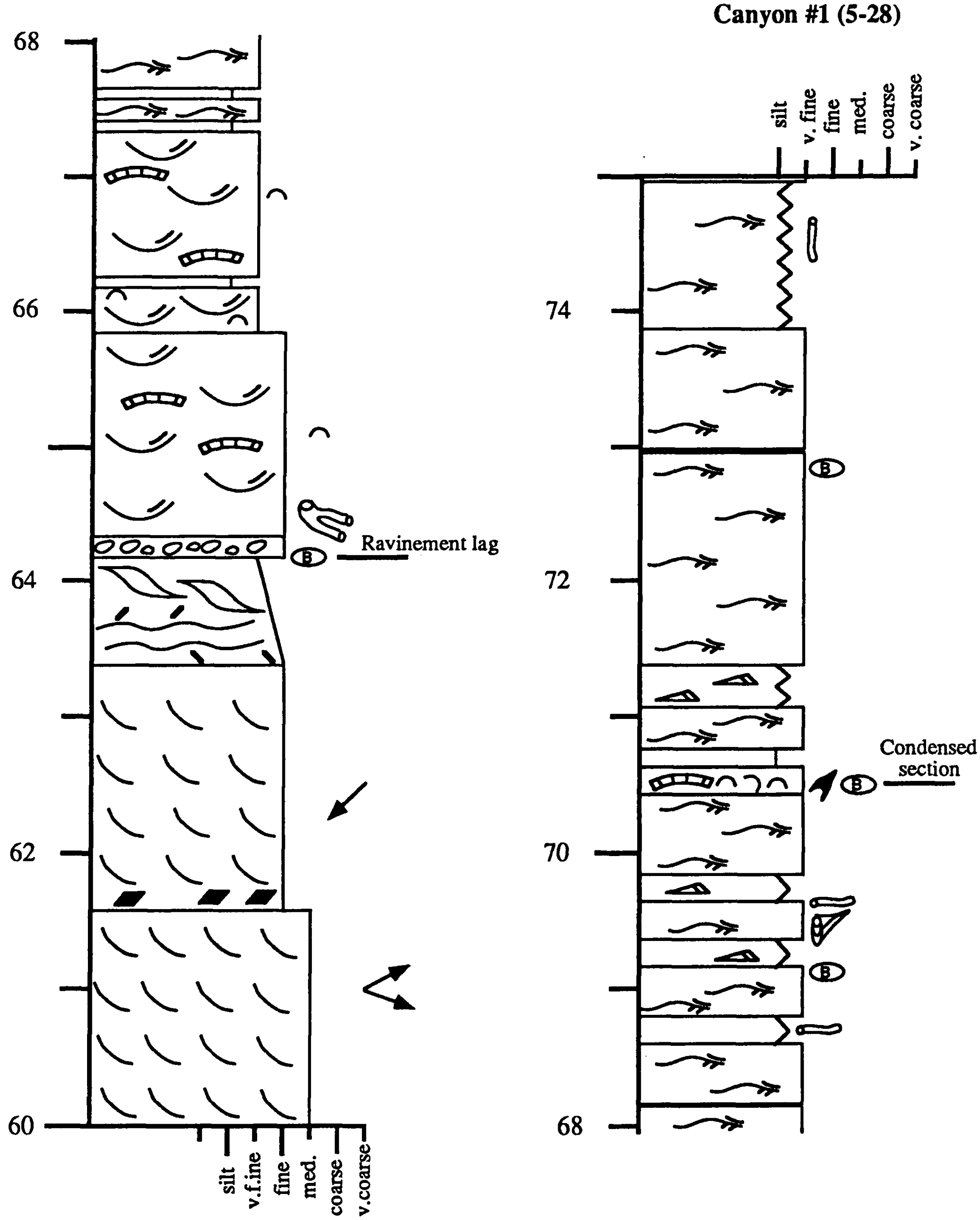
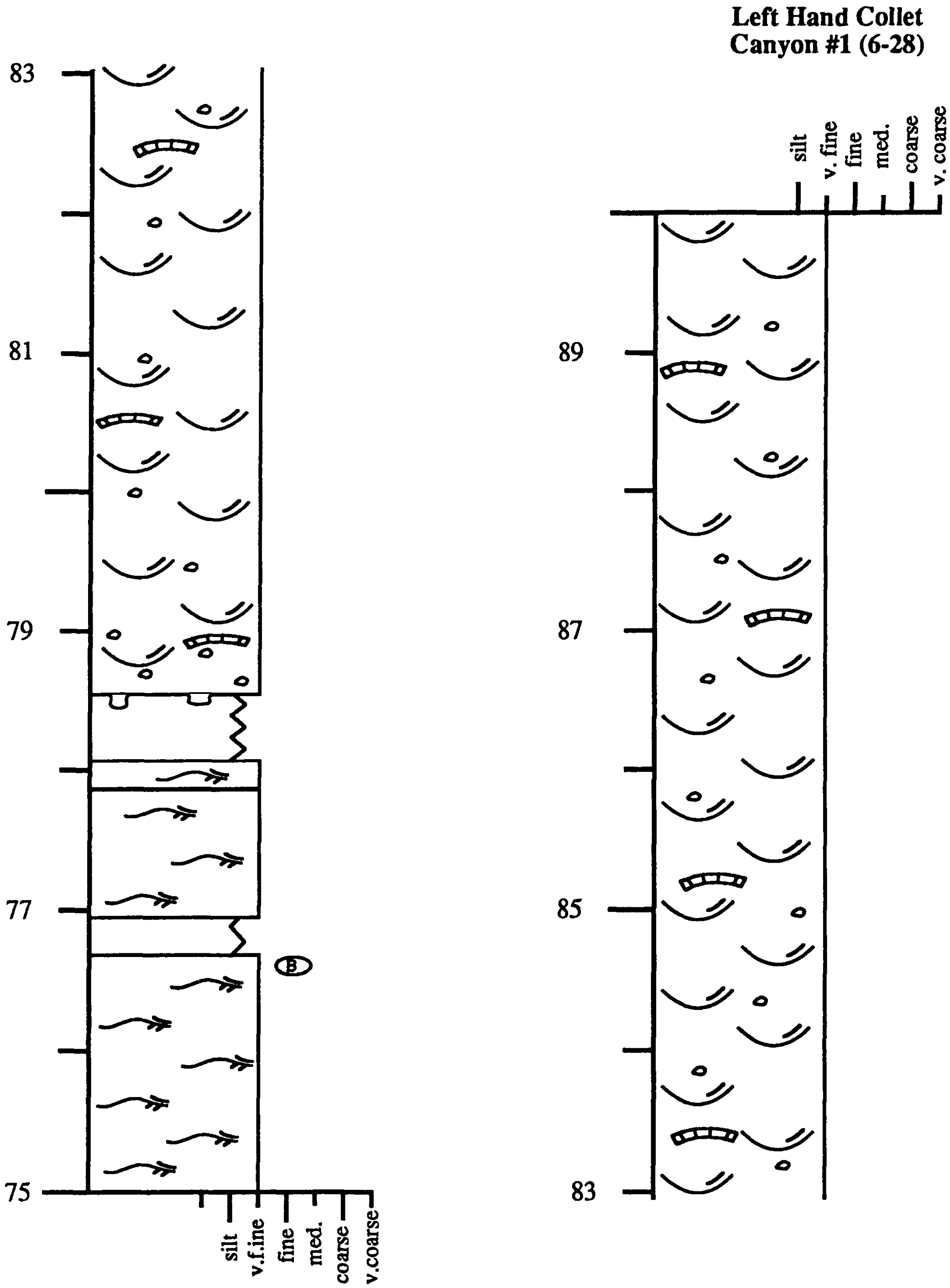
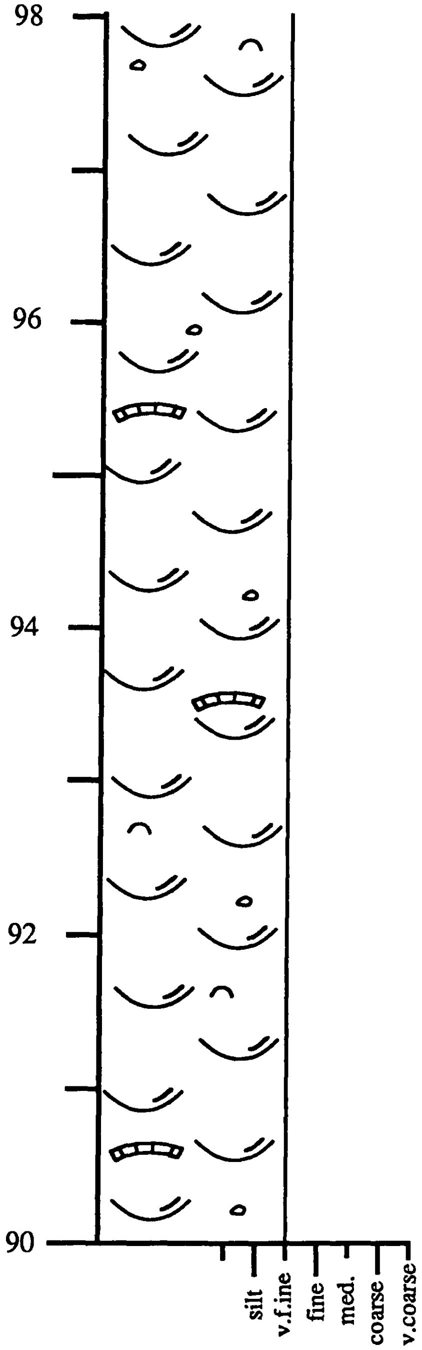
51
49
47
45
Calico
SB
P
silt
v.f.ine
fine
med.
coarse
v.coarse


Left Hand Collet
Canyon #1 (4-28)
silt
v. fine
fine
med.
coarse
v. coarse
59
57
55
53

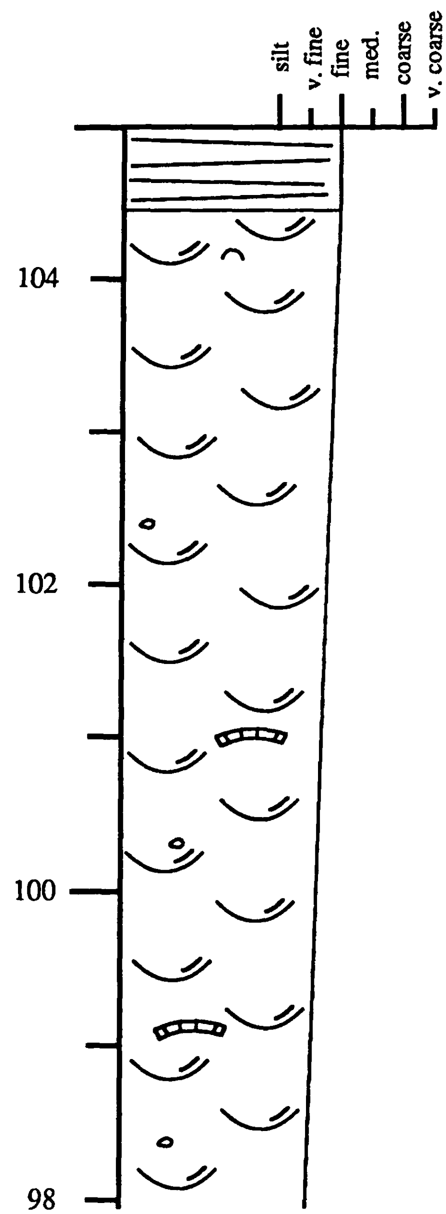
Left Hand Collet Canyon #1 (5-28)

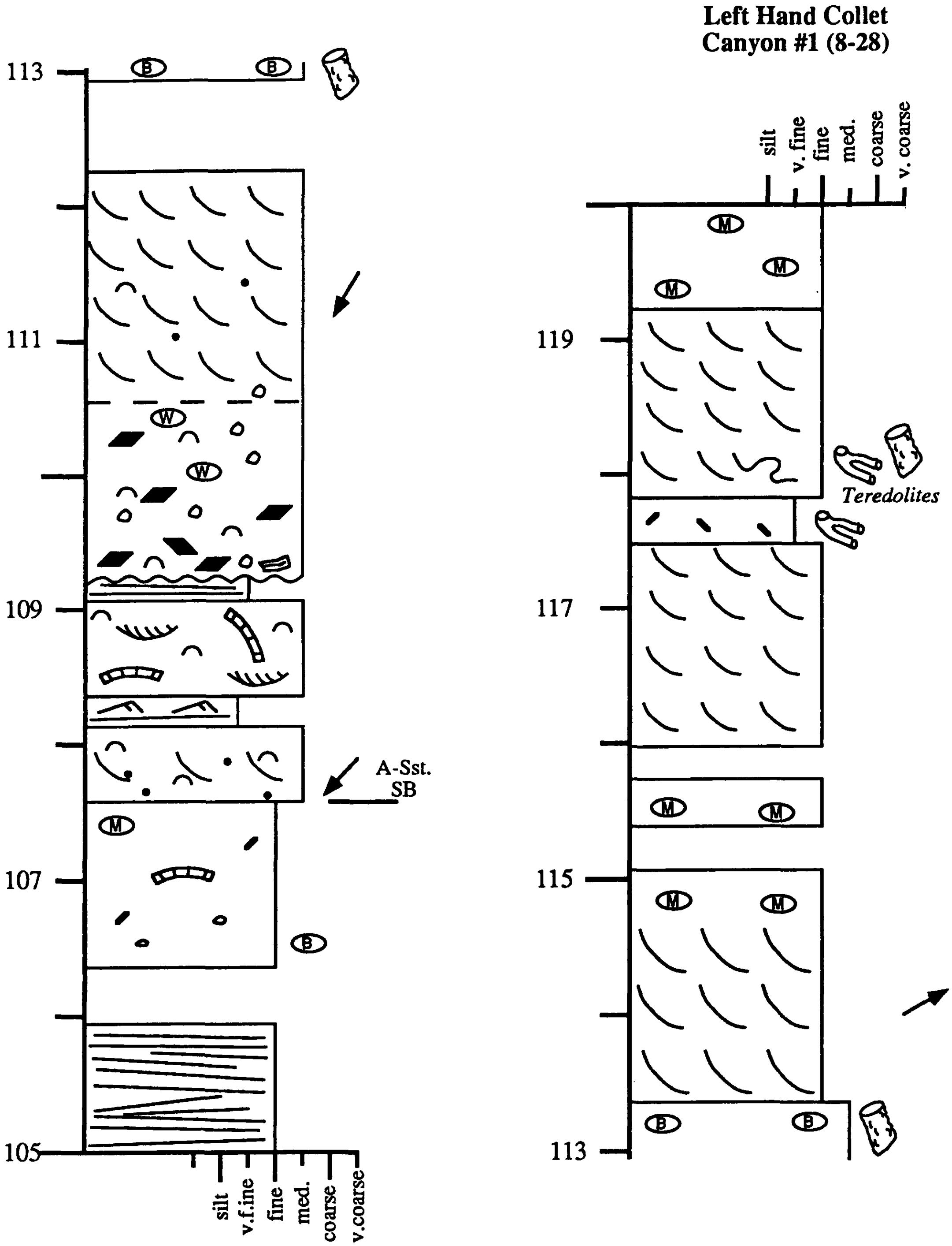



83
81
79
77
75
B
silt
v.f.ine
fine
med.
coarse
v.coarse
Left Hand Collet
Canyon #1 (6-28)
silt
v. fine
fine
med.
coarse
v. coarse
89
87
85
83



Left Hand Collet
Canyon #1 (7-28)

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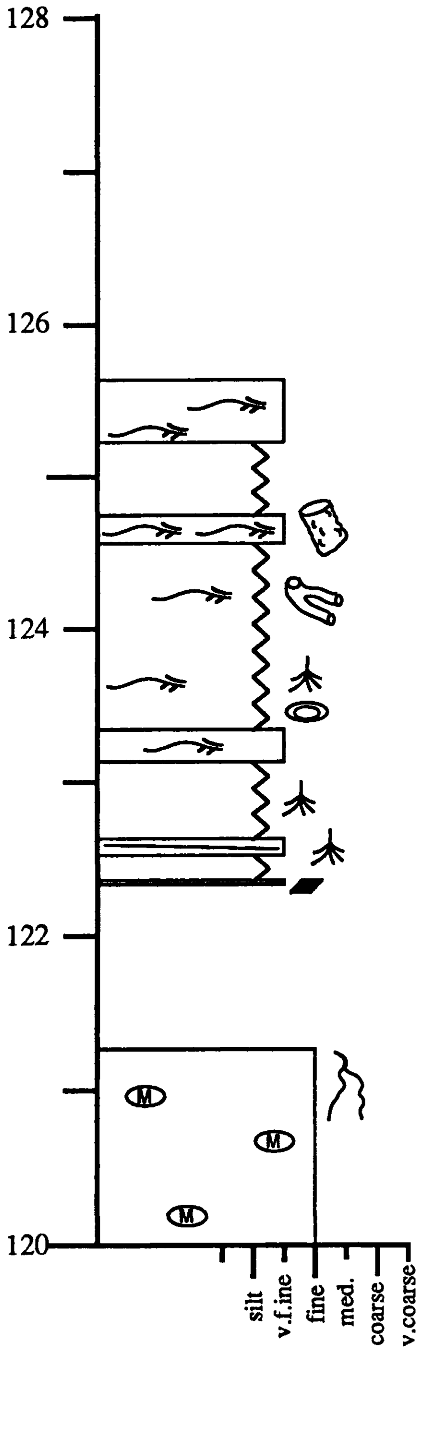
111
109
107
105
A-Sst.
SB
silt
v.f.ine
fine
med.
coarse
v.coarse
Left Hand Collet
Canyon #1 (8-28)
silt
v. fine
fine
med.
coarse
v. coarse
119
117
115
113
Teredolites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122
120
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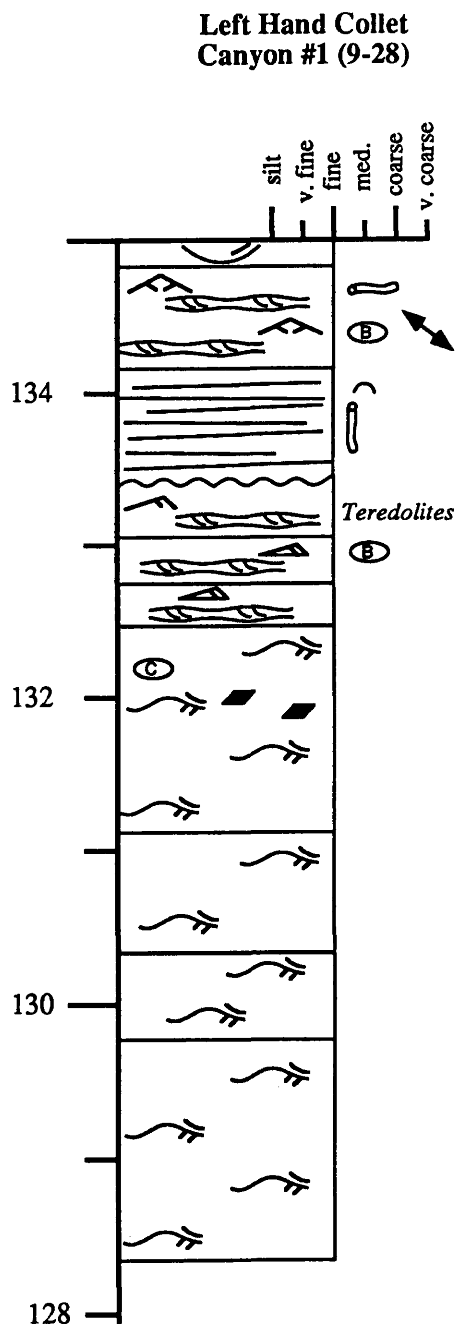
fine
med.
coarse
v.coarse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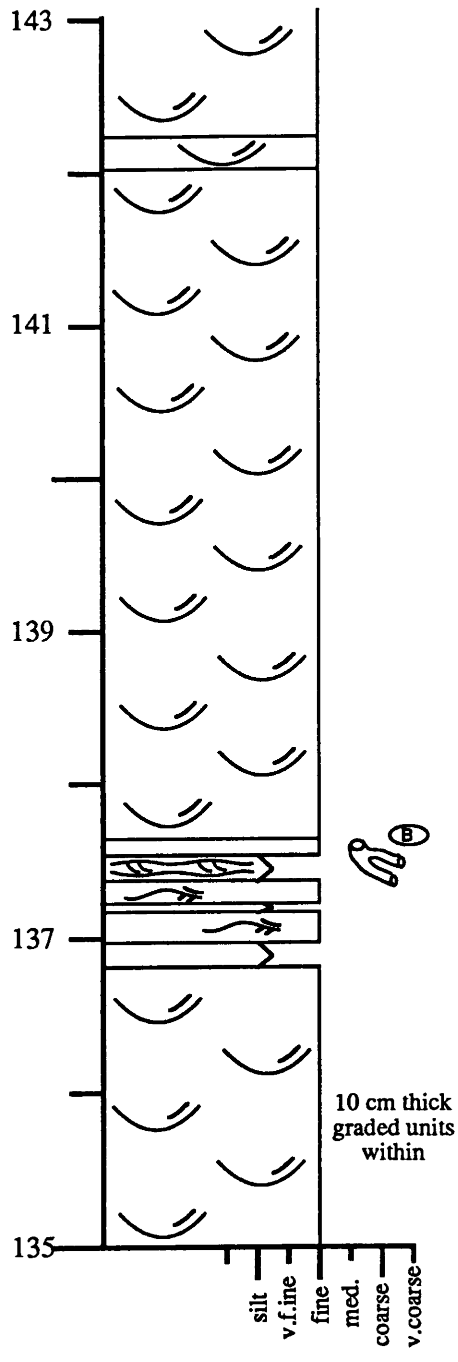
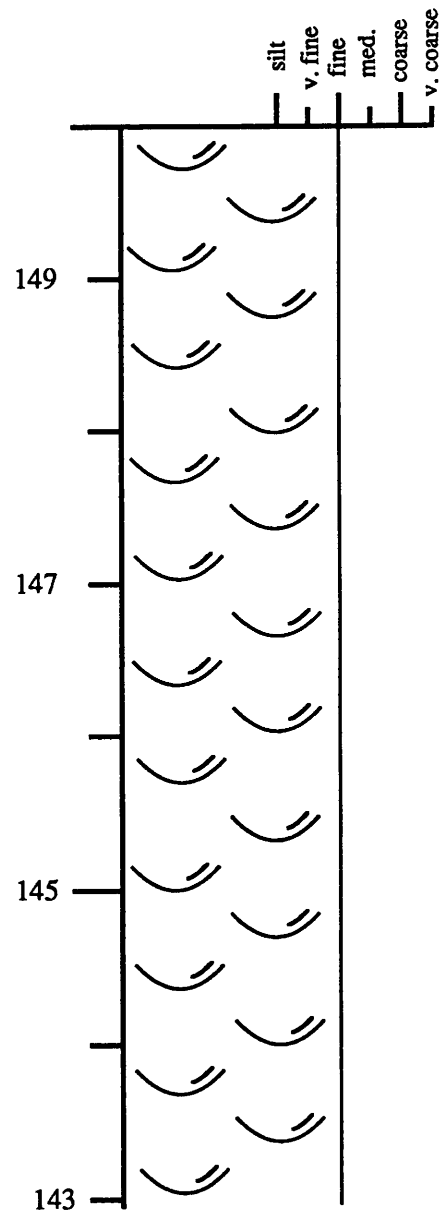
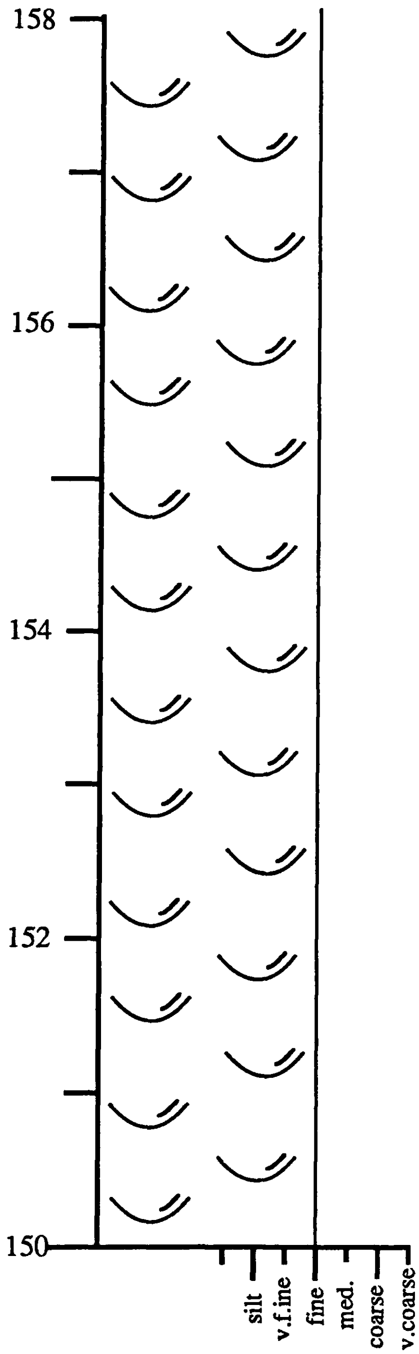
v. fine
fine
med.
coarse
v. coarse
134
132
130
128
Teredolites



Left Hand Collet
Canyon #1 (10-28)

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152
150
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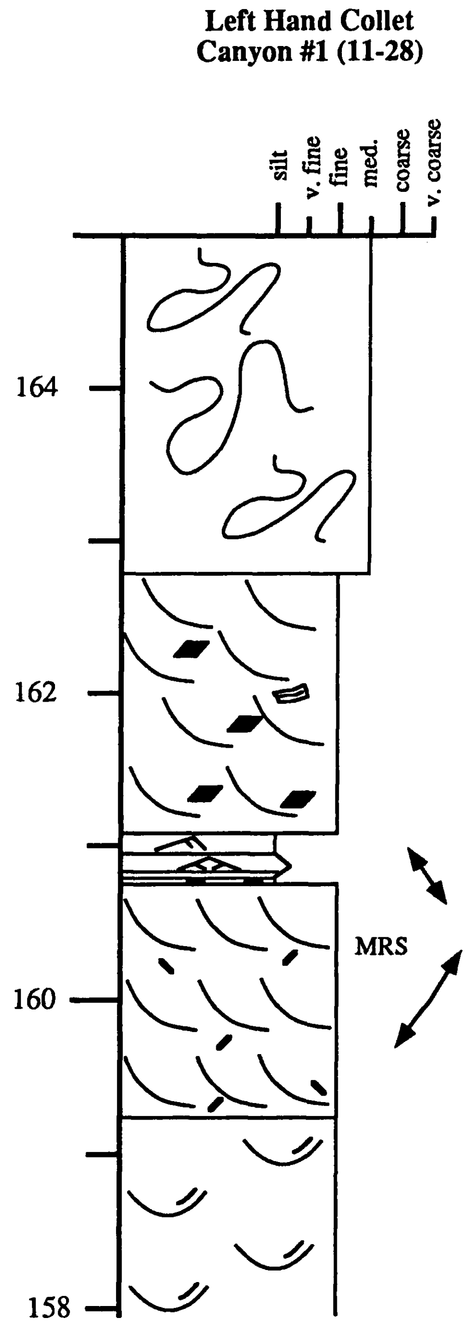
fine
med.
coarse
v.coarse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Canyon #1 (11-28)
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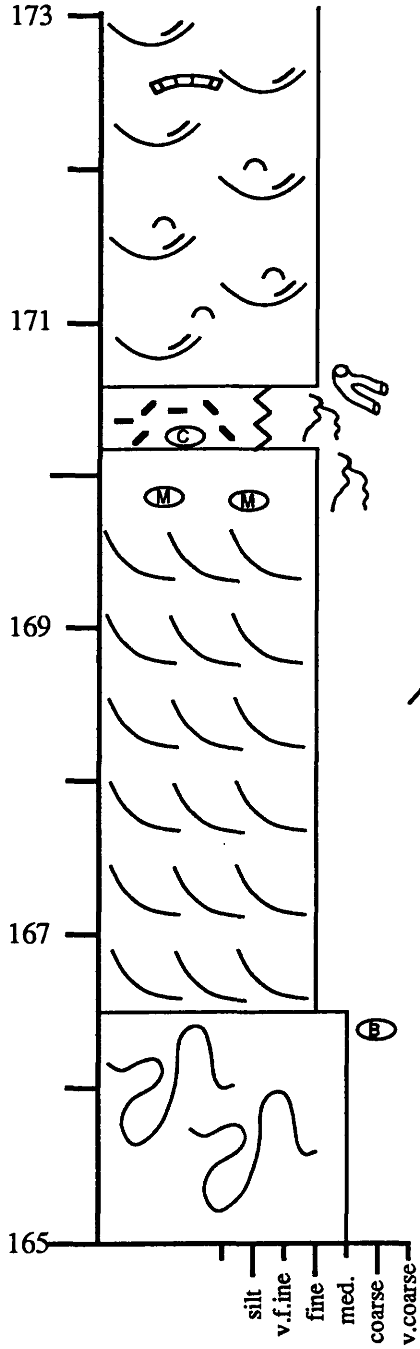
v. fine
fine
med.
coarse
v. coarse
164
162
160
158
MRS



Left Hand Collet
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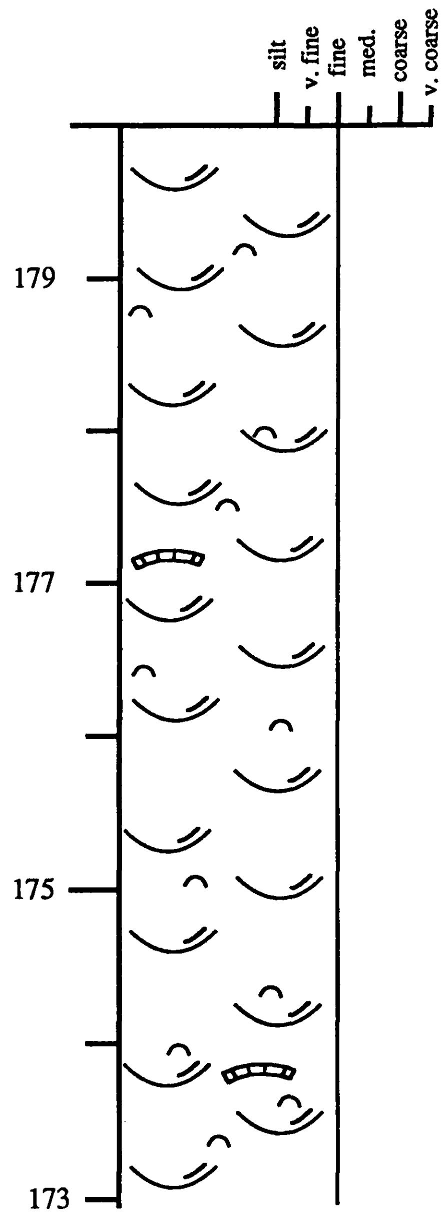

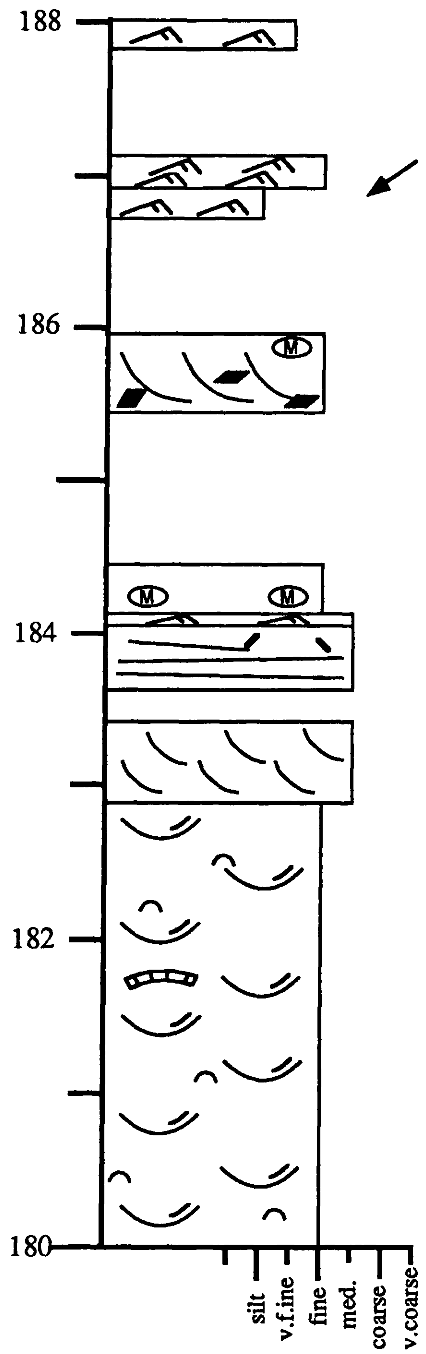
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180
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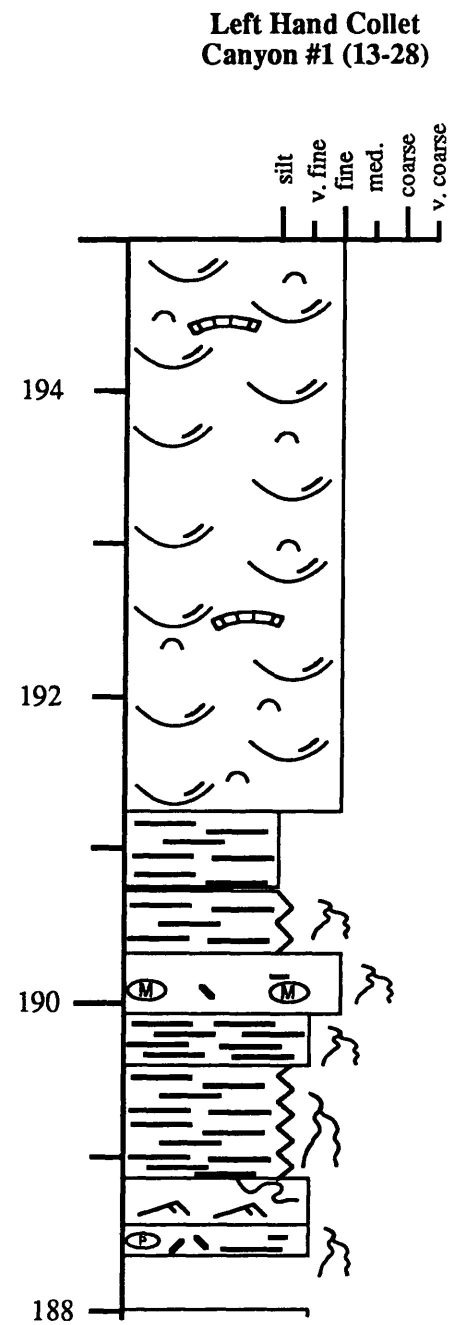
med.
coarse
v.coarse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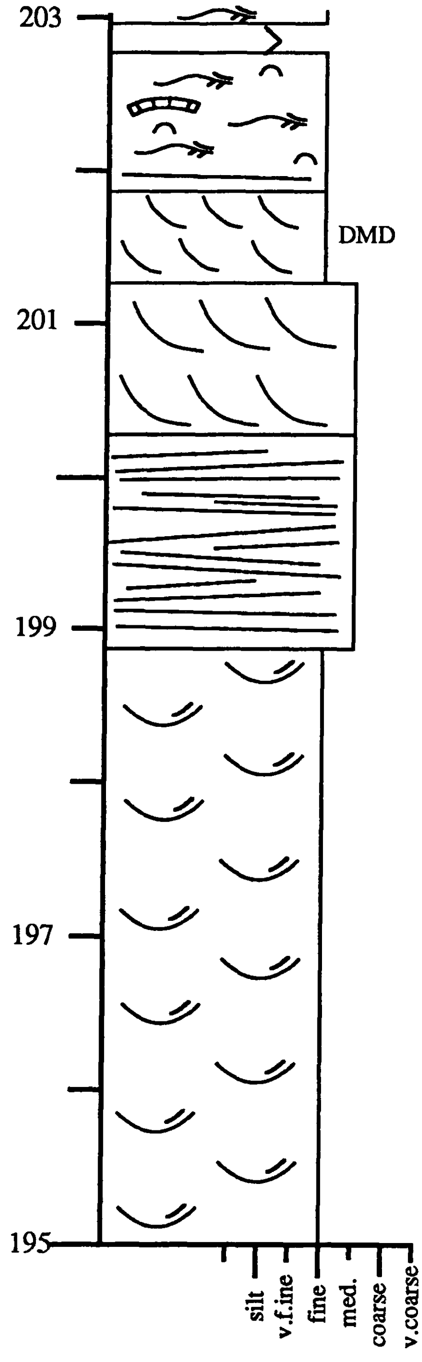
v. fine
fine
med.
coarse
v. coarse
194
192
190
188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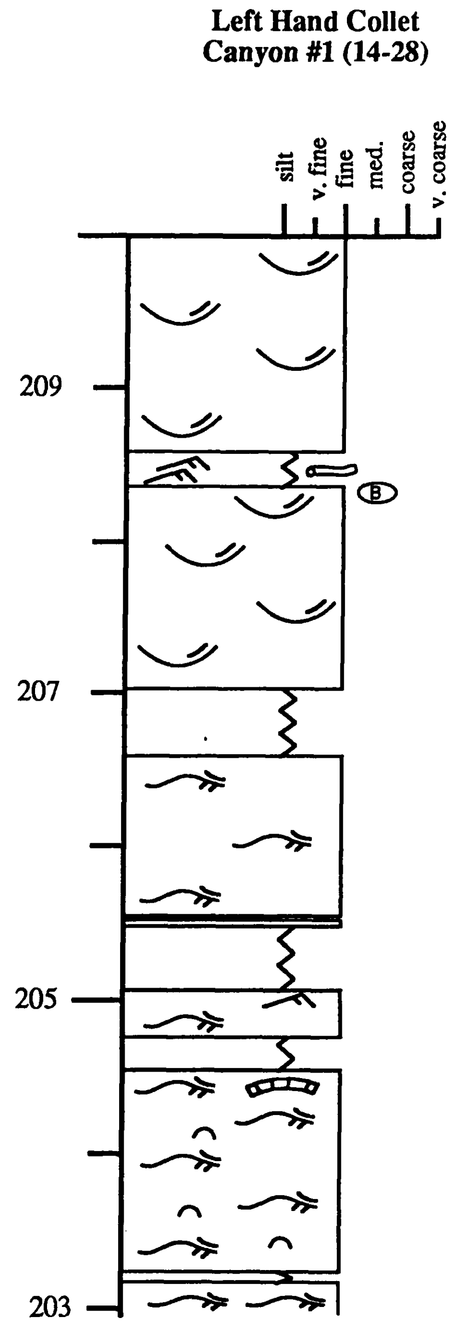
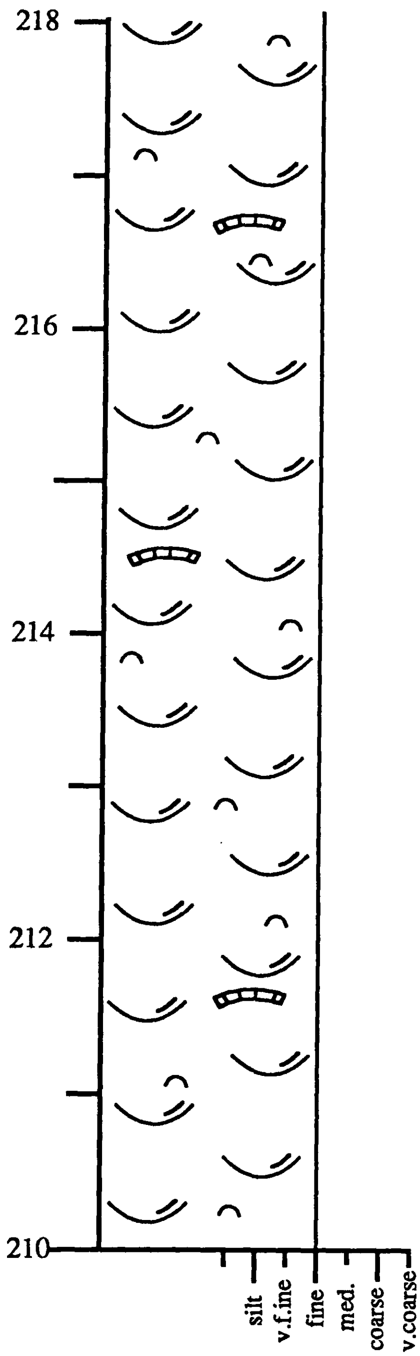
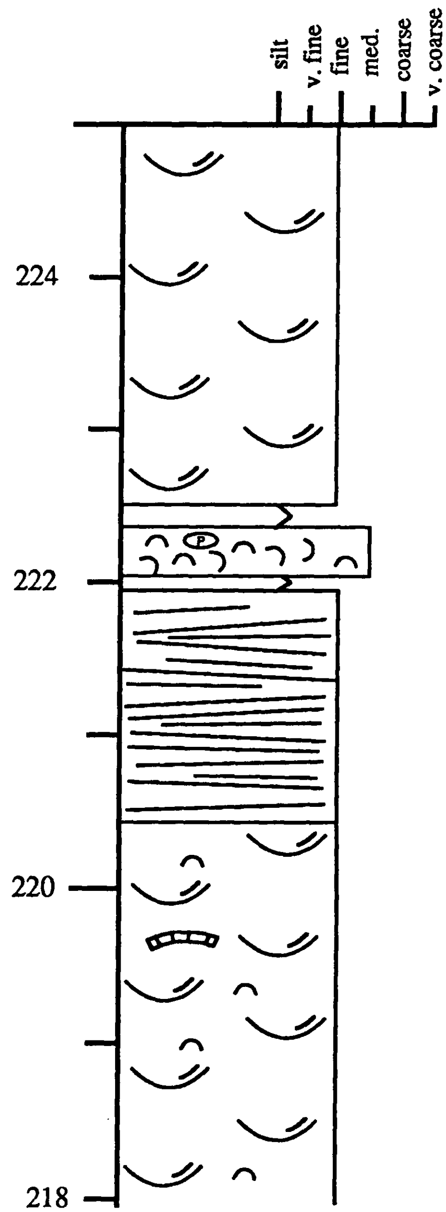
med.
coarse
v.coarse

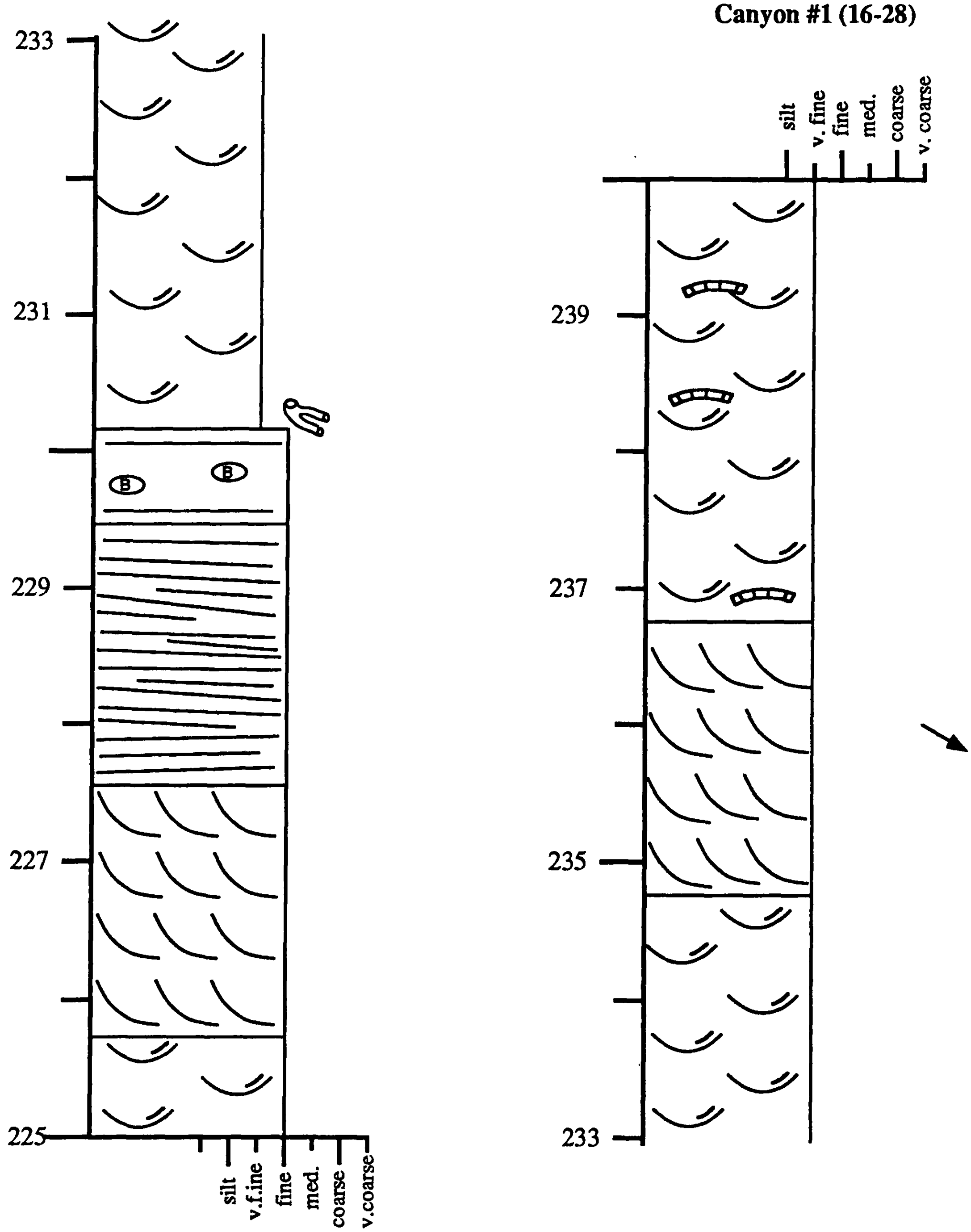

Left Hand Collet
Canyon #1 (14-28)
silt
v. fine
fine
med.
coarse
v. coarse
209
207
205
203
B

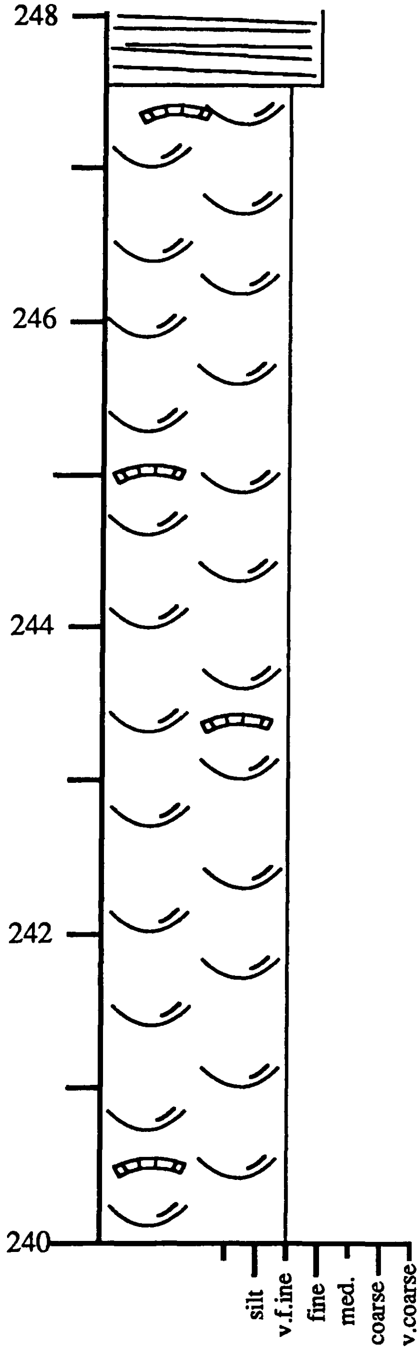
Left Hand Collet Canyon #1 (15-28)





Left Hand Collet
Canyon #1 (16-28)

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240
silt
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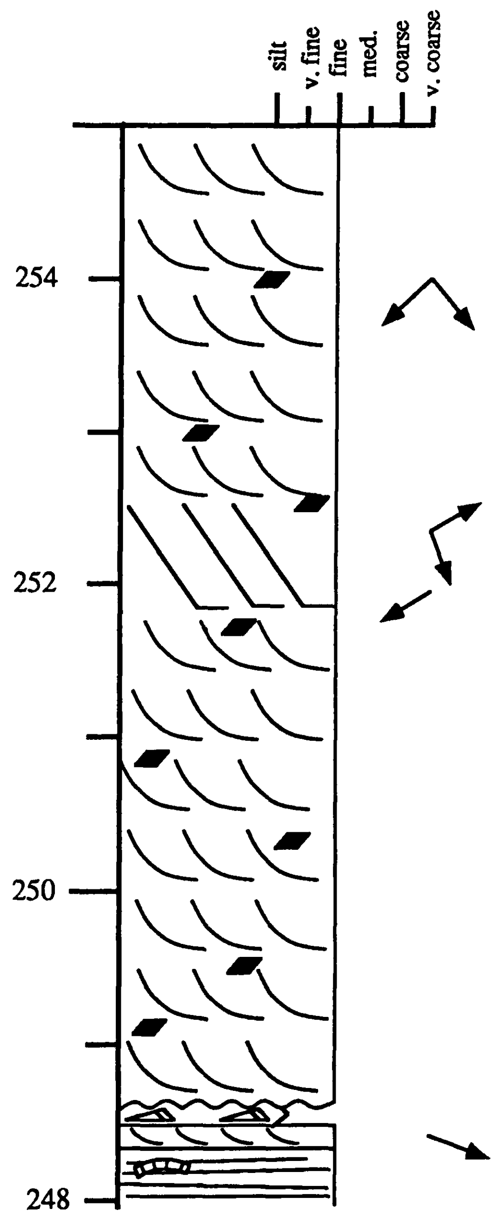
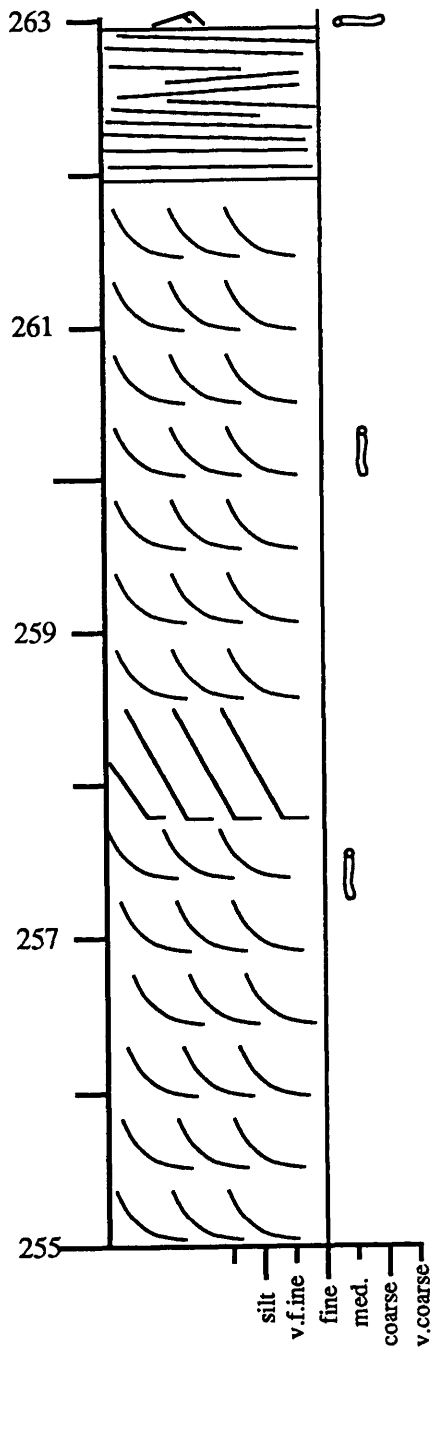
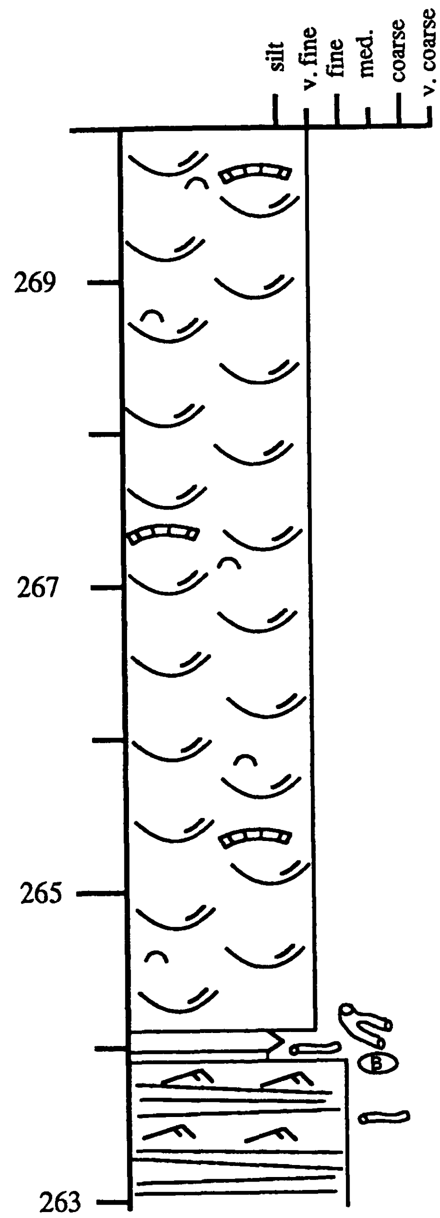
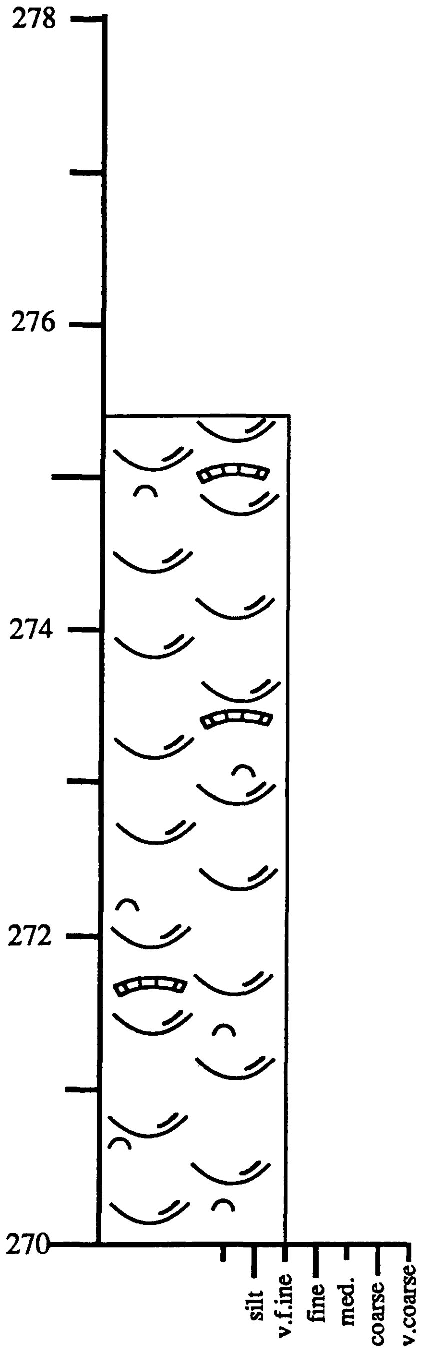
fine
med.
coarse
v.coarse

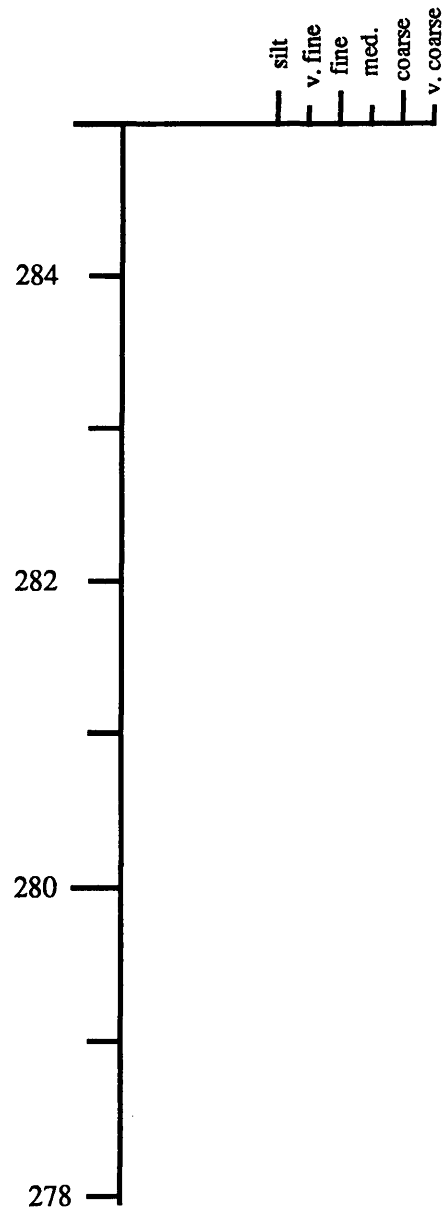

Left Hand Collet
Canyon #1 (17-28)
silt
v. fine
fine
med.
coarse
v. coarse
254
252
250
248

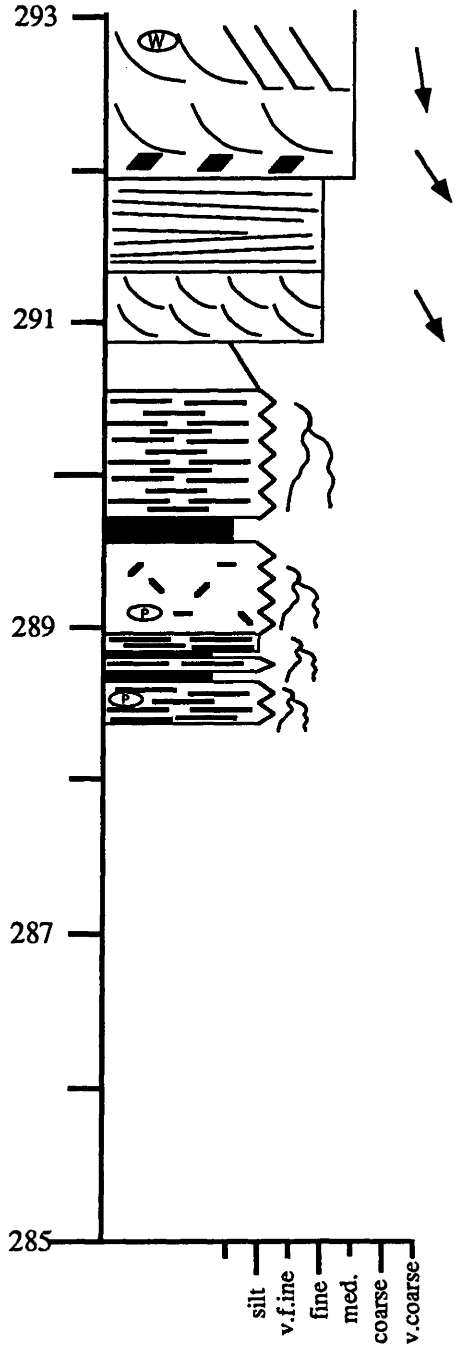

263
261
259
257
255
silt
v.f.ine
fine
med.
coarse
v.coarse


Left Hand Collet
Canyon #1 (18-28)
silt
v. fine
fine
med.
coarse
v. coarse
269
267
265
263

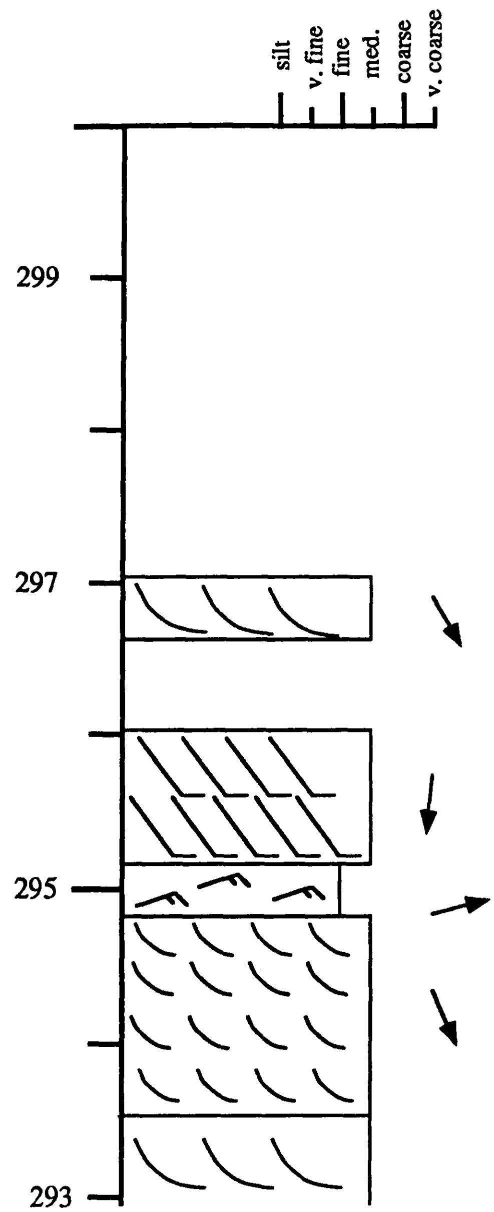


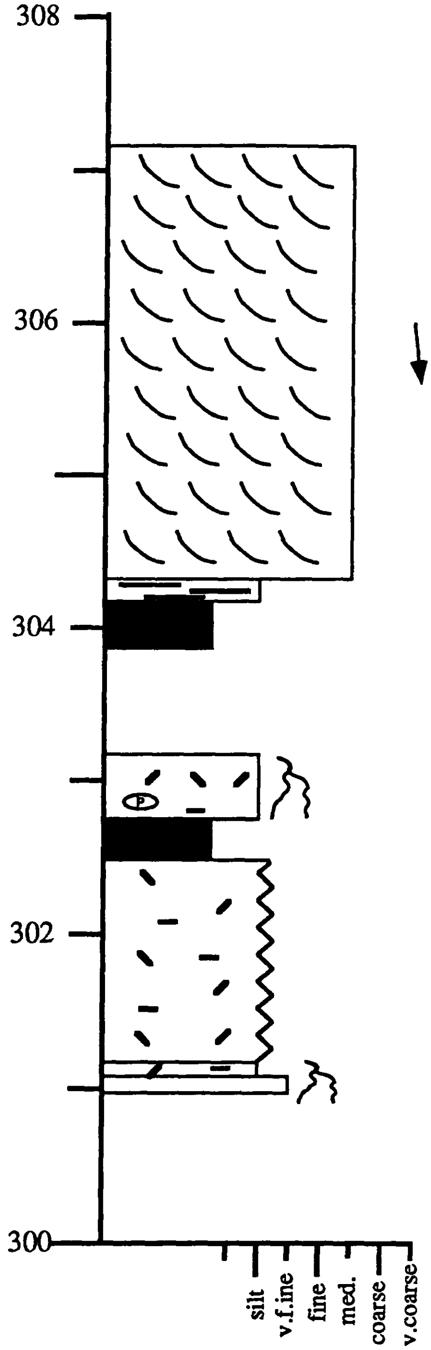
Left Hand Collet
Canyon #1 (19-28)

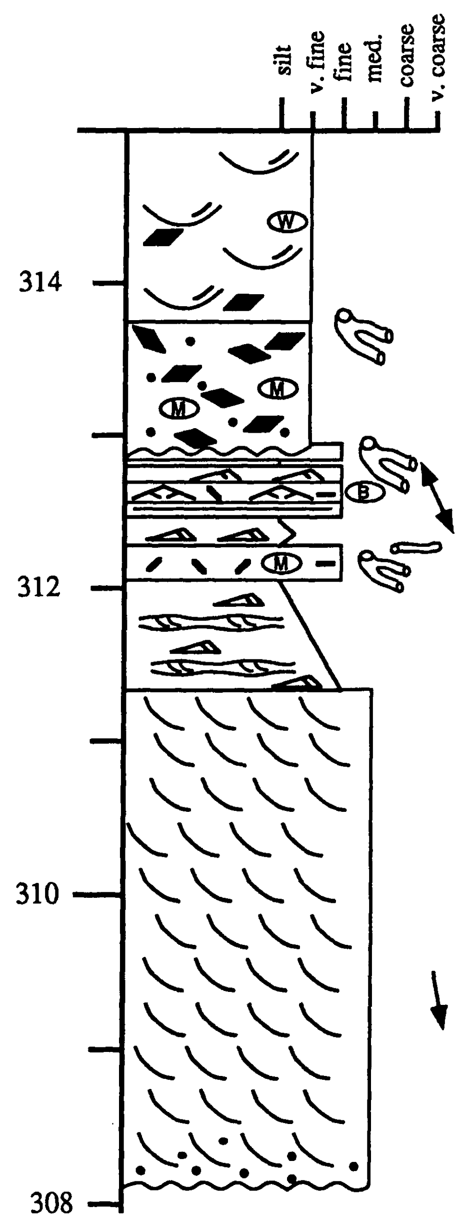


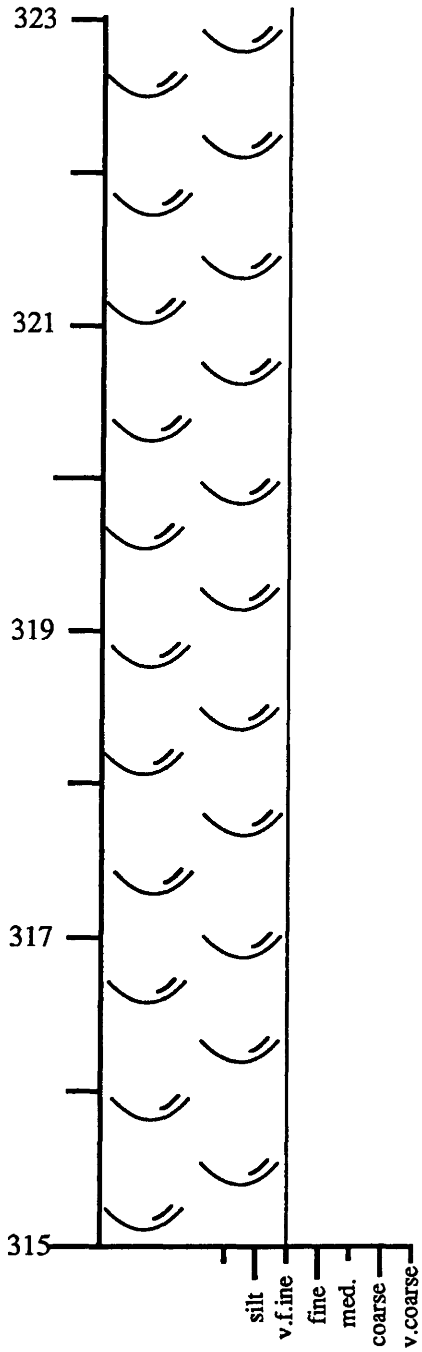


Left Hand Collet Canyon #1 (20-28)

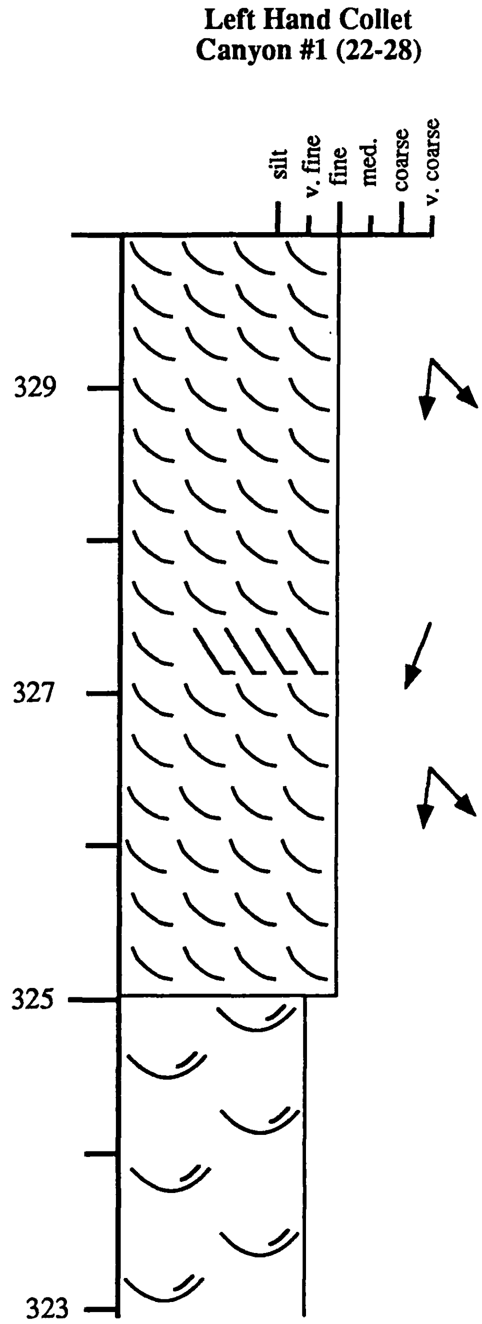



308
306
304
302
300
silt
v.f.ine
fine
med.
coarse
v.coarse

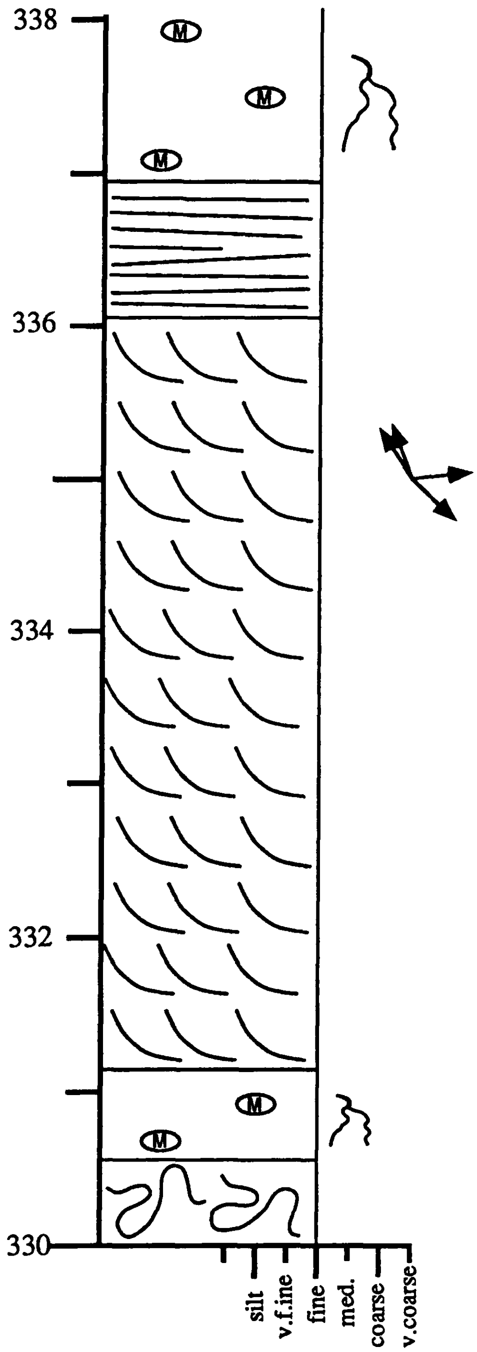

Left Hand Collet
Canyon #1 (21-28)
silt
v. fine
fine
med.
coarse
v. coarse
314
312
310
308



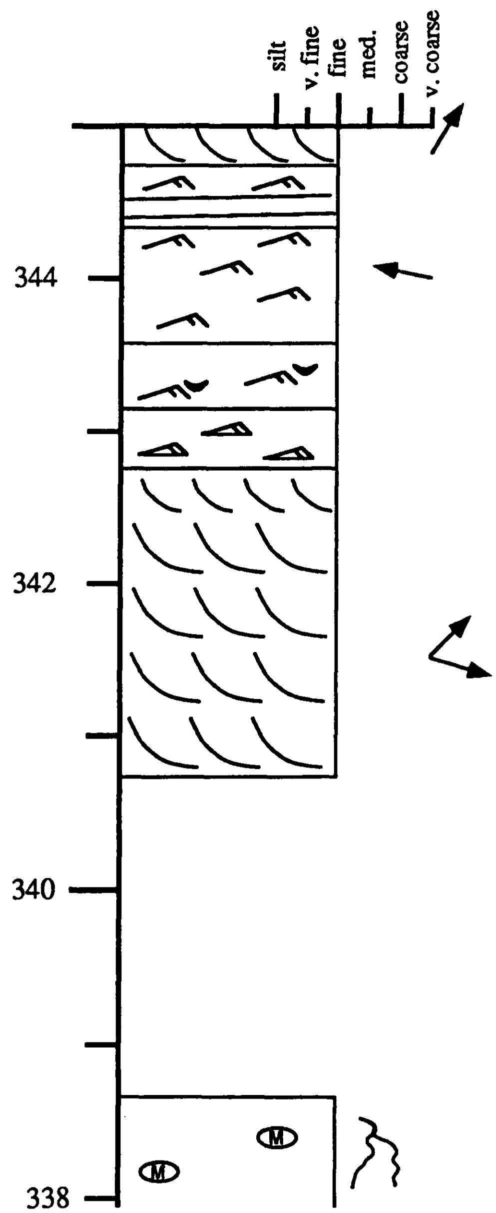
323
321
319
317
315
silt
v.f.ine
fine
med.
coarse
v.coarse

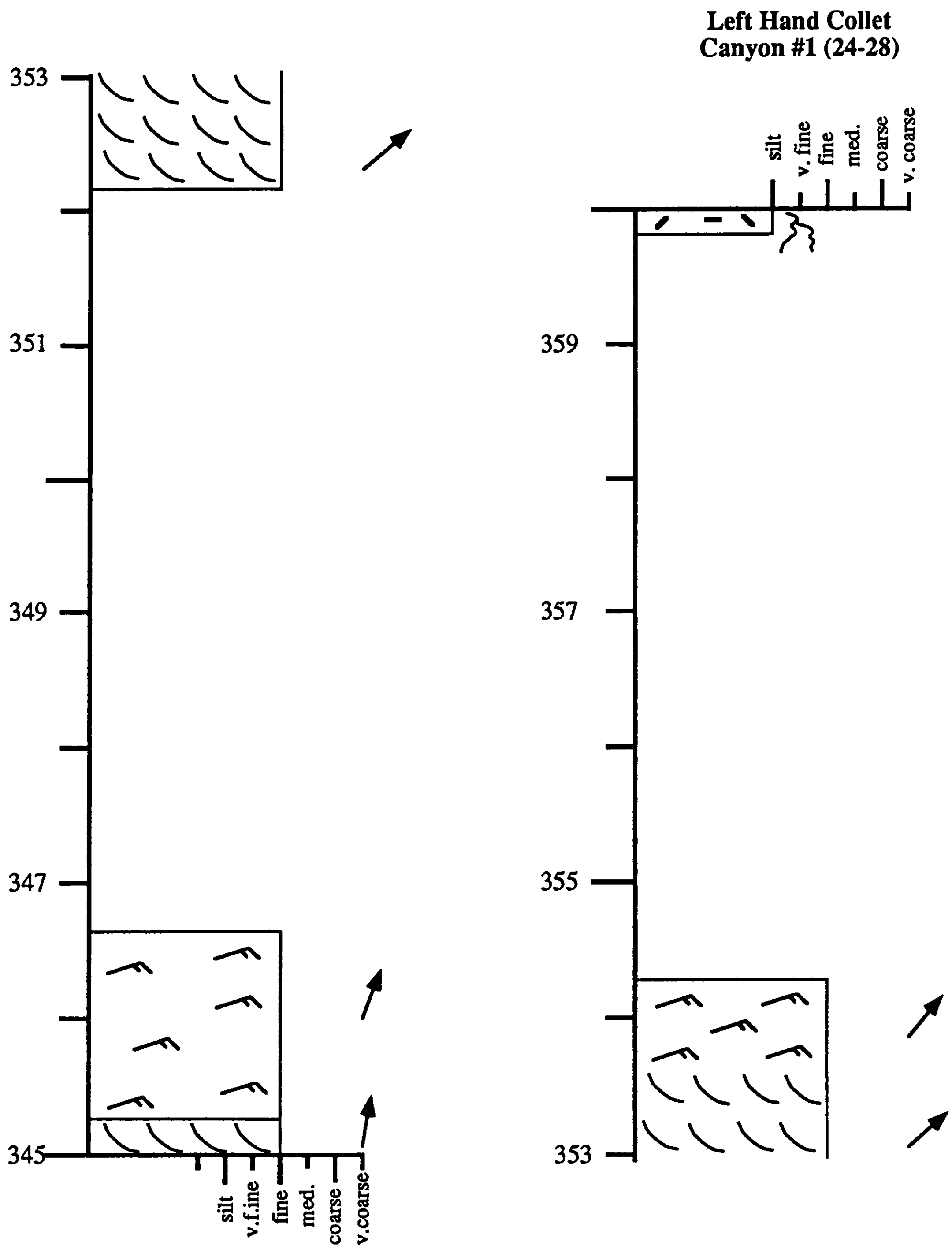


Left Hand Collet
Canyon #1 (22-28)
silt
v. fine
fine
med.
coarse
v. coarse
329
327
325
323

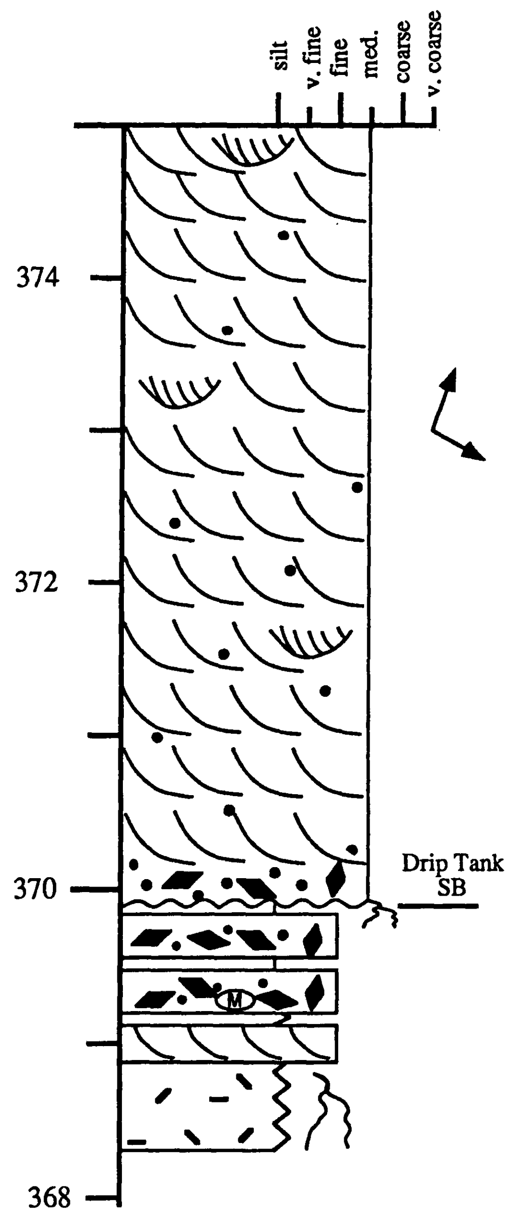


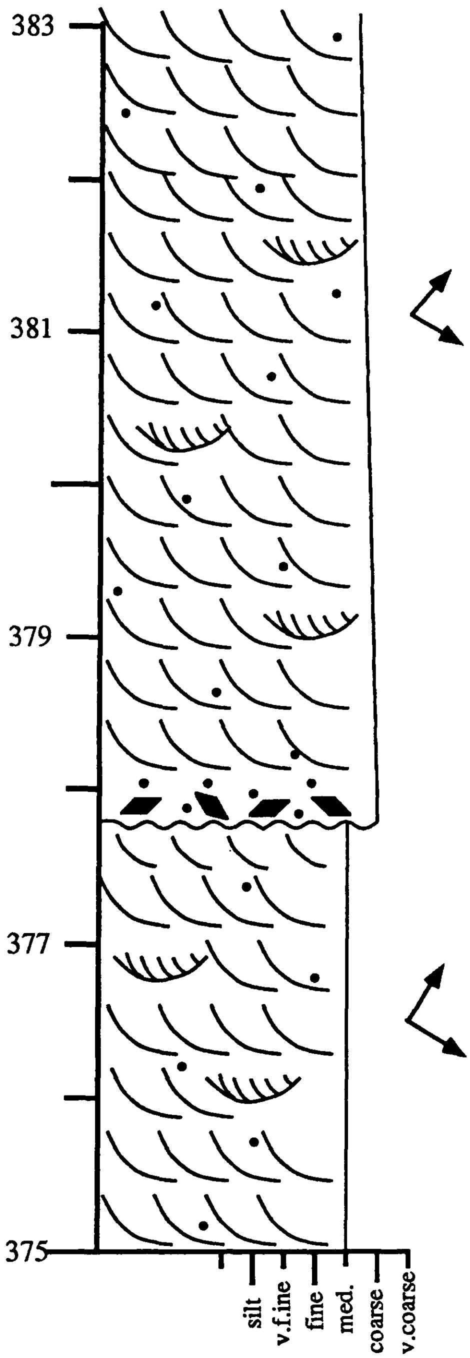
Left Hand Collet
Canyon #1 (23-28)



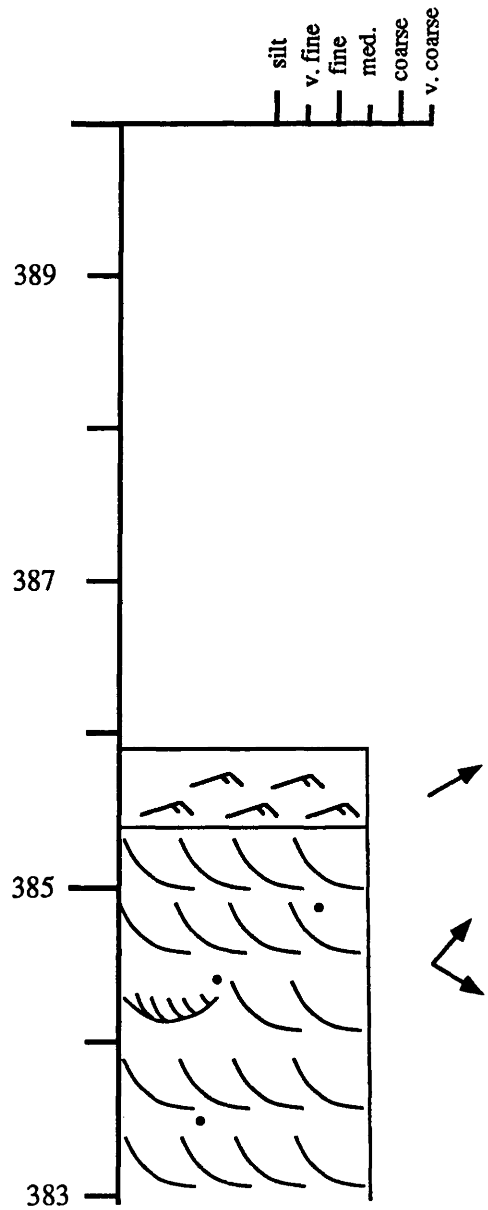

Left Hand Collet
Canyon #1 (24-28)
353
351
349
347
345
silt
v.f.ine
fine
med.
coarse
v.coarse
silt
v. fine
fine
med.
coarse
v. coarse
359
357
355
353

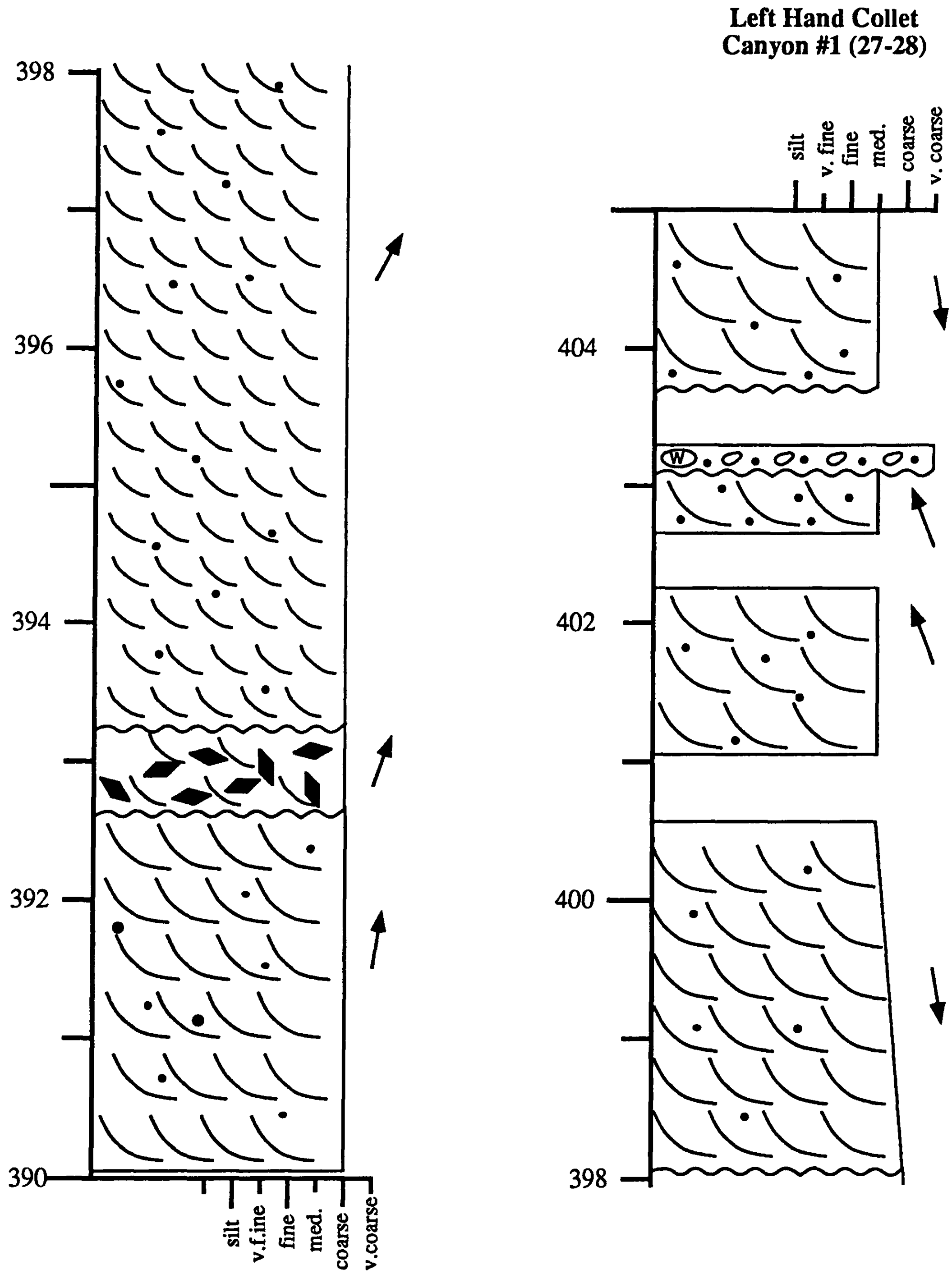
Left Hand Collet
Canyon #1 (25-28)

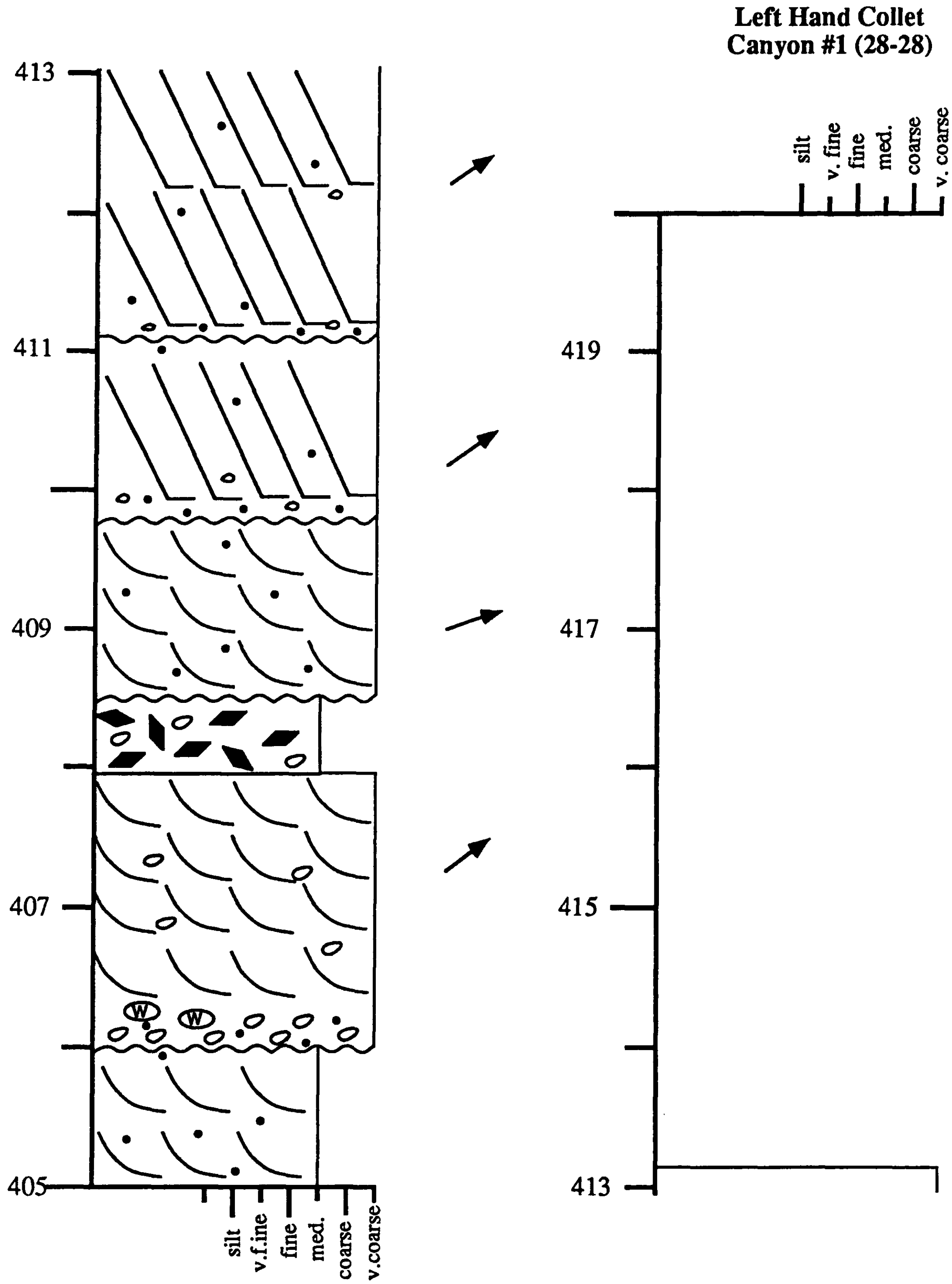




Left Hand Collet Canyon #1 (26-28)



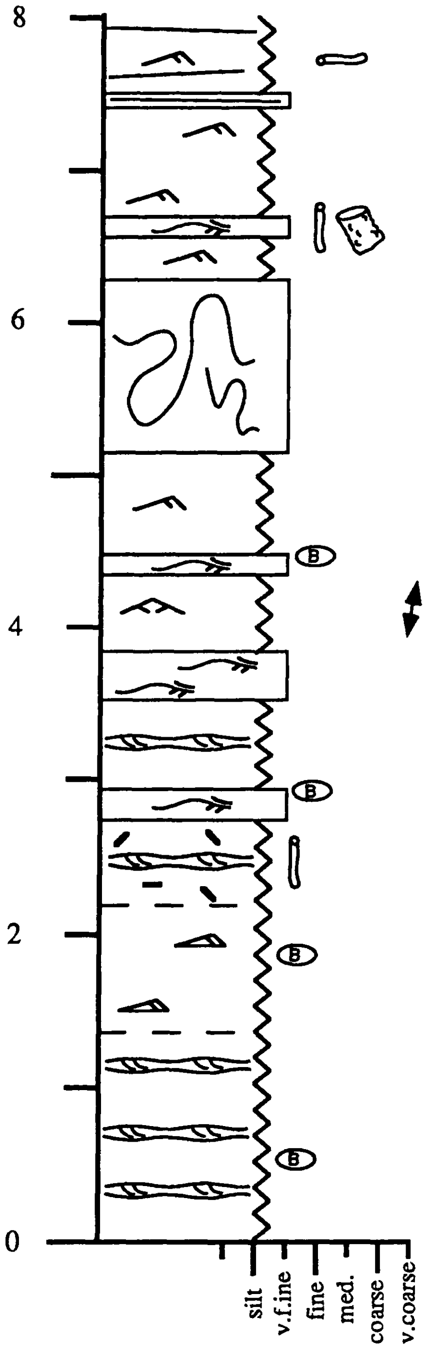

Left Hand Collet
Canyon #1 (27-28)
398
396
394
392
390
silt
v.f.ine
fine
med.
coarse
v.coarse
silt
v. fine
fine
med.
coarse
v. coarse
404
402
400
398
W

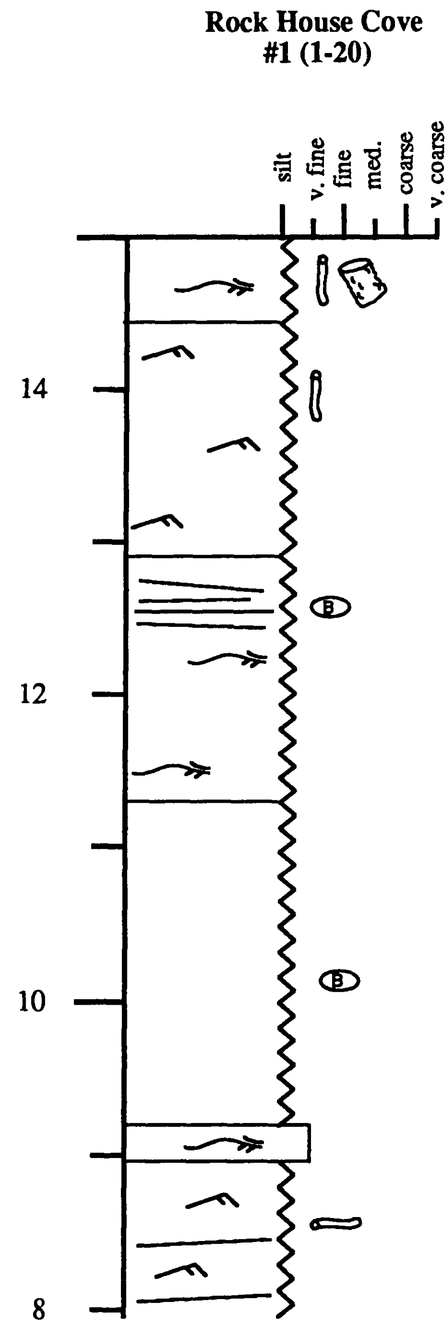

Left Hand Collet
Canyon #1 (28-28)
413
411
409
407
405
silt
v.f.ine
fine
med.
coarse
v.coarse
419
417
415
413
silt
v. fine
fine
med.
coarse
v. coarse
W

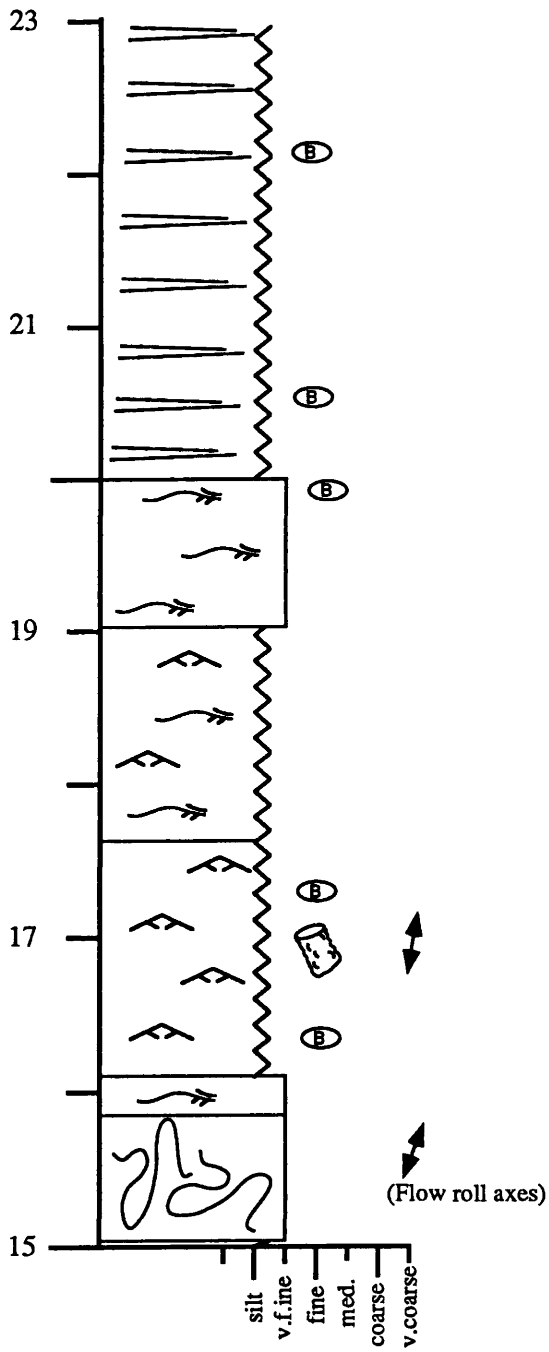
Appendix C

MEASURED SECTION, ROCK HOUSE COVE

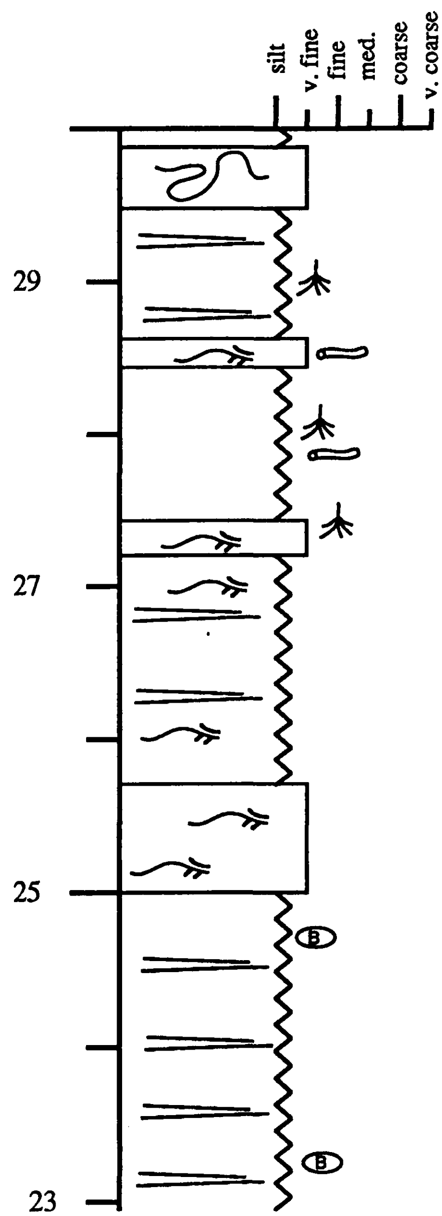
A detailed stratigraphic section was measured along a south- to southwest-trending ridge located to the east of the Cockscomb Road in Kane County Utah. The section extends from the upper part of the Tropic Shale to the lower part of the Drip Tank Member of the Straight Cliffs Formation. The measured section begins in section 4, Township 42 south, Range 1 west, at a position approximately 1250 feet from the north line of section 4 and 900 feet from the west line of section 4. The measured section ends in section 33, Township 41 south, Range 1 west, at a position approximately 1775 from the north line of section 33 and 1175 feet from the east line of section 33. This area can be located on the U.S.G.S Fivemile Valley Quadrangle - 7.5 minute topographic map. All measurements on the Rock House Cove section are in meters.


8
6
4
2
0
silt
v.f.ine
fine
med.
coarse
v.coarse

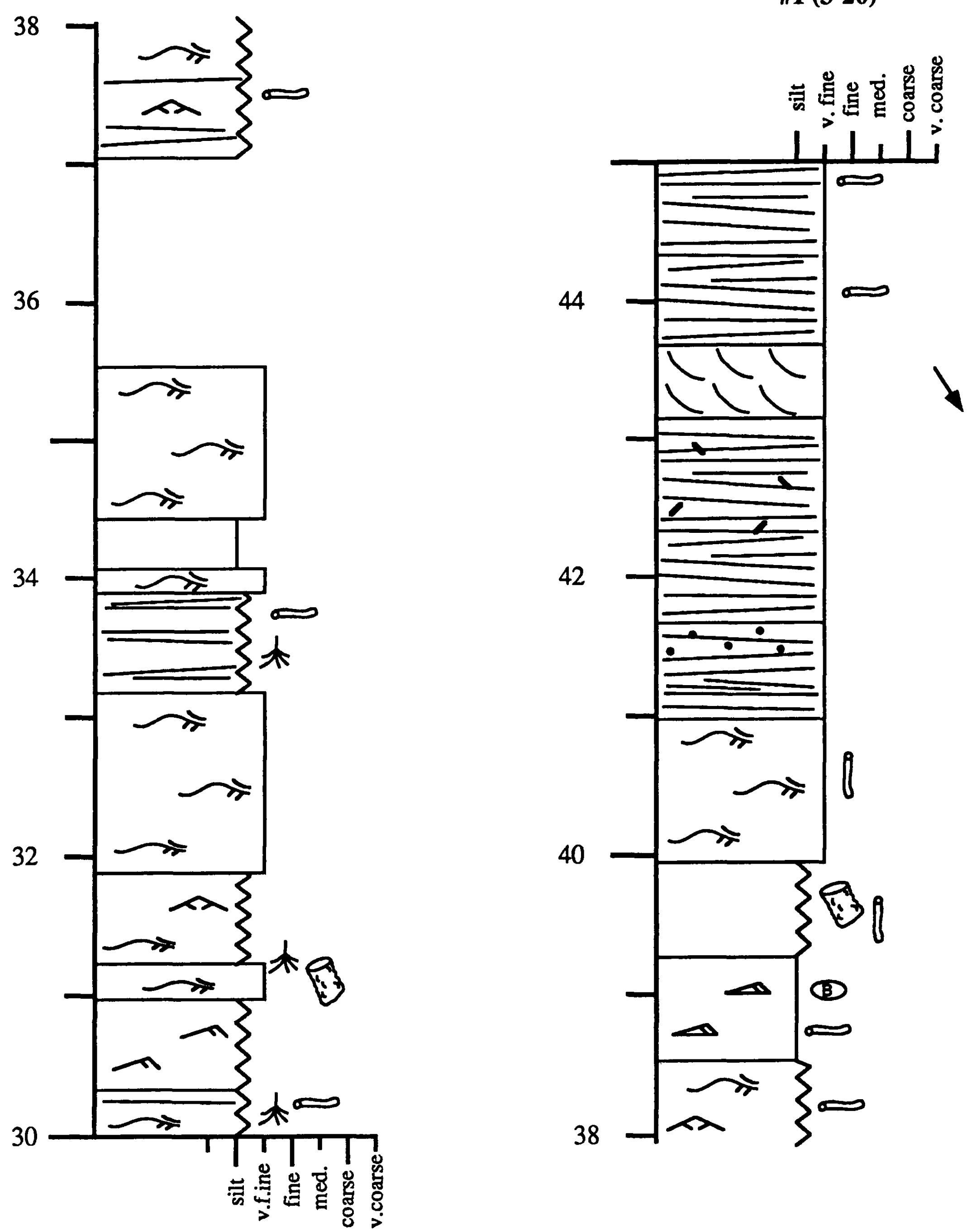

Rock House Cove
#1 (1-20)
silt
v. fine
fine
med.
coarse
v. coarse
14
12
10
8



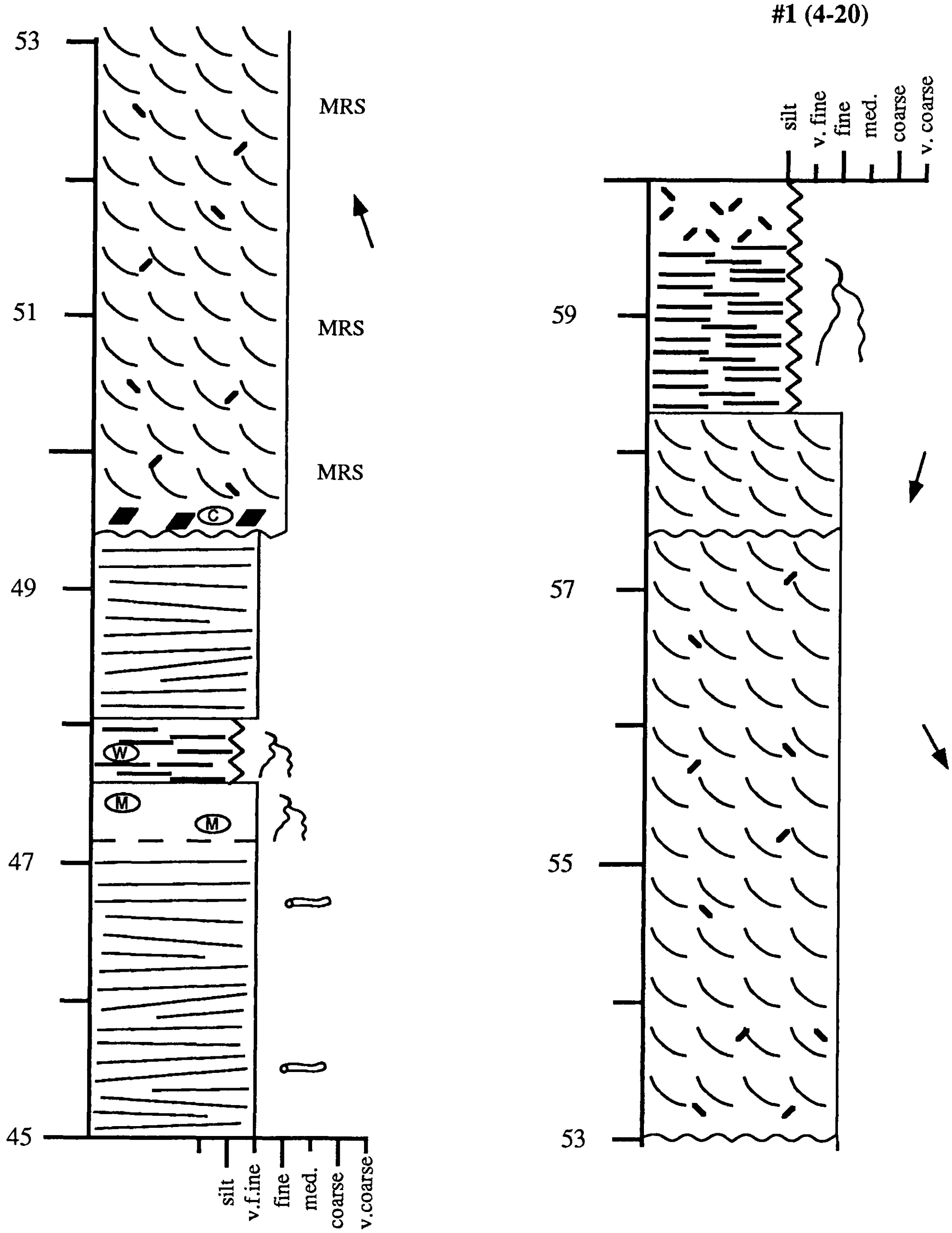
Rock House Cove
#1 (2-20)

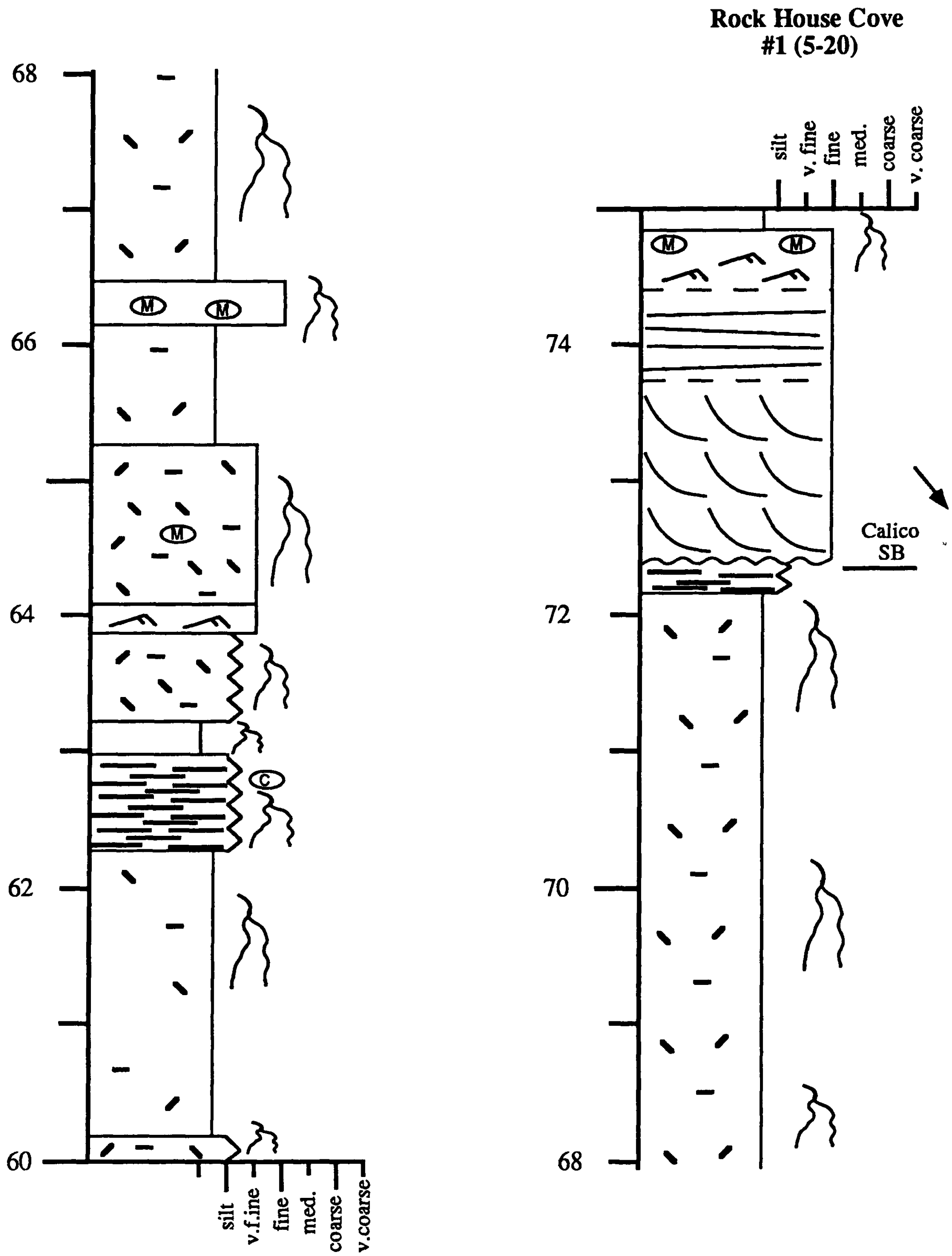


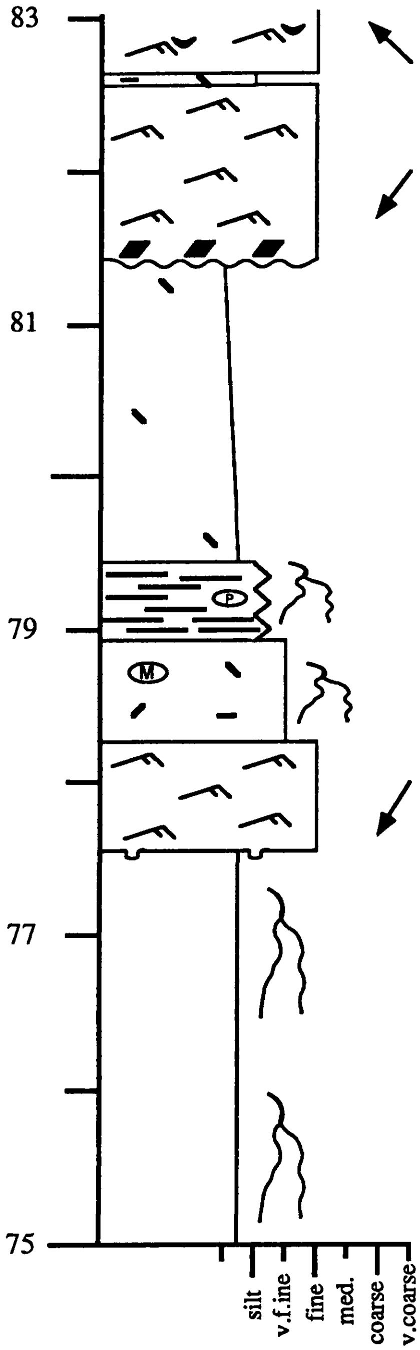
Rock House Cove
#1 (3-20)

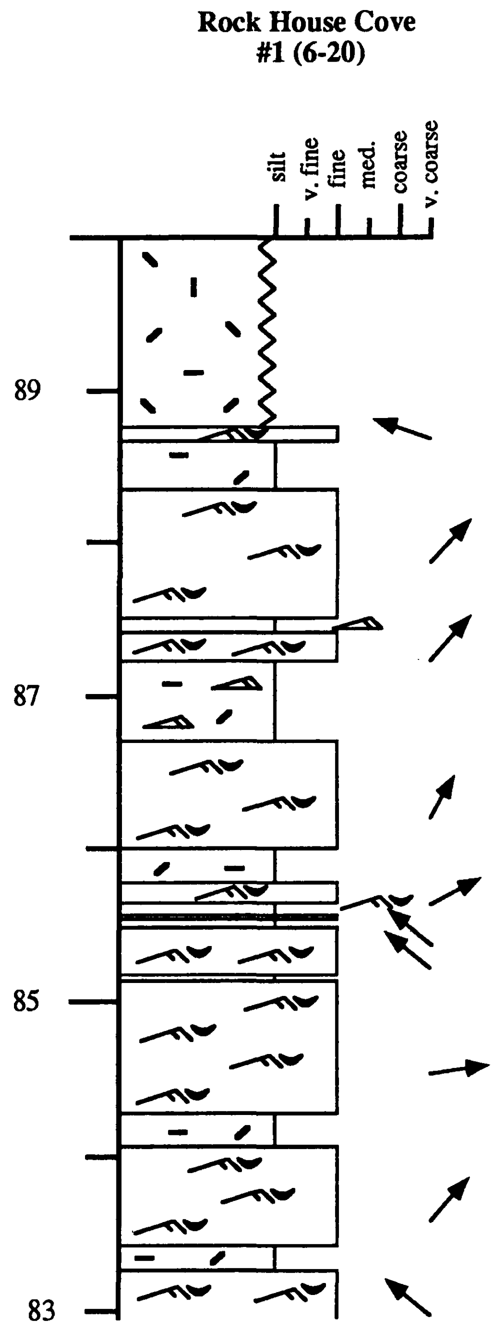


Rock House Cove
#1 (4-20)

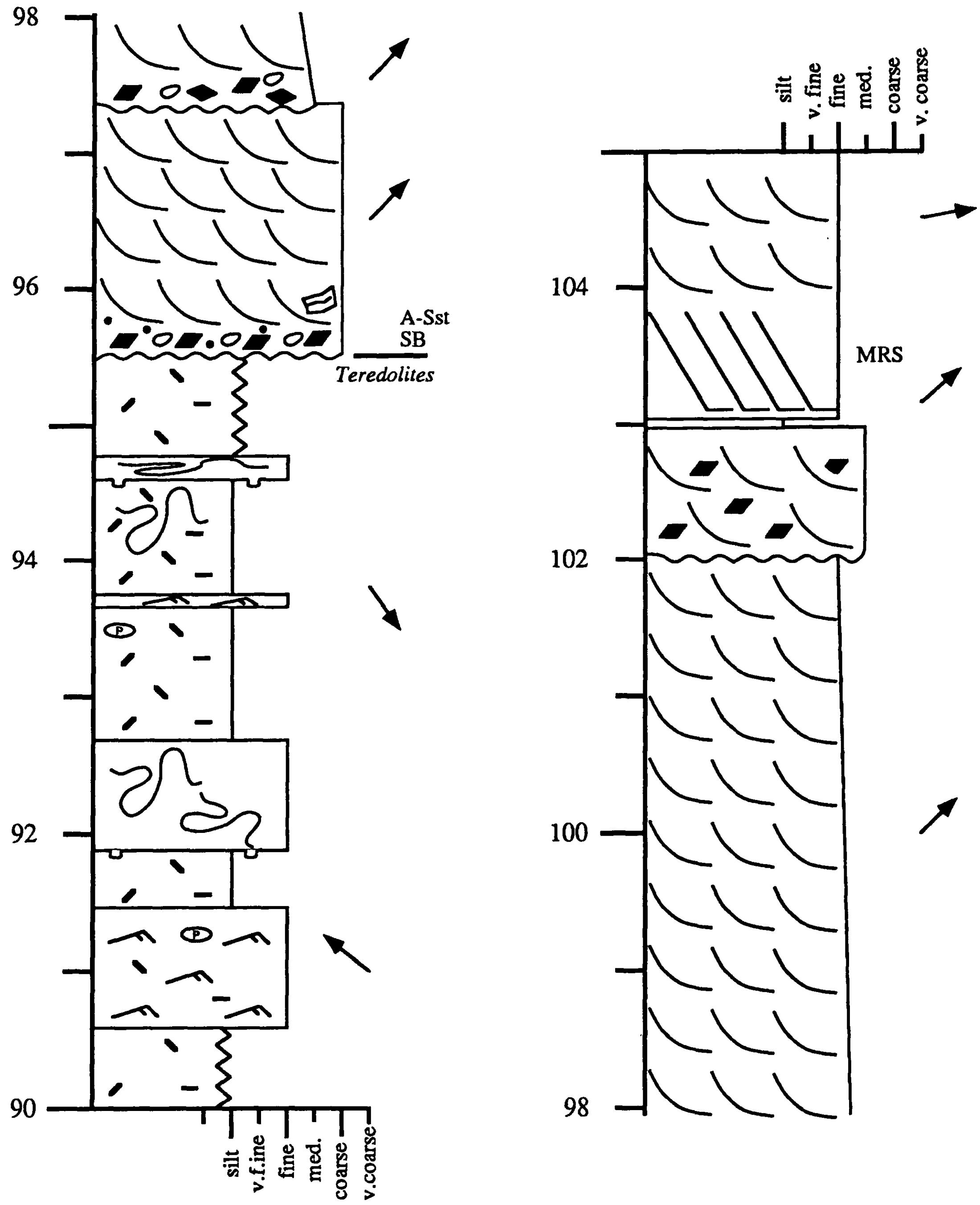


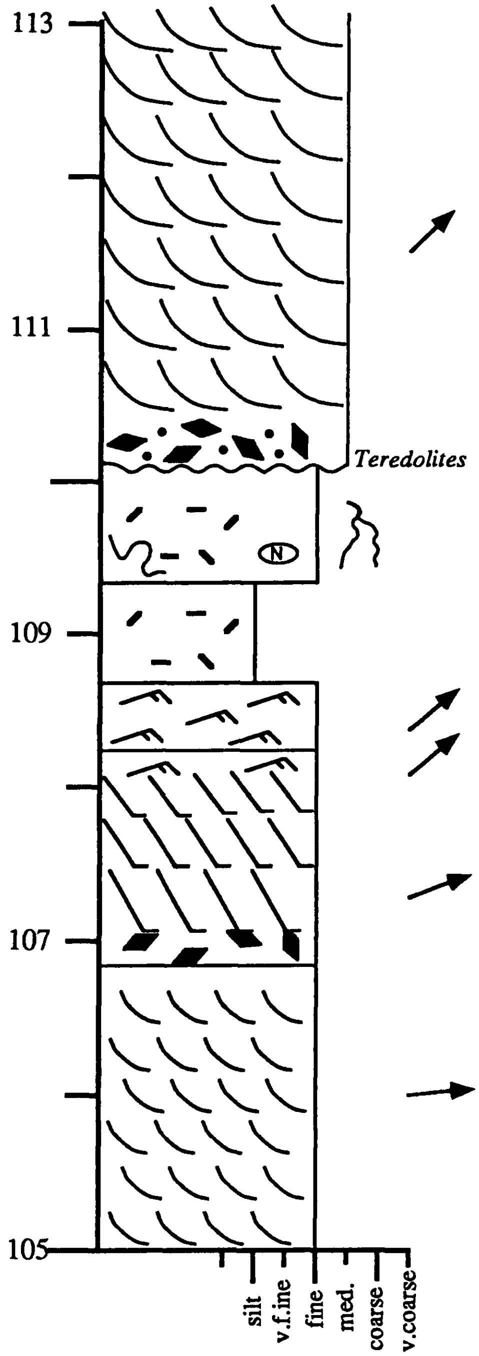

Rock House Cove
#1 (5-20)
68
66
64
62
60
silt
v.f.ine
fine
med.
coarse
v.coarse
silt
v. fine
fine
med.
coarse
v. coarse
74
72
70
68
Calico
SB


83
81
79
77
75
silt
v.f.ine
fine
med.
coarse
v.coarse
M
P

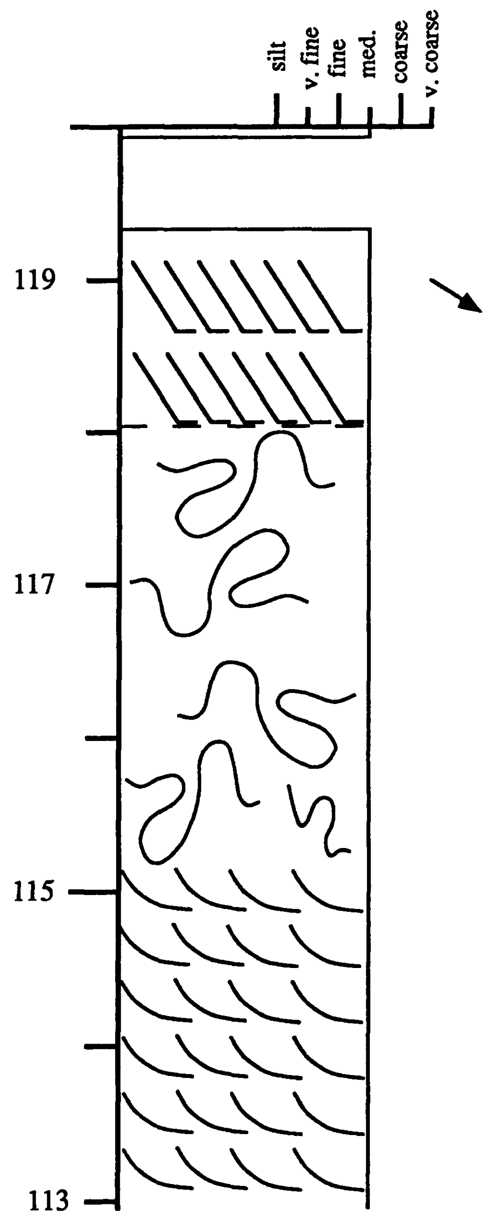

Rock House Cove
#1 (6-20)
silt
v. fine
fine
med.
coarse
v. coarse
89
87
85
83

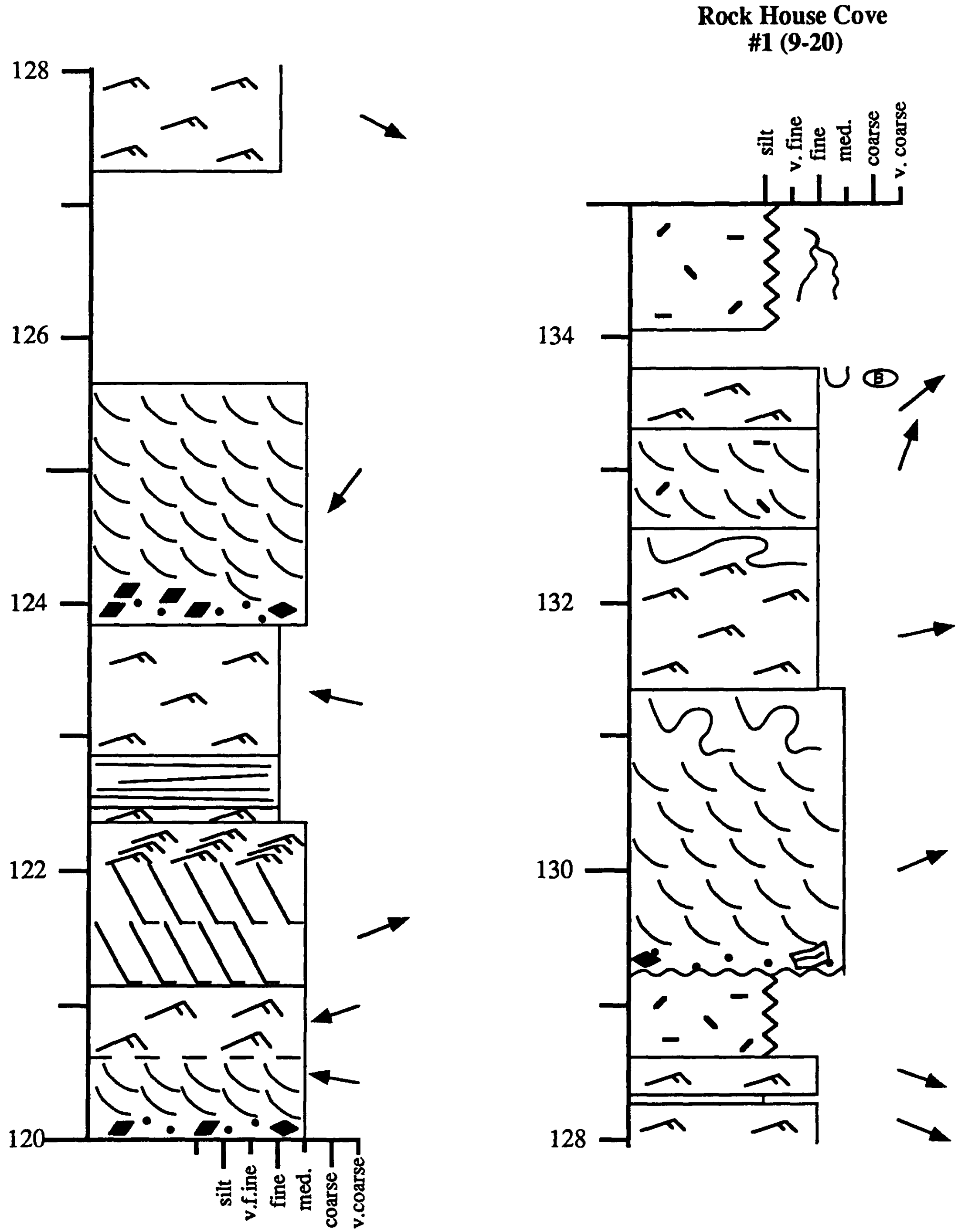
Rock House Cove #1 (7-20)



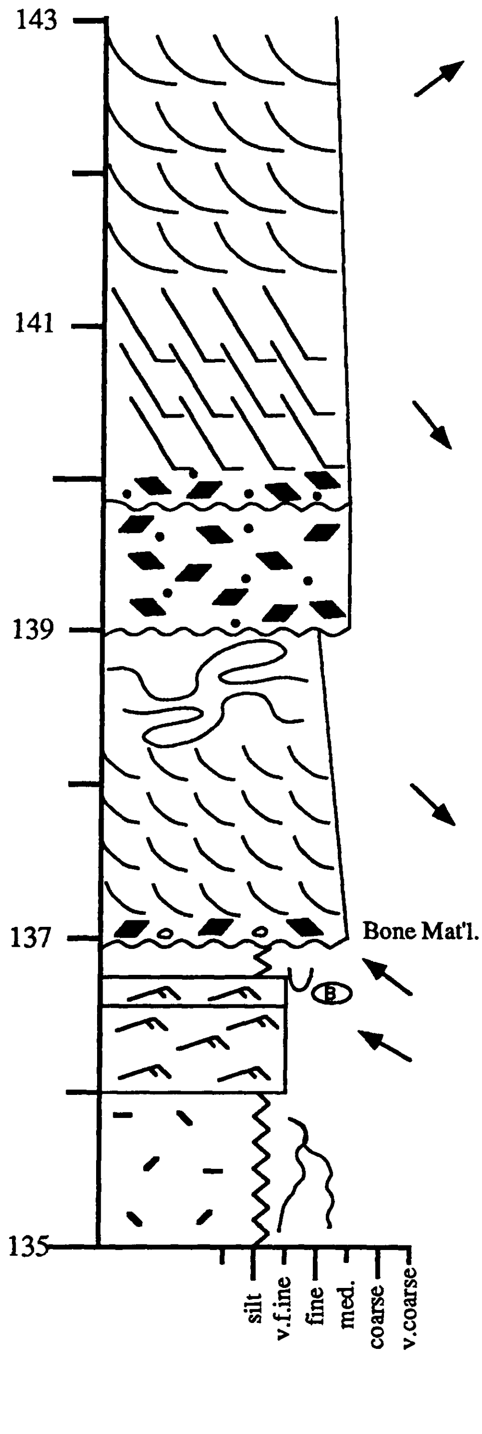


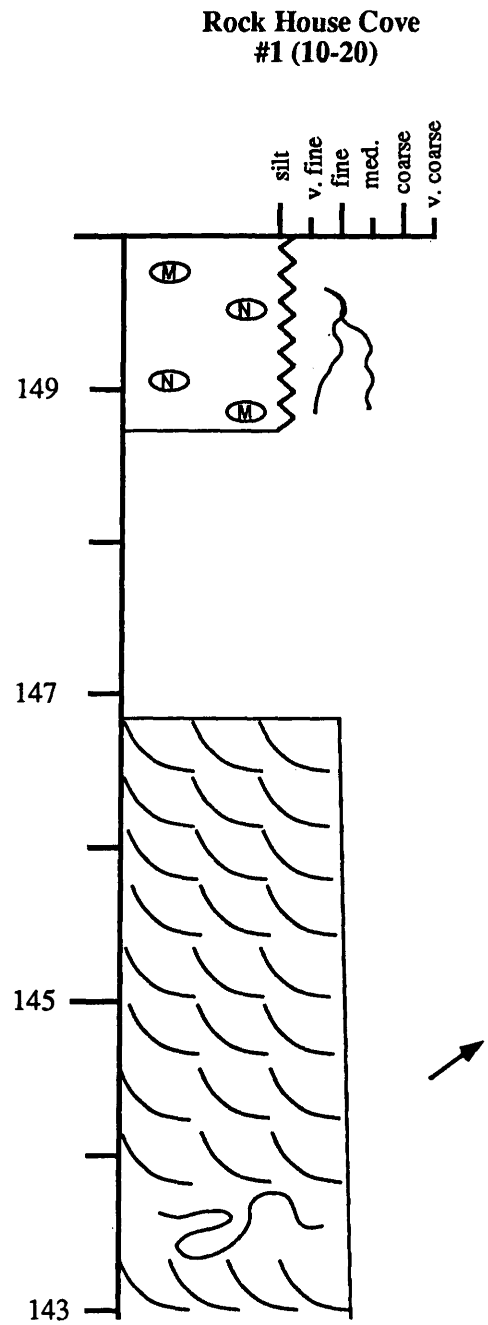
Rock House Cove
#1 (8-20)

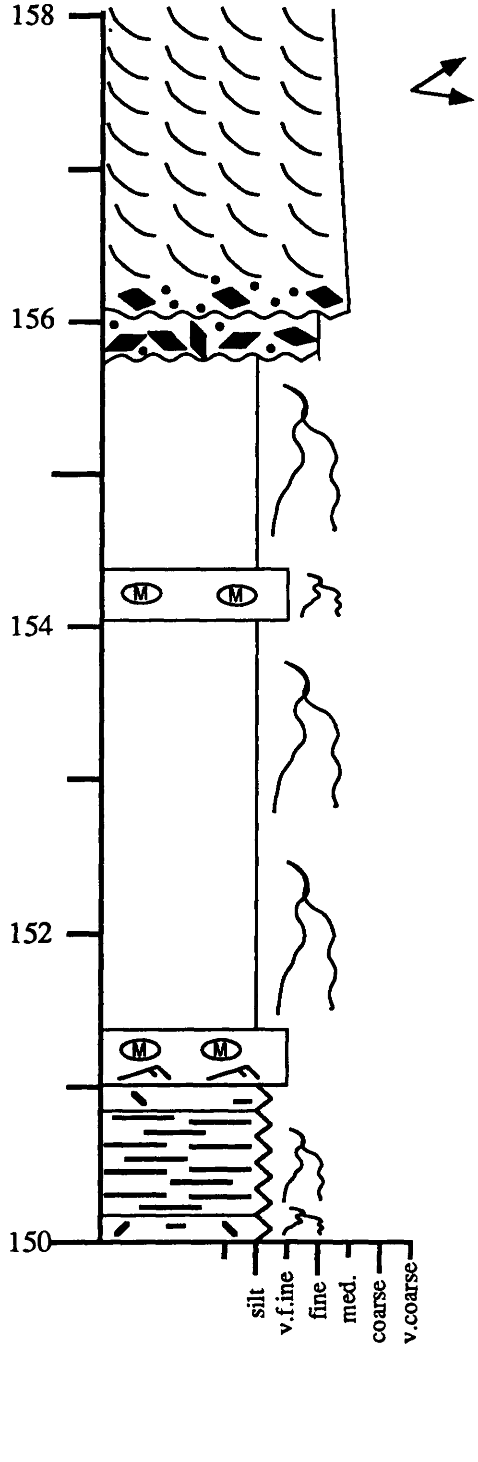




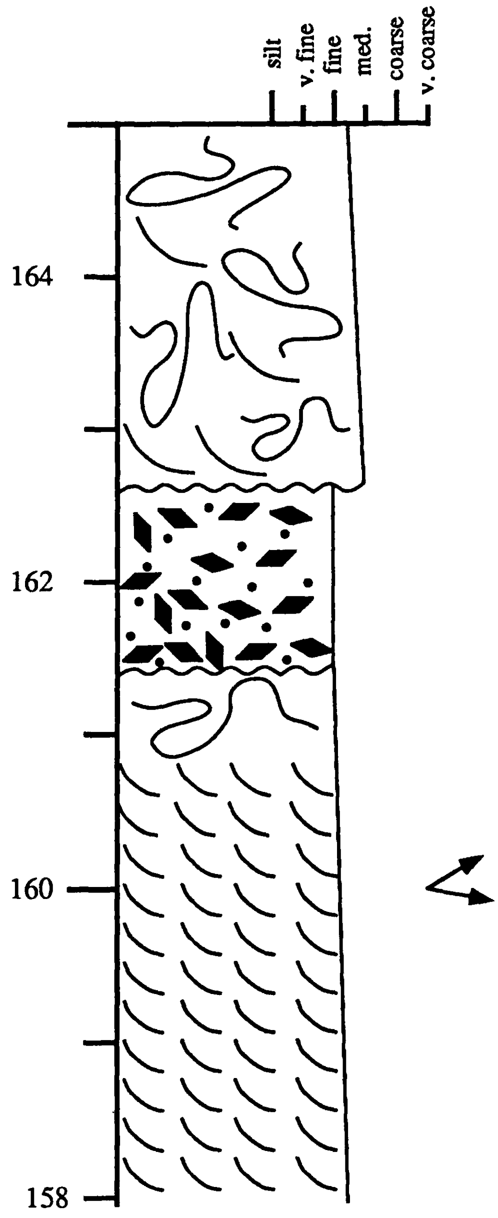
128
126
124
122
120
silt
v.f.ine
fine
med.
coarse
v.coarse
Rock House Cove
#1 (9-20)
silt
v. fine
fine
med.
coarse
v. coarse
134
132
130
128


143
141
139
137
135
Bone Mat'l.
B
silt
v.f.ine
fine
med.
coarse
v.coarse

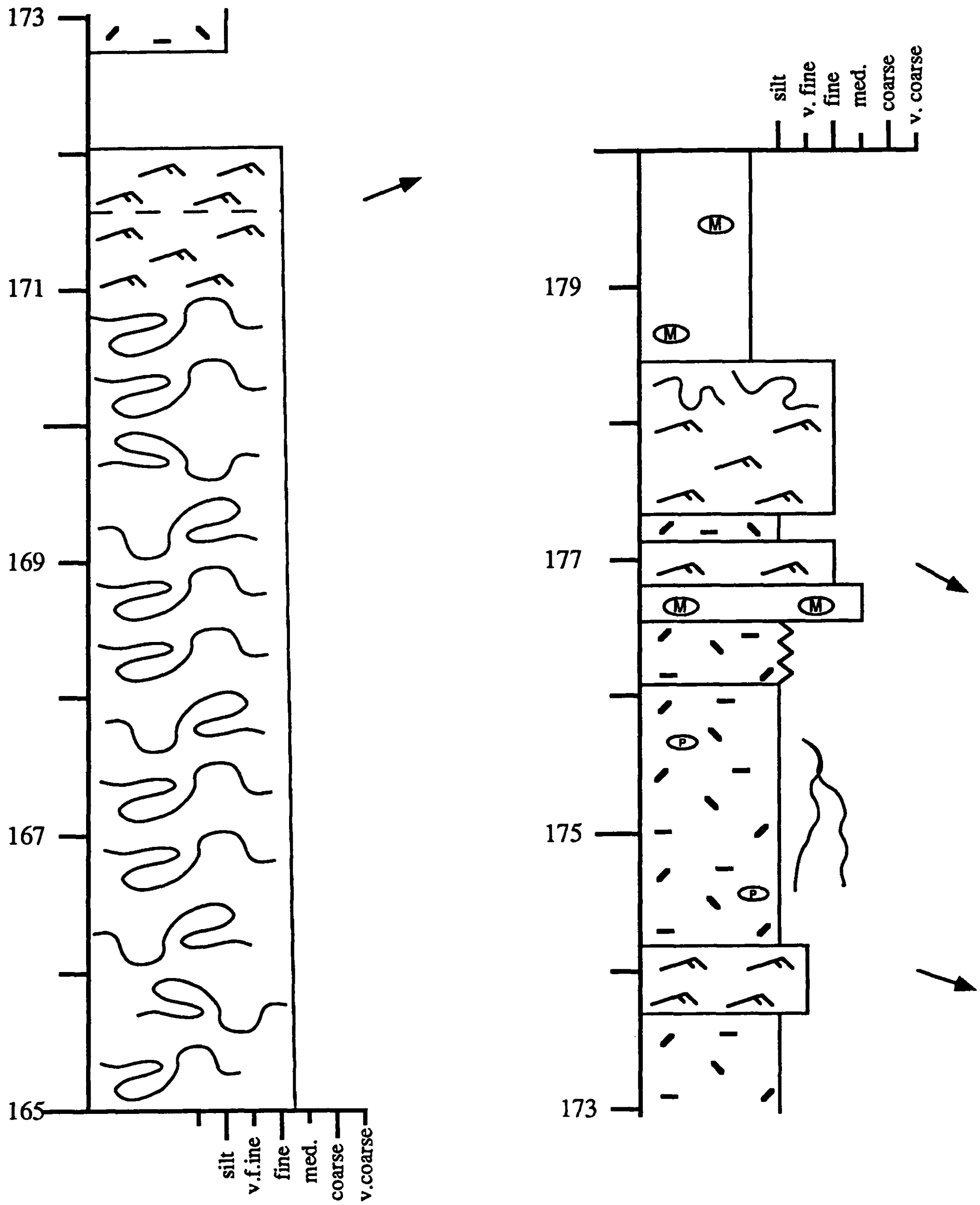

Rock House Cove
#1 (10-20)
silt
v. fine
fine
med.
coarse
v. coarse
M
N
149
147
145
143



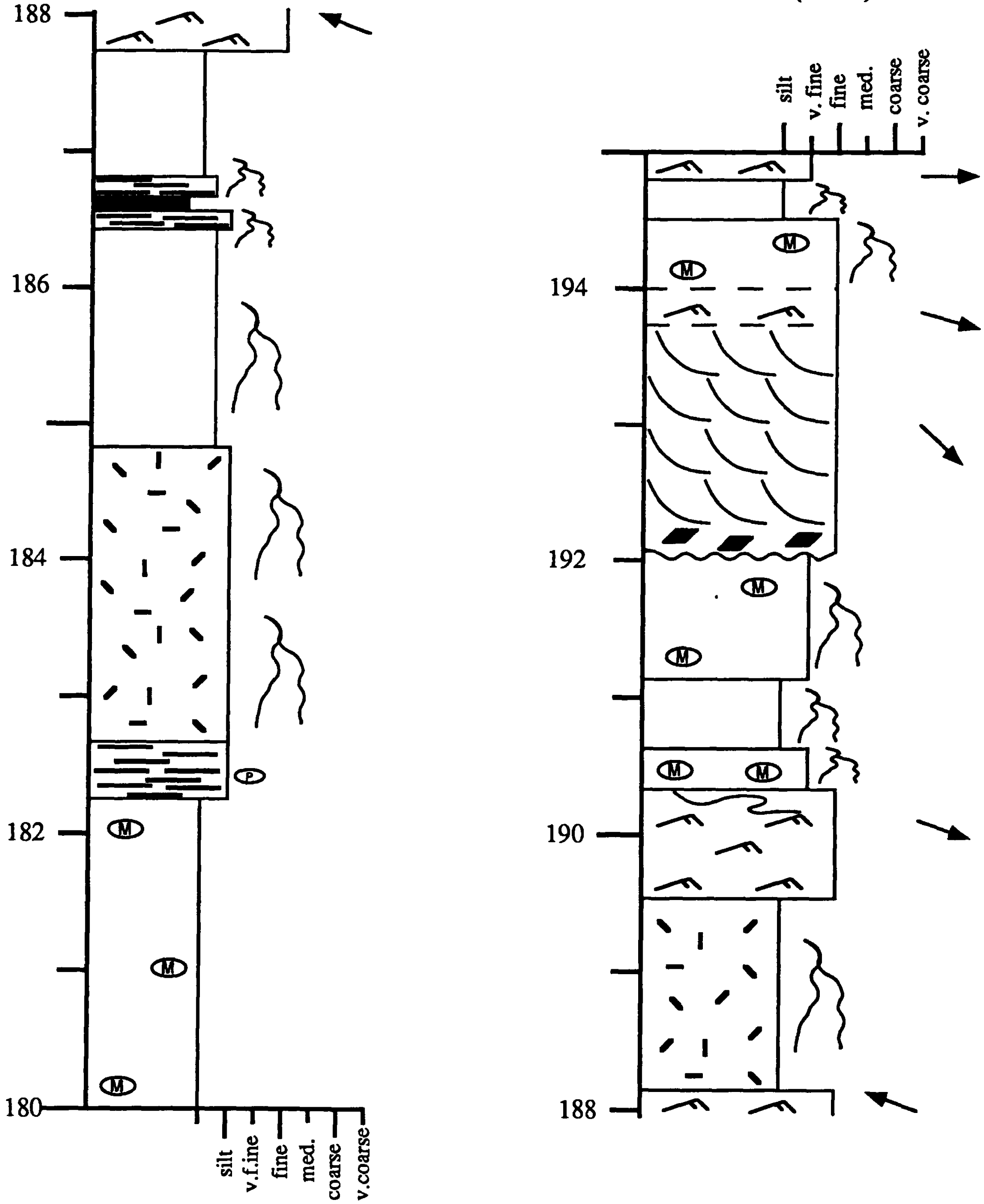
Rock House Cove
#1 (11-20)



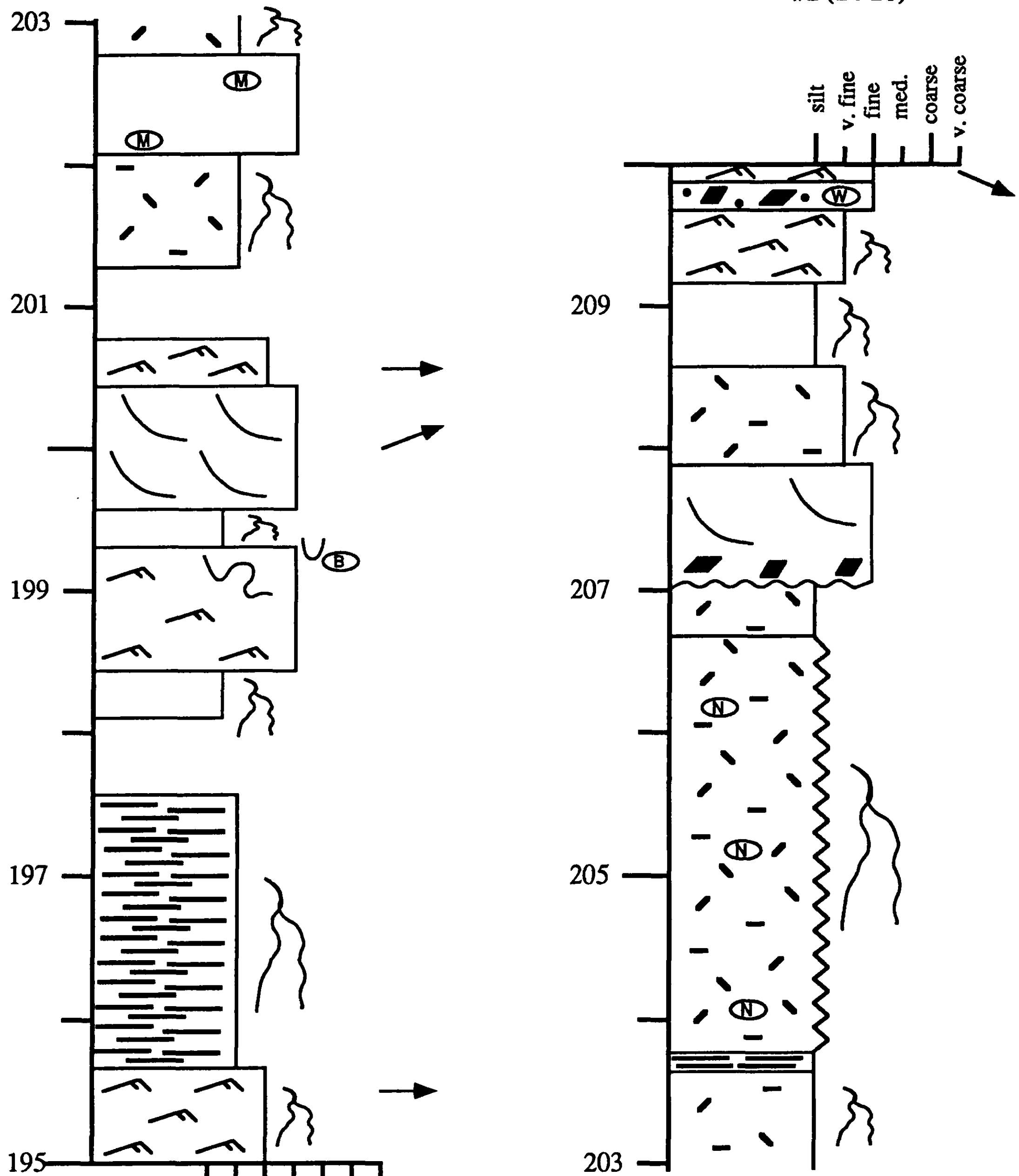
Rock House Cove
#1 (12-20)

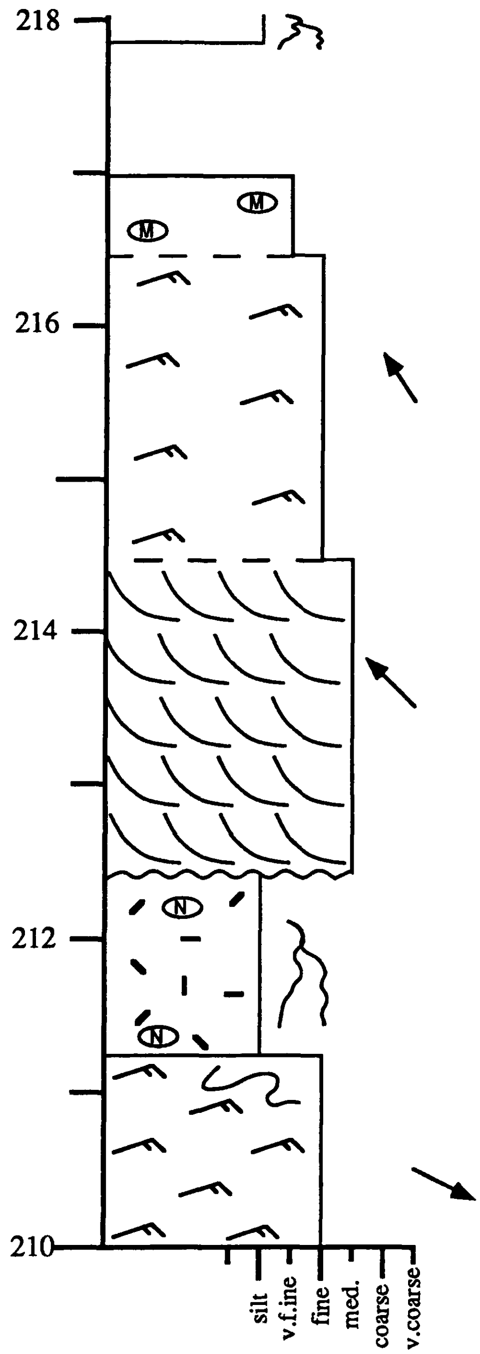


Rock House Cove
#1 (13-20)

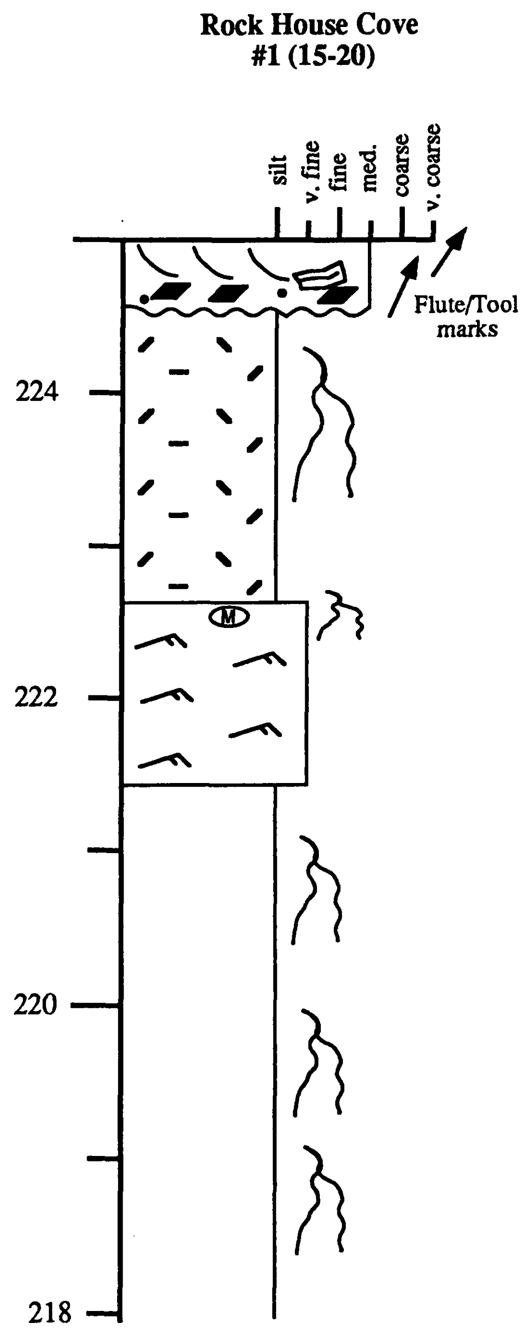


Rock House Cove
#1 (14-20)

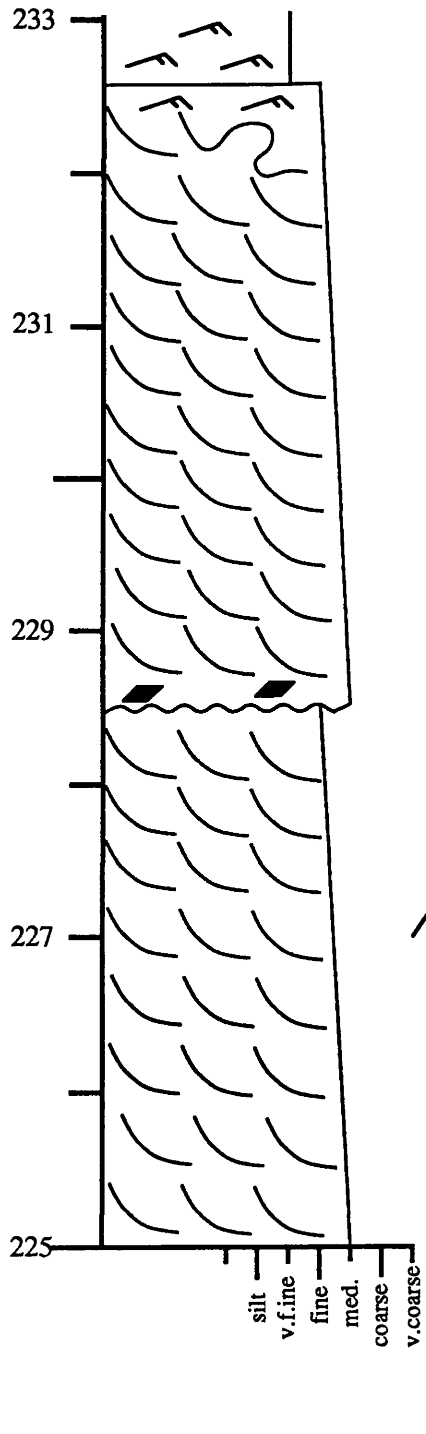




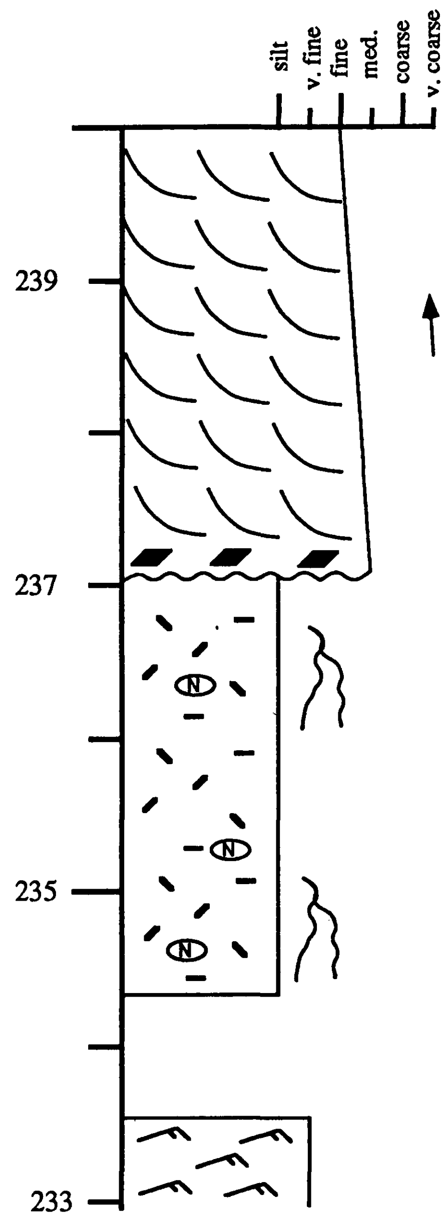
218
216
214
212
210
silt
v.f.ine
fine
med.
coarse
v.coarse



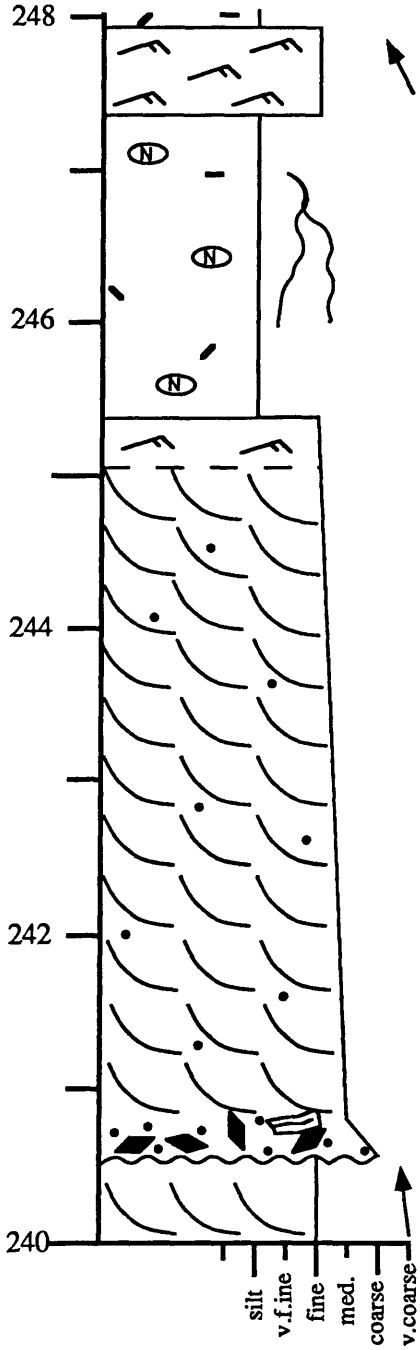
Rock House Cove
#1 (15-20)
silt
v. fine
fine
med.
coarse
v. coarse
Flute/Tool marks
224
222
220
218



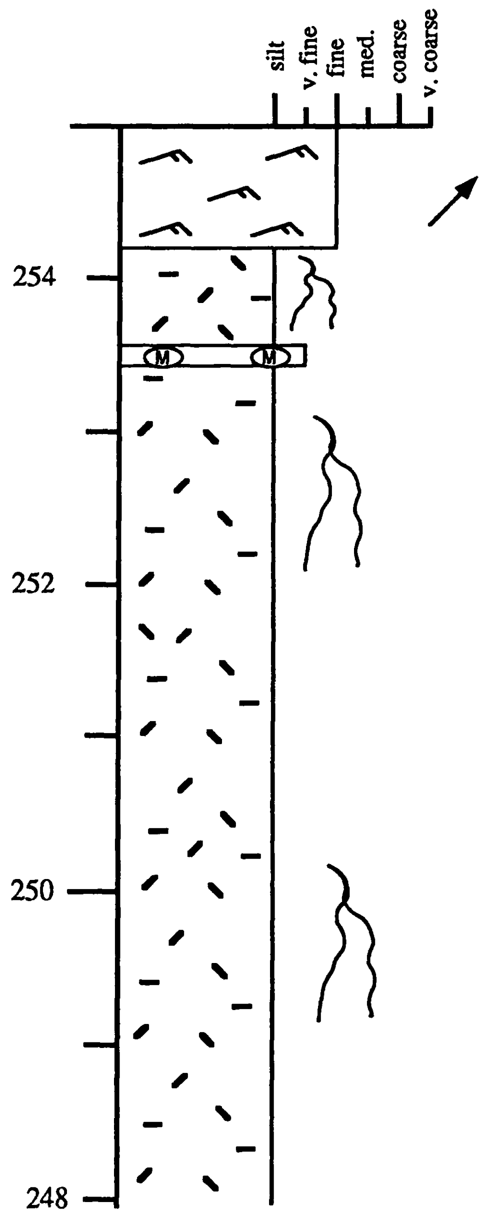
233
231
229
227
225
silt
v.f.ine
fine
med.
coarse
v.coarse

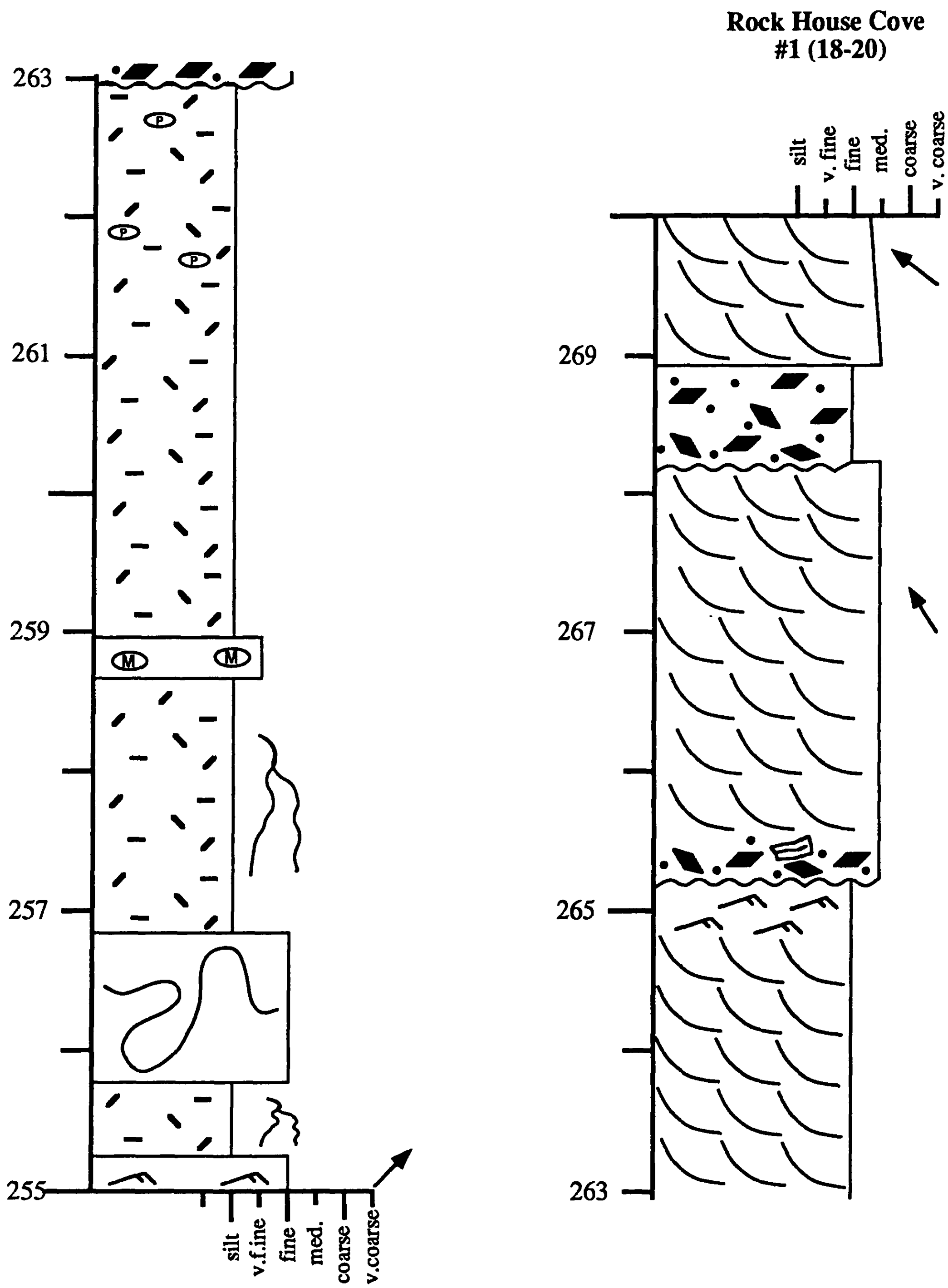


Rock House Cove
#1 (16-20)
silt
v. fine
fine
med.
coarse
v. coarse
239
237
235
233

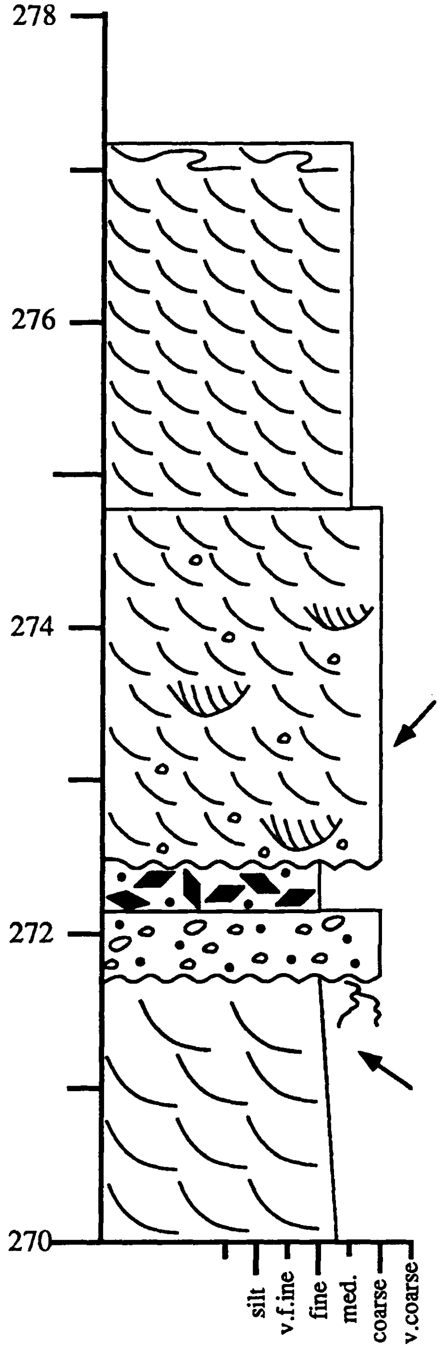


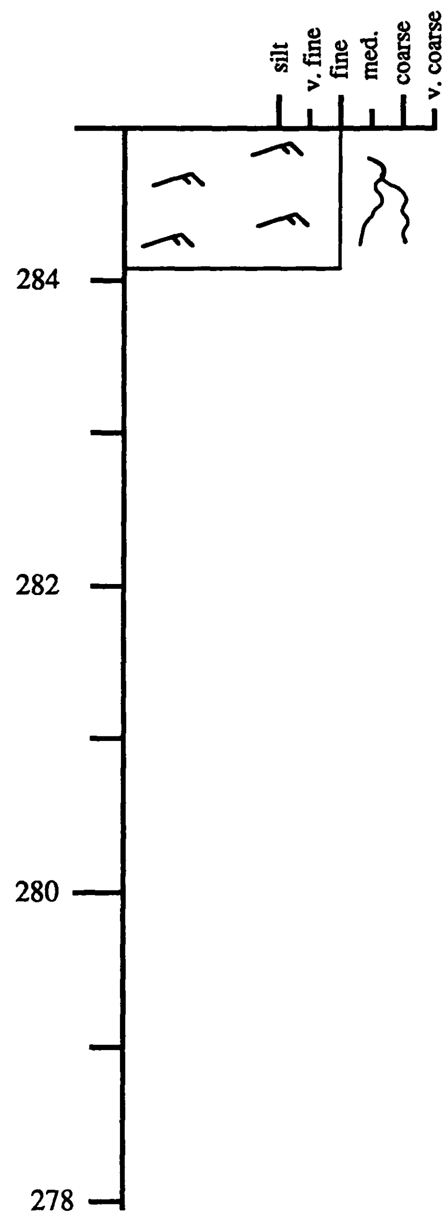
Rock House Cove
#1 (17-20)

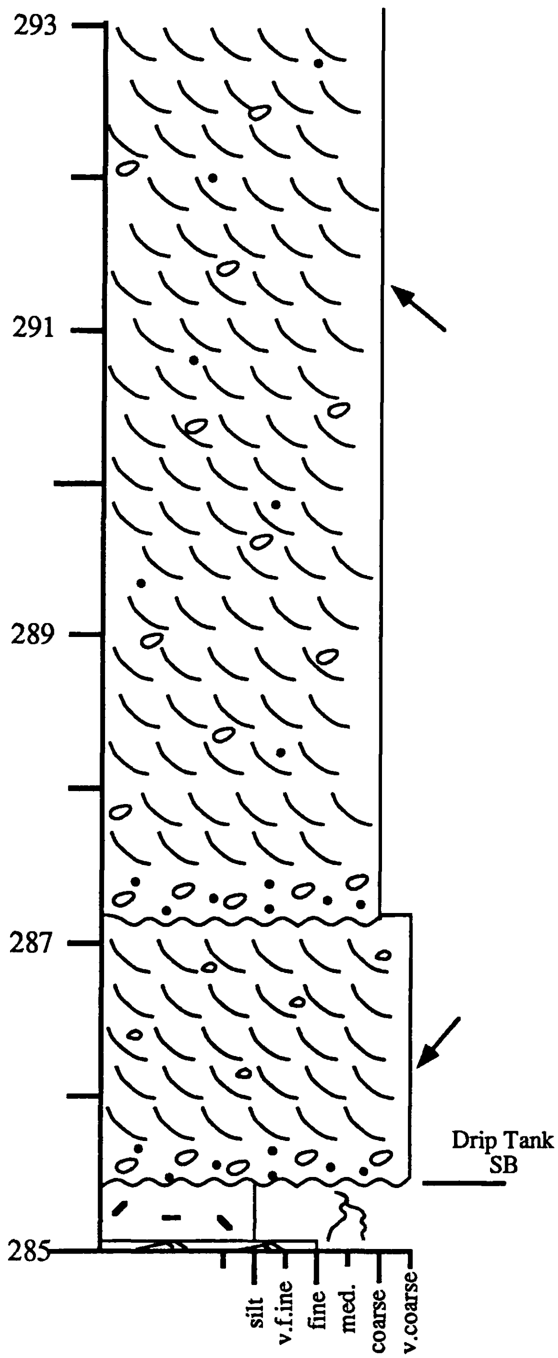


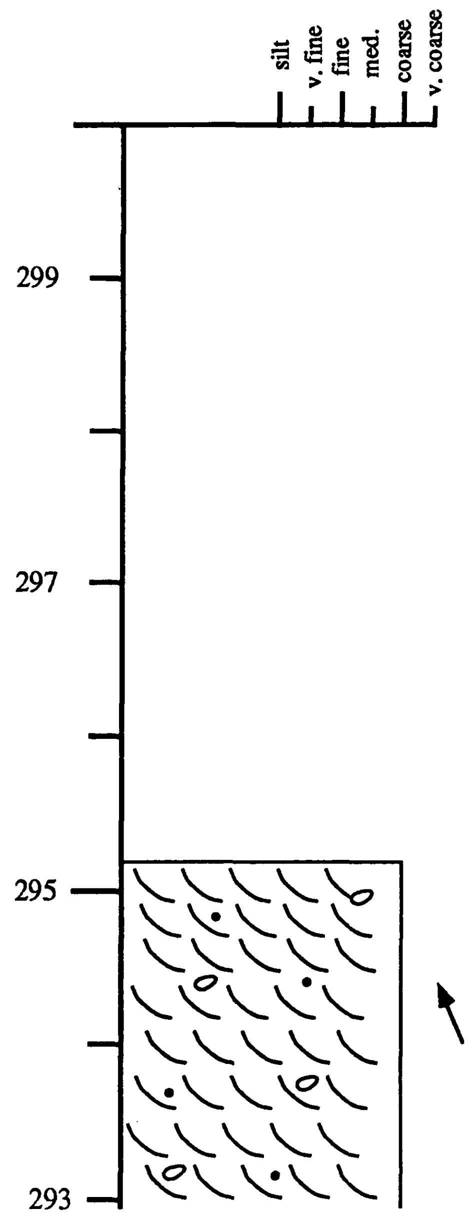

Rock House Cove
#1 (18-20)
263
261
259
257
255
silt
v.f.ine
fine
med.
coarse
v.coarse
269
267
265
263
silt
v. fine
fine
med.
coarse
v. coarse

Rock House Cove
#1 (19-20)






293
291
289
287
285
Drip Tank
SB
silt
v.f.ine
fine
med.
coarse
v.coarse

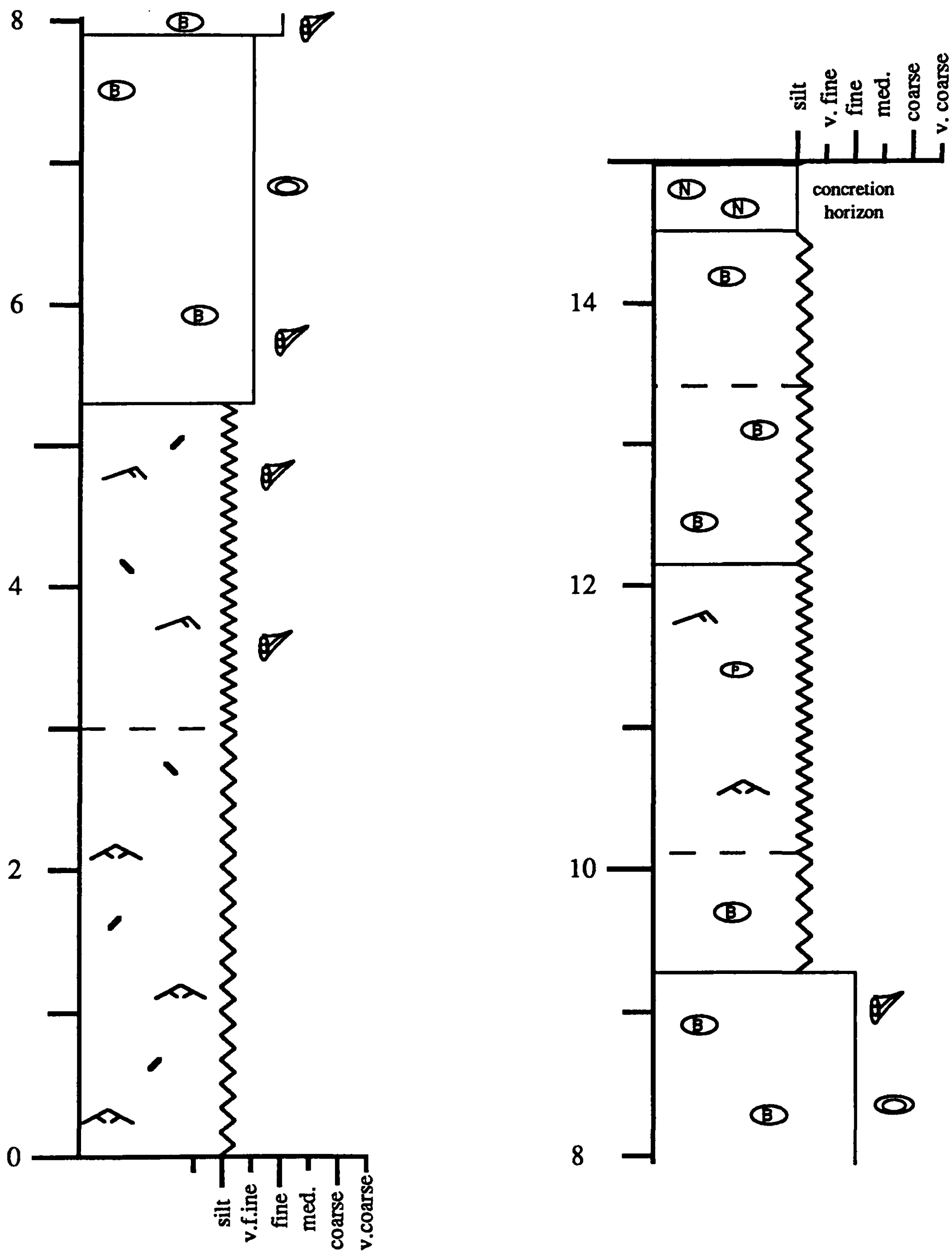

Rock House Cove
#1 (20-20)
silt
v. fine
fine
med.
coarse
v. coarse
299
297
295
293

Appendix D

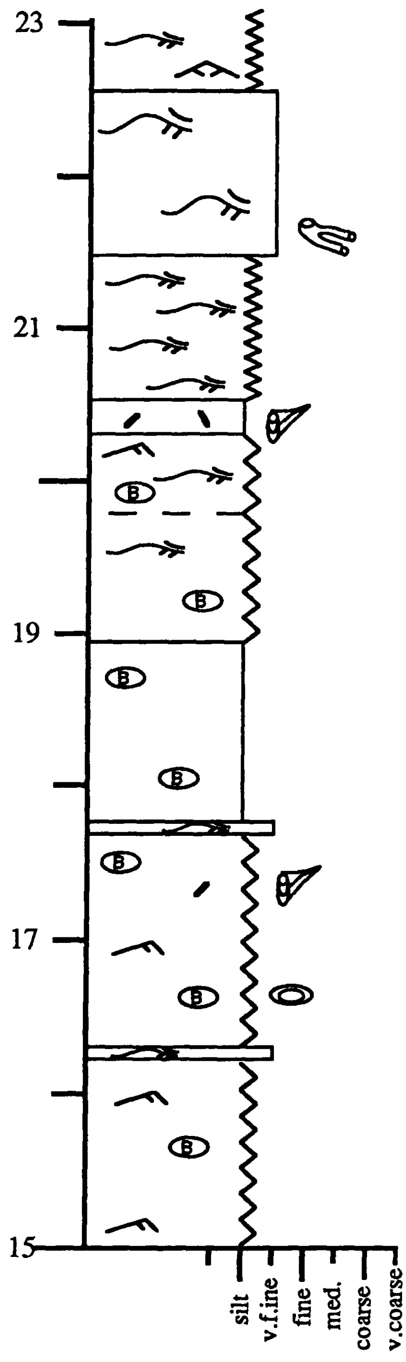
MEASURED SECTION, TIBBET CANYON

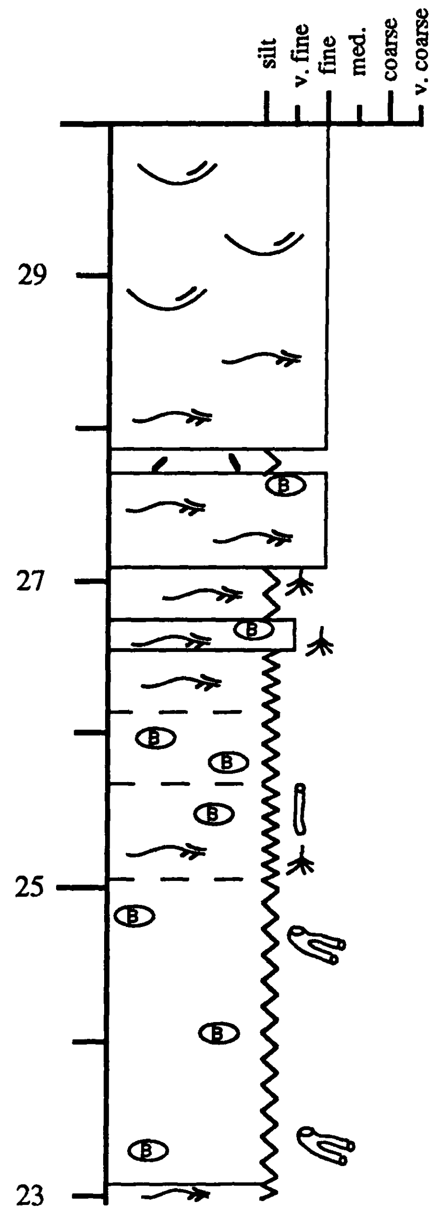
A detailed stratigraphic section was measured along a south- to southeast-trending ridge located at the entrance to Tibbet Canyon in Kane County, Utah; the section begins just north of the dirt road that passes through the canyon. The section extends from the upper part of the Tropic Shale to the lower part of the Drip Tank Member of the Straight Cliffs Formation. The measured section begins in section 13, Township 42 south, Range 3 east, at a position approximately 400 feet from the north line of section 13 and 1320 feet from the west line of section 13. The measured section ends in section 12, Township 42 south, Range 3 east, at a position approximately 2300 from the south line of section 12 and 315 feet from the west line of section 12. This area can be located on the U.S.G.S Tibbet Bench Quadrangle - 7.5 minute topographic map. All measurements on the Tibbet Canyon section are in meters.

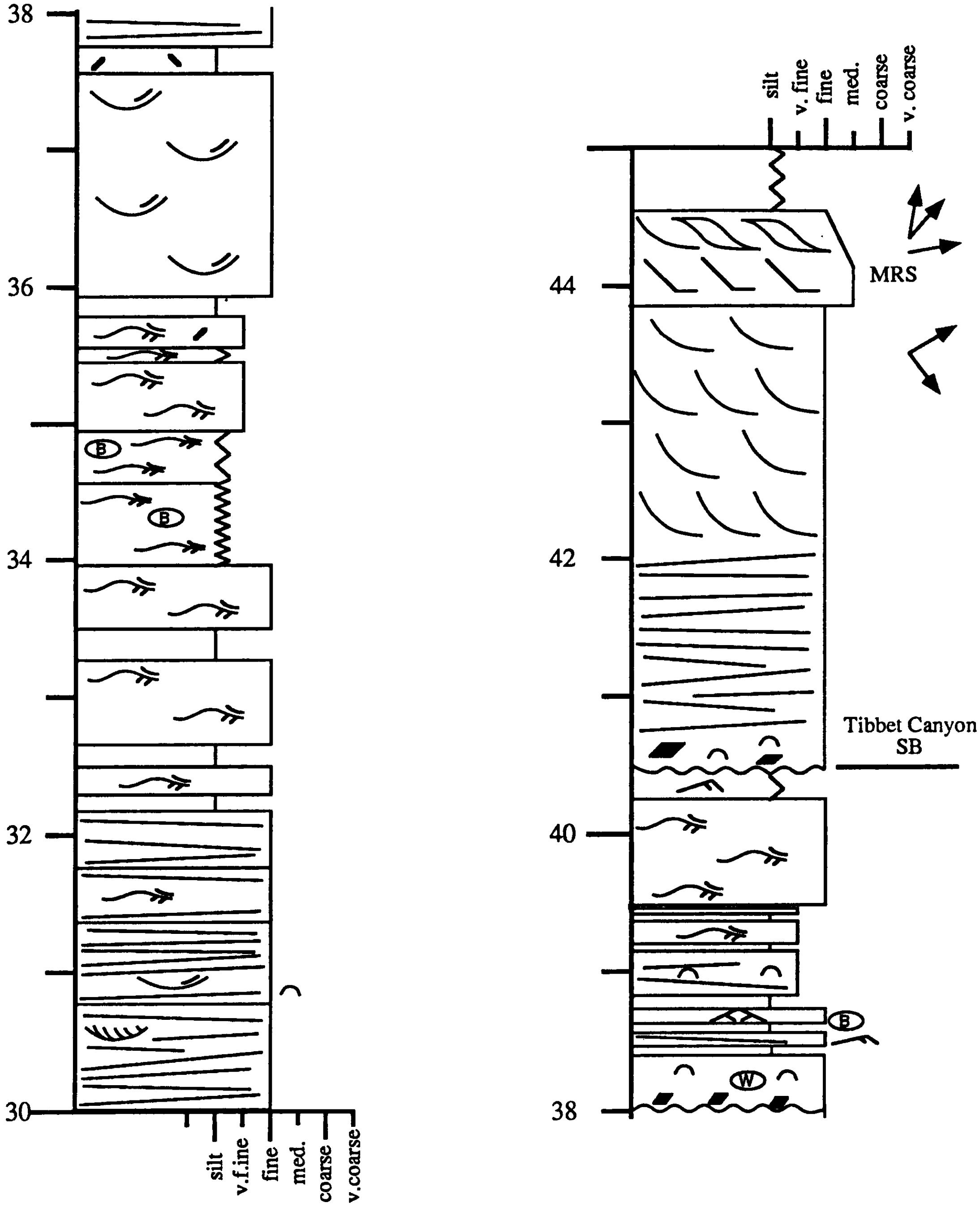
Tibbet Canyon #1 (1-22)



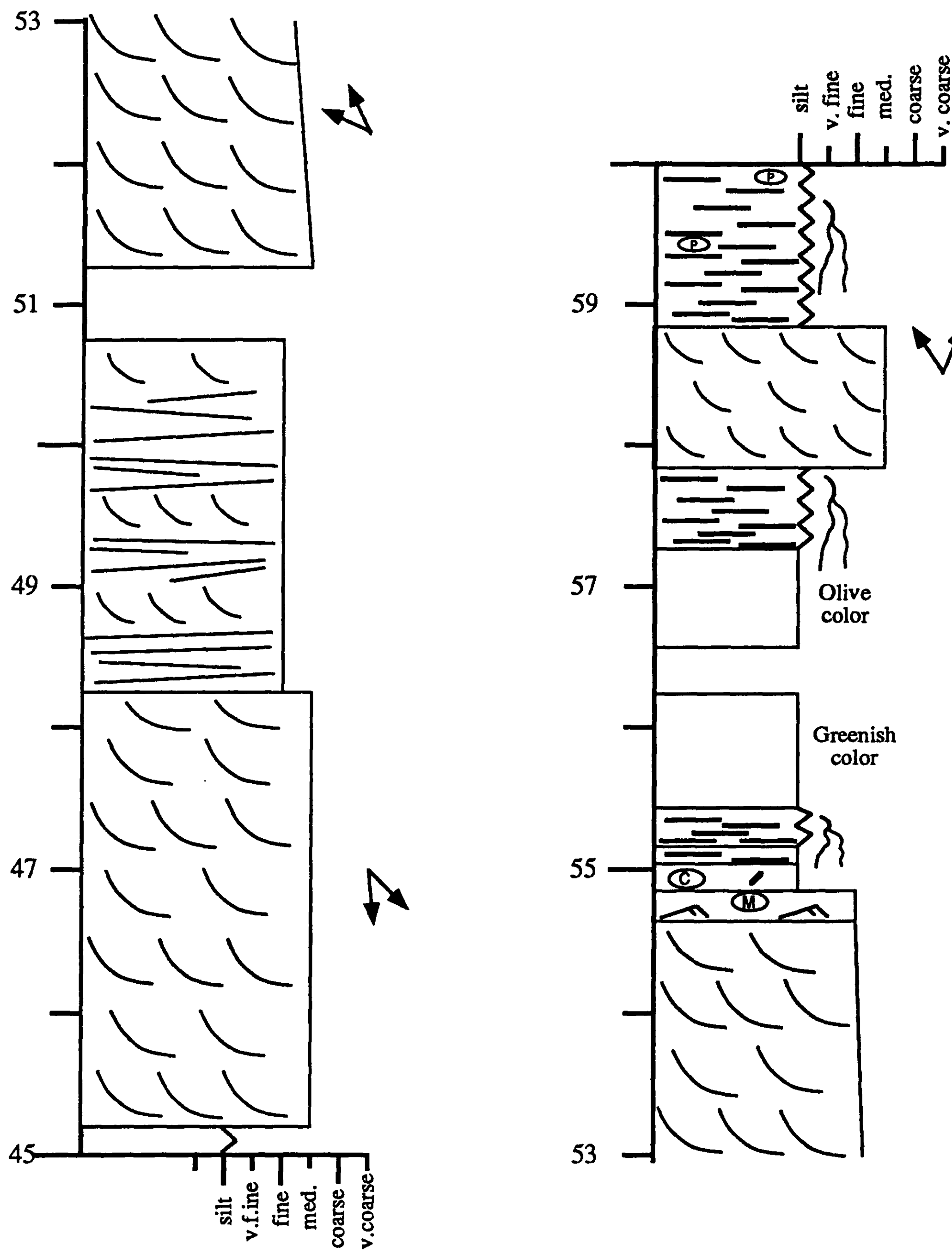
Tibbet Canyon #1 (2-22)

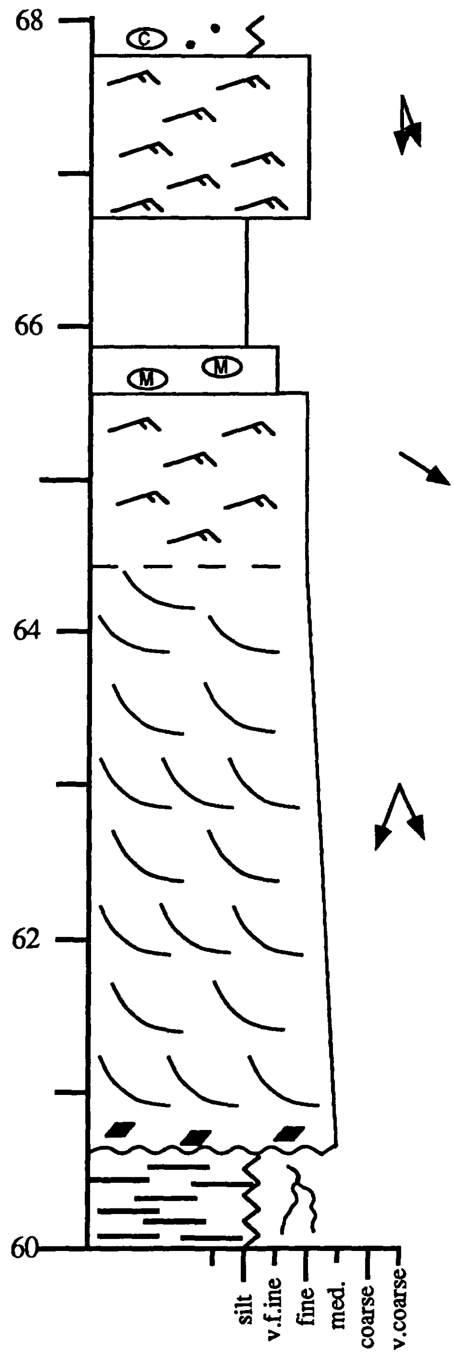




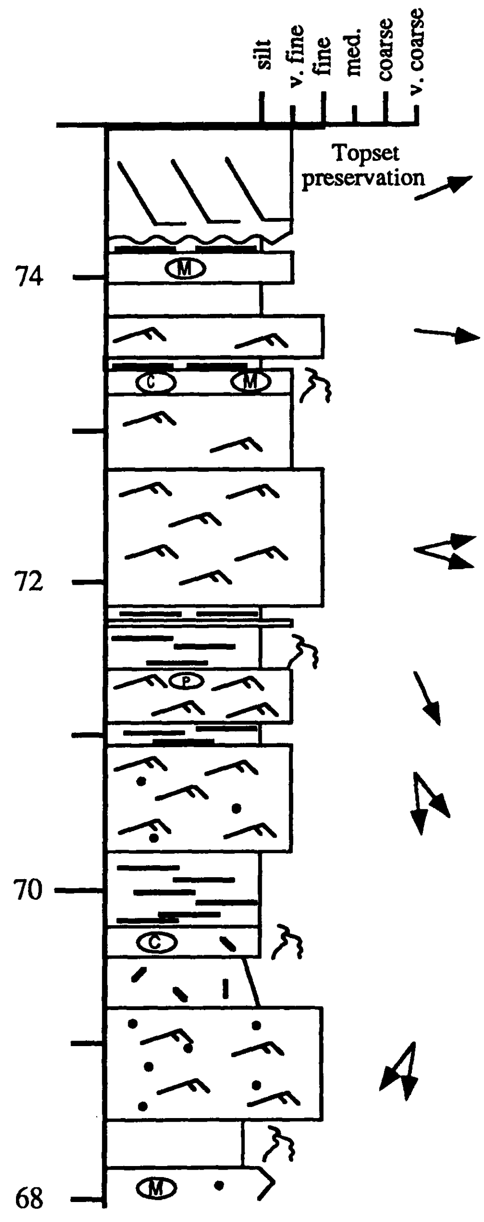

Tibbet Canyon #1 (3-22)
38
36
34
32
30
silt
v.f.ine
fine
med.
coarse
v.coarse
B
B
silt
v. fine
fine
med.
coarse
v. coarse
44
42
40
38
MRS
Tibbet Canyon
SB
B
W

Tibbet Canyon #1 (4-22)

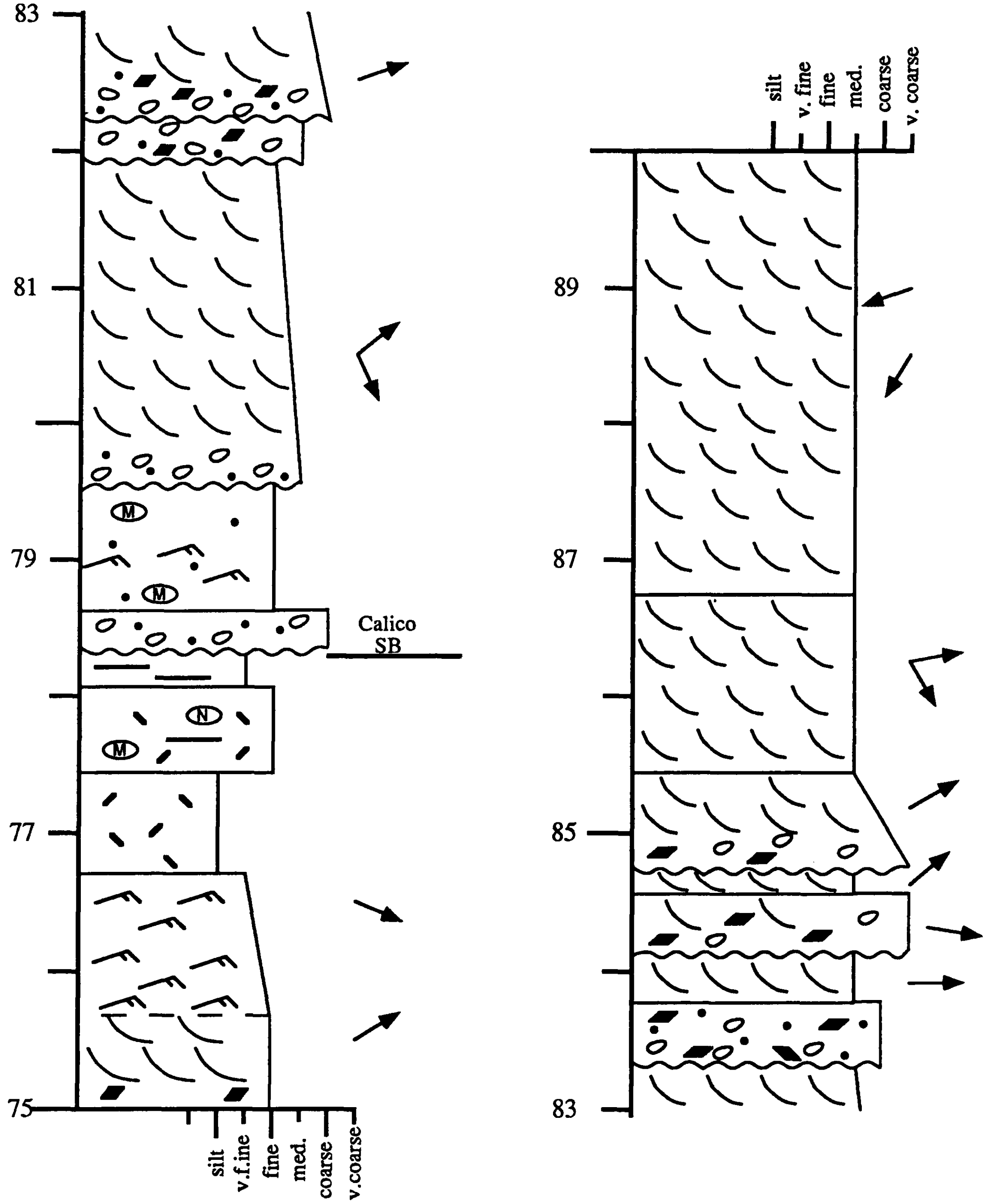




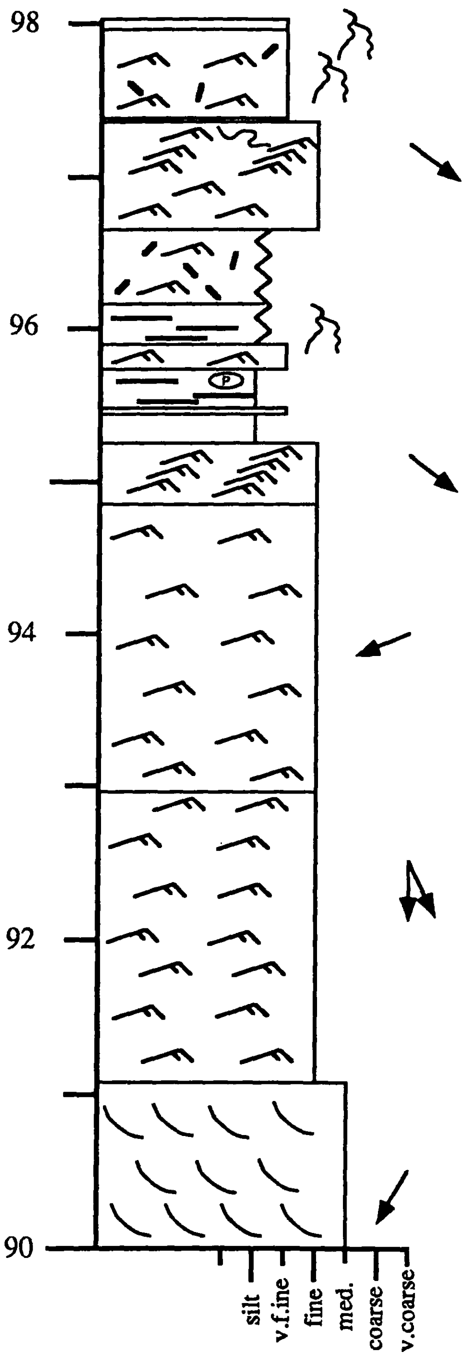
Tibbet Canyon #1 (5-22)

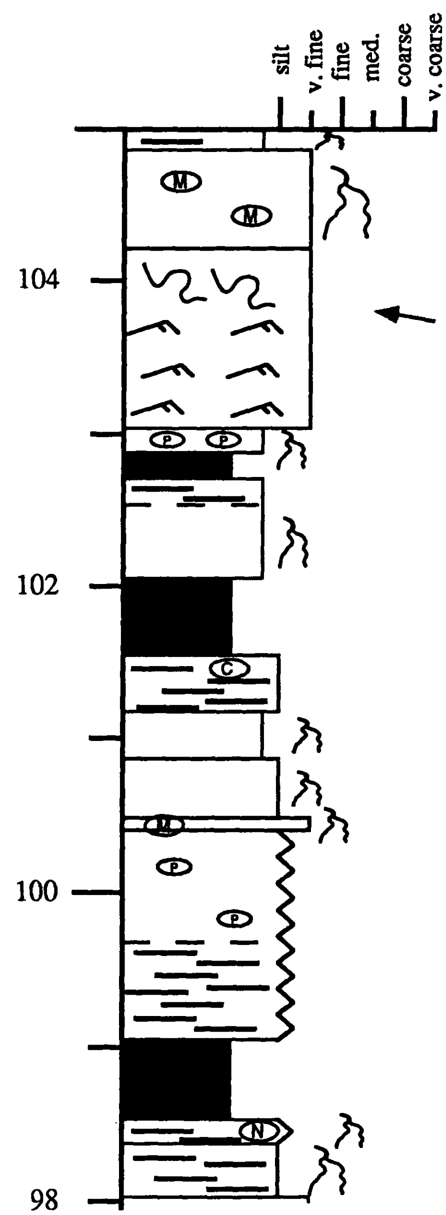


Tibbet Canyon #1 (6-22)

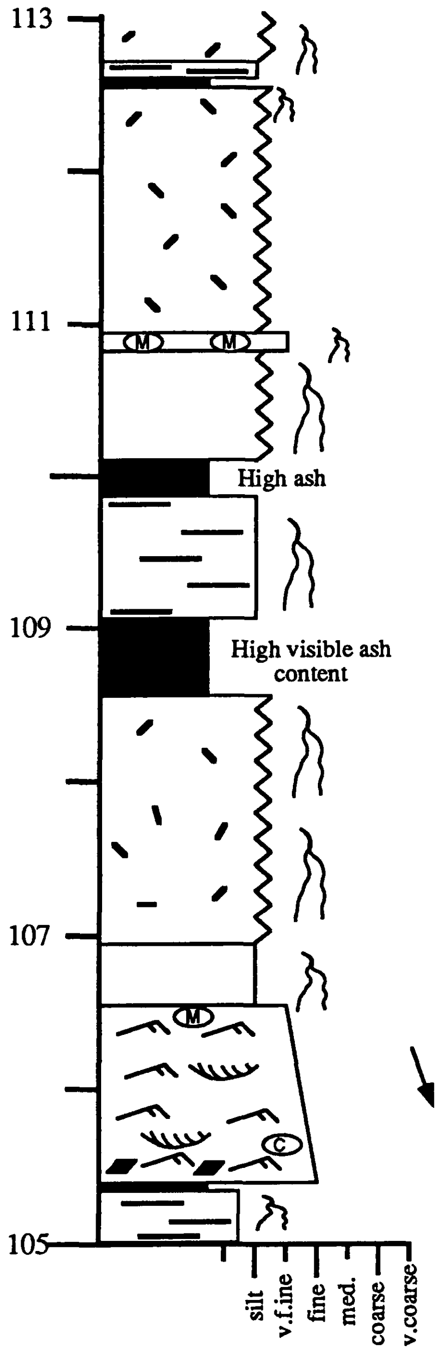


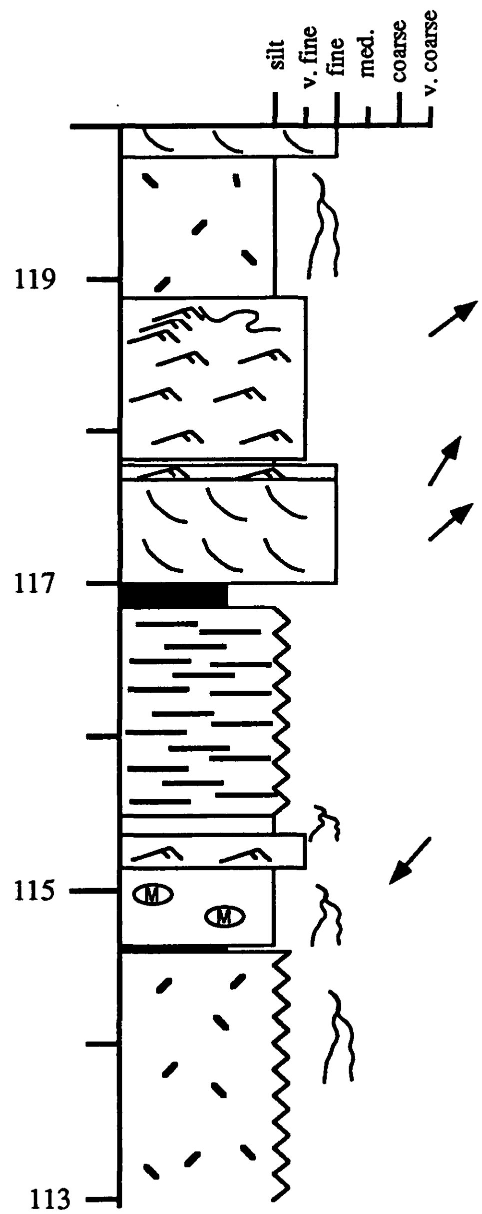
Tibbet Canyon #1 (7-22)



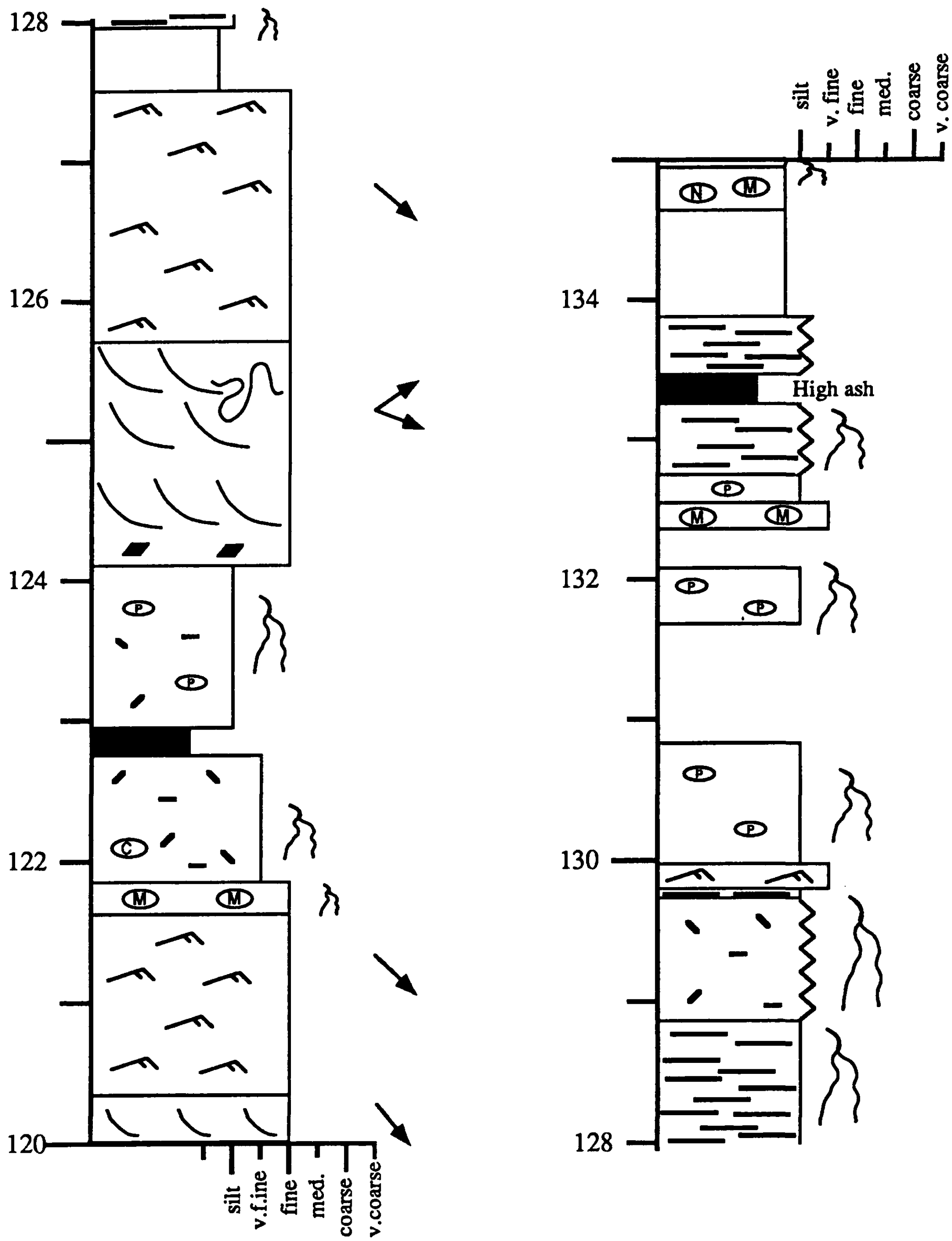


Tibbet Canyon #1 (8-22)

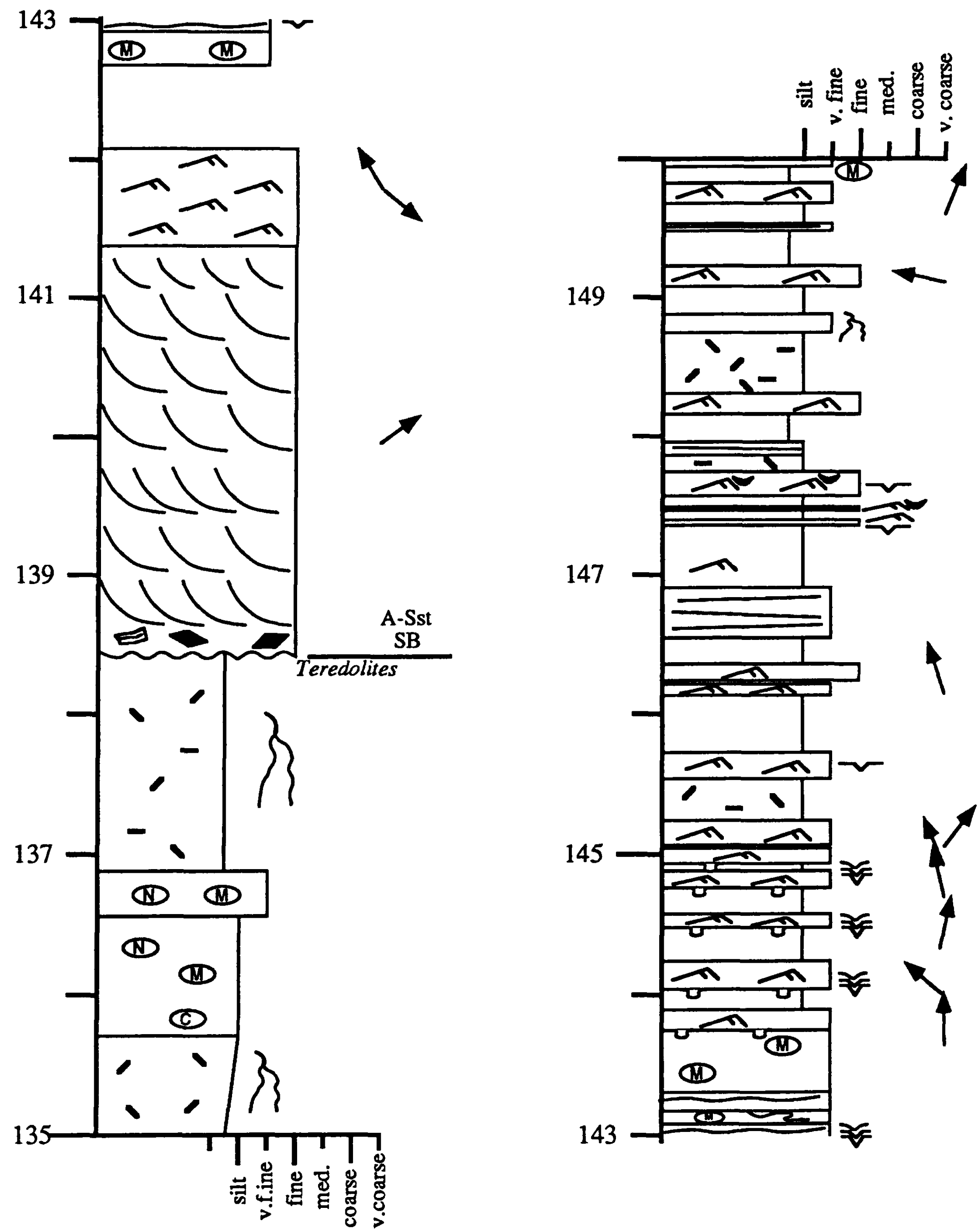


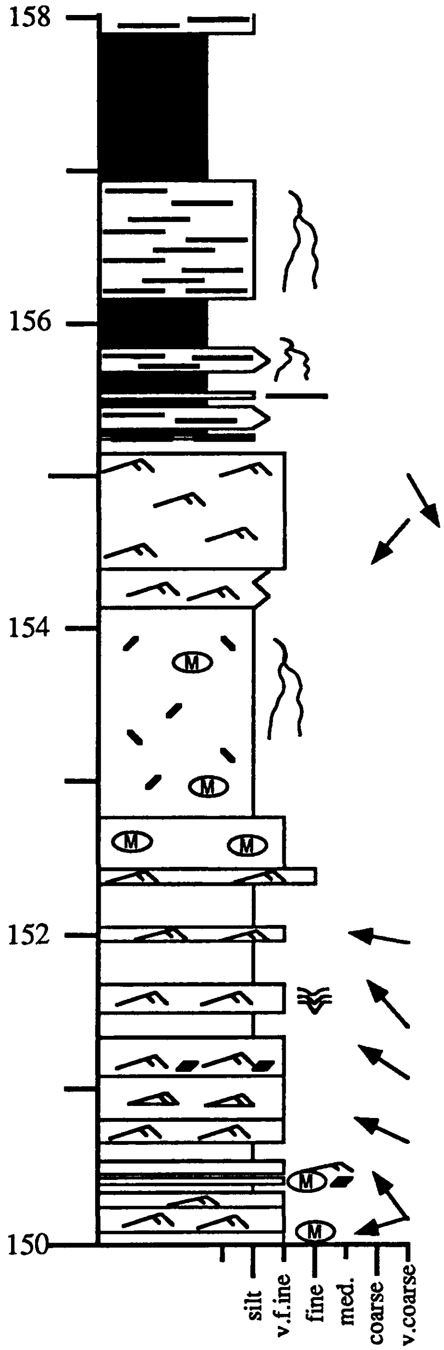


Tibbet Canyon #1 (9-22)

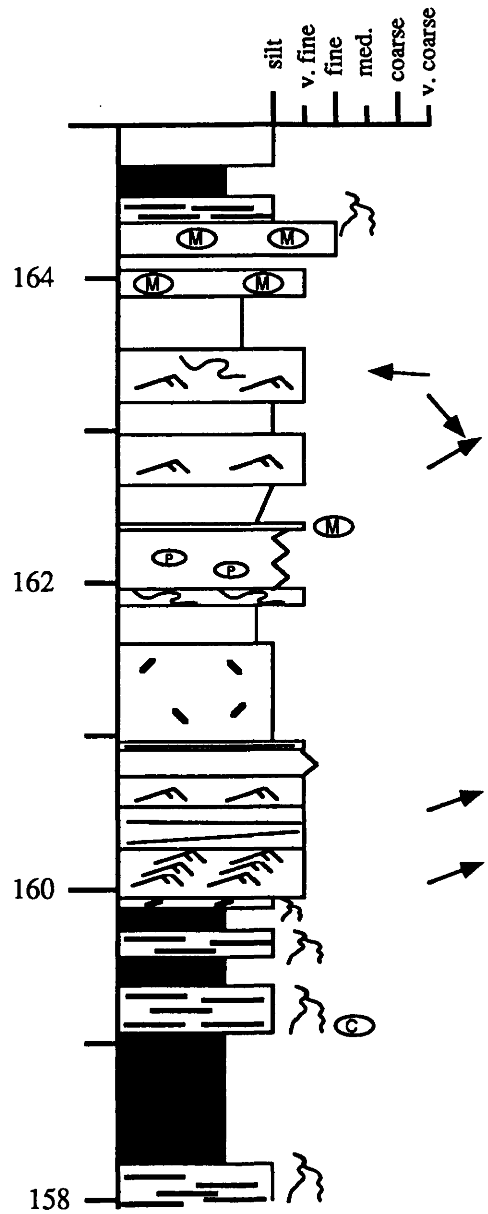


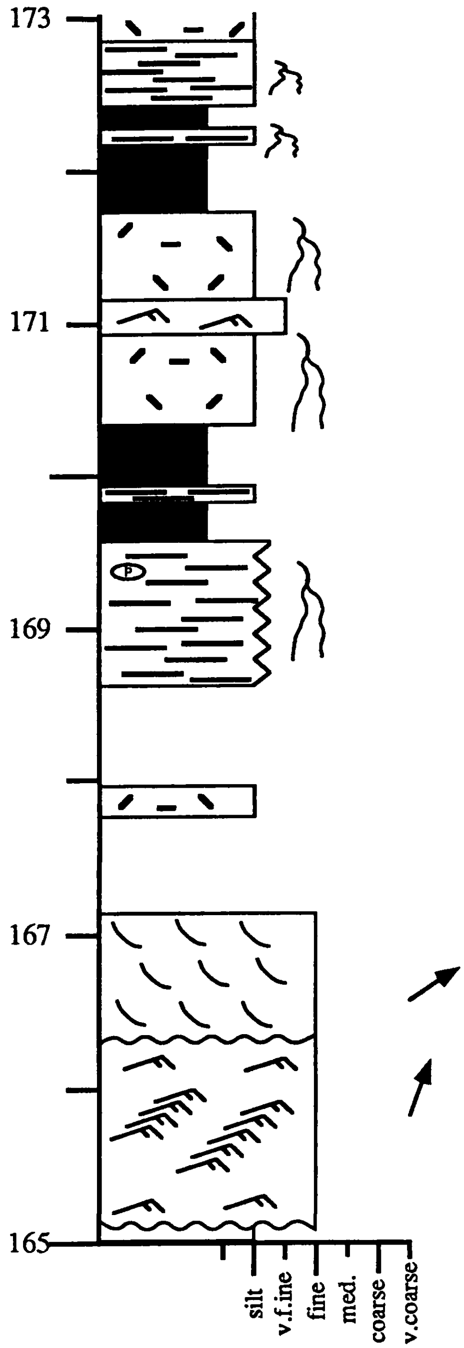
Tibbet Canyon #1 (10-22)



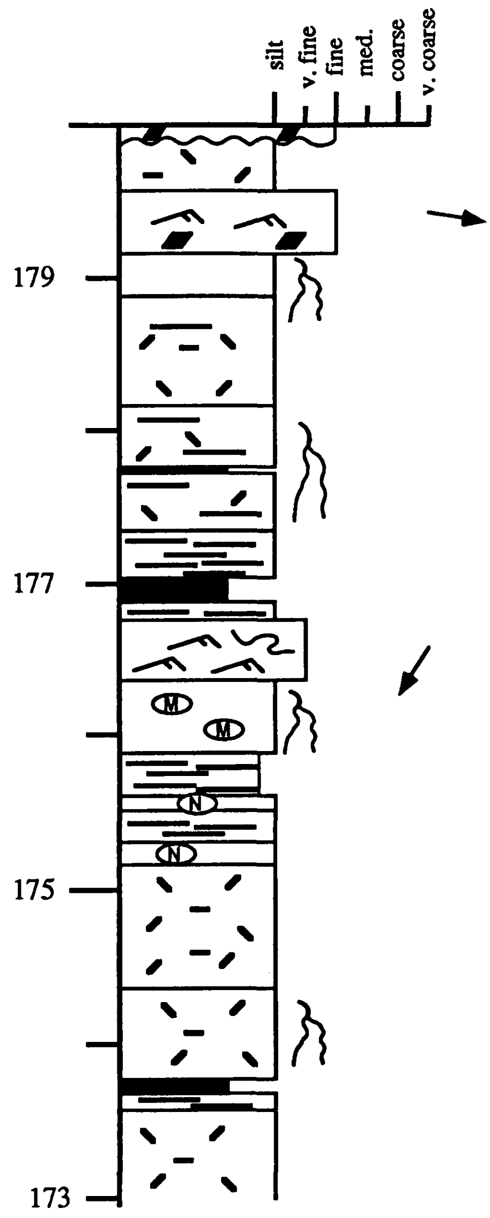


Tibbet Canyon #1 (11-22)

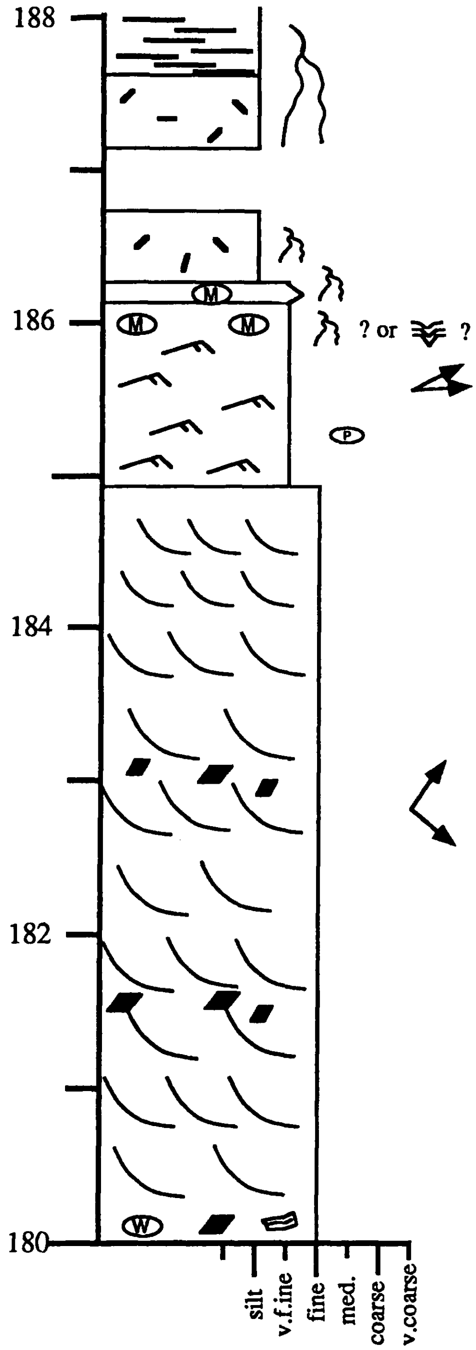


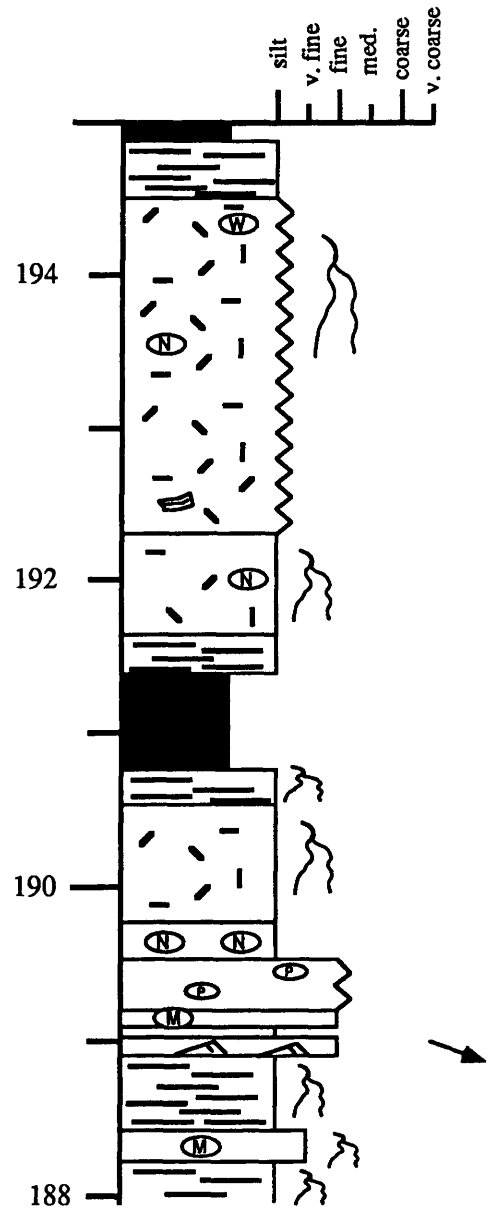


Tibbet Canyon #1 (12-22)

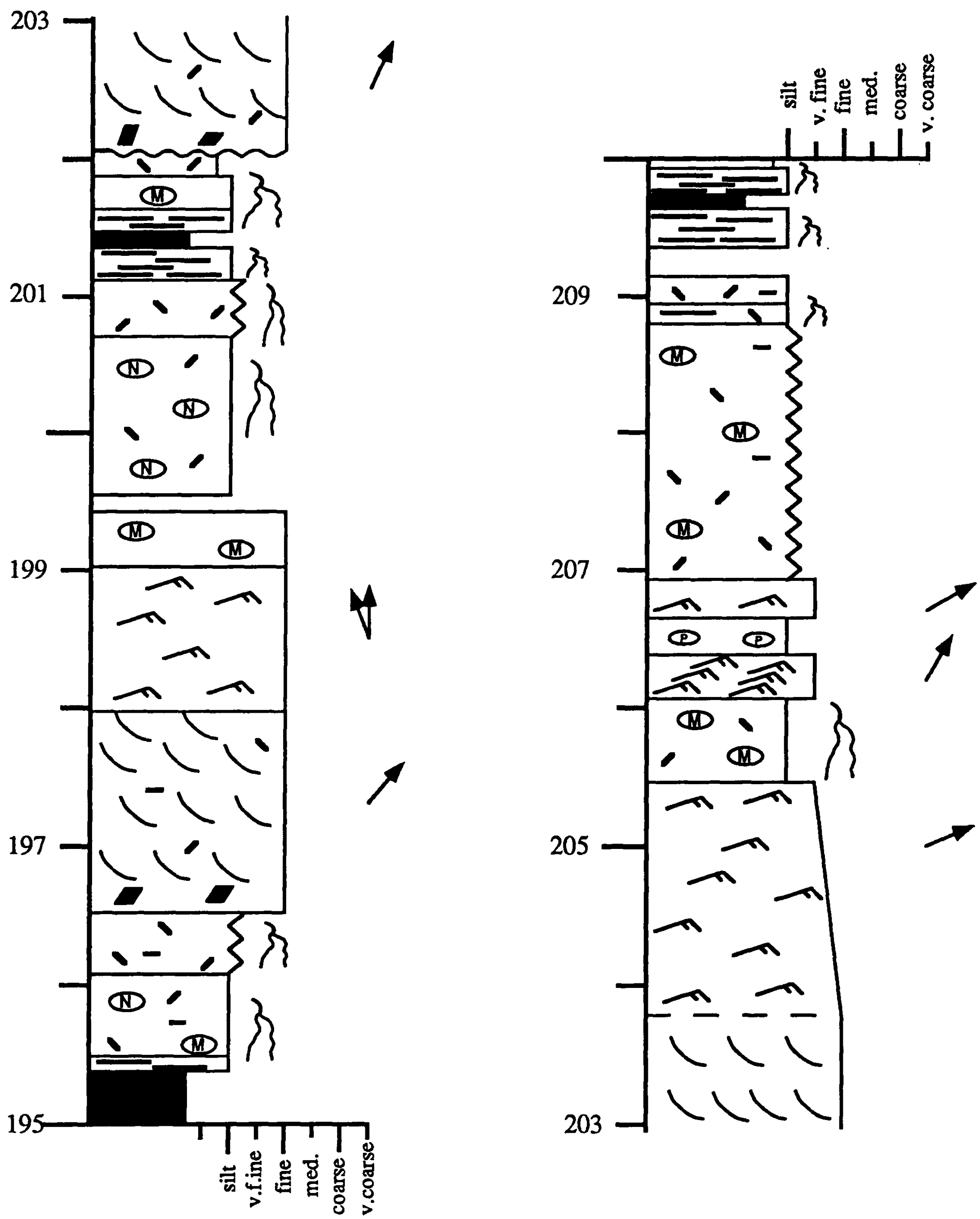


Tibbet Canyon #1 (13-22)

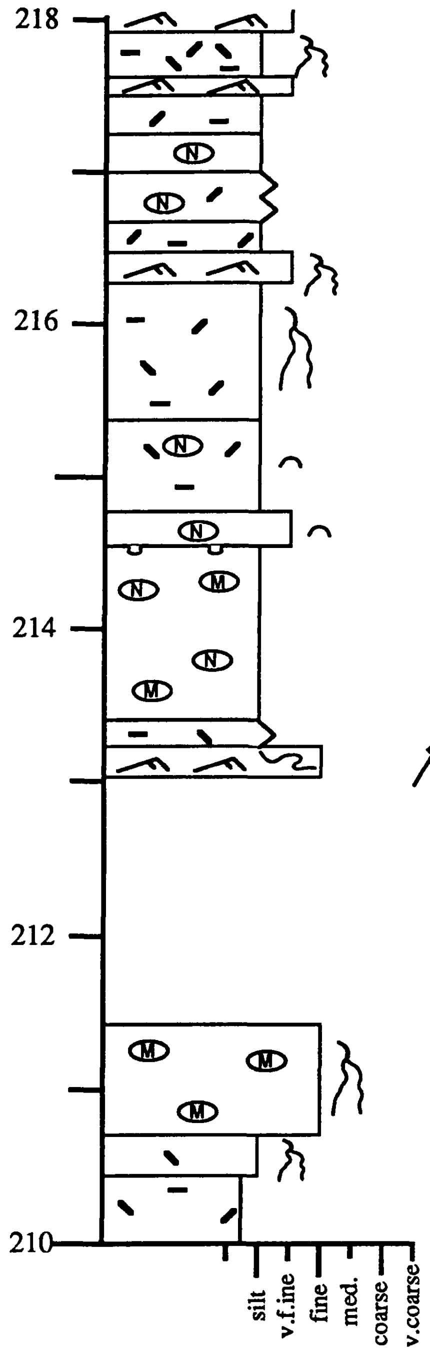


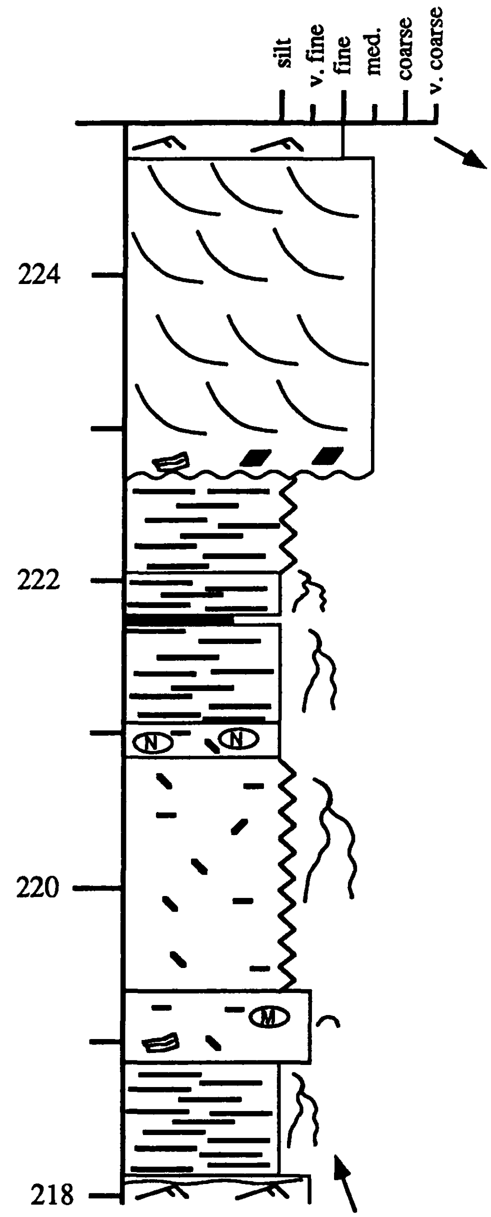


Tibbet Canyon #1 (14-22)



Tibbet Canyon #1 (15-22)





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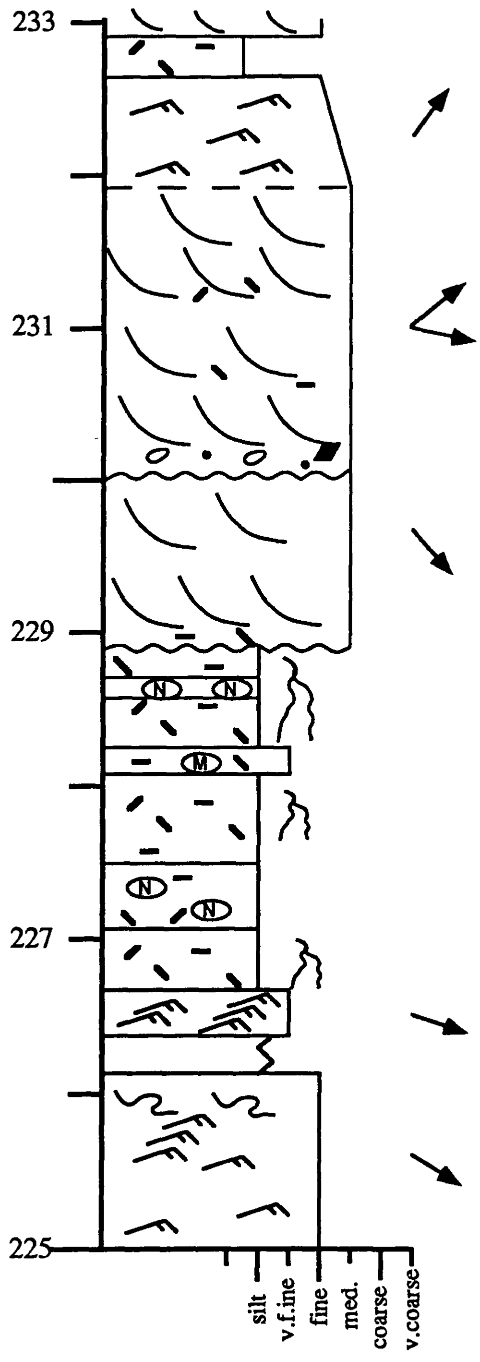
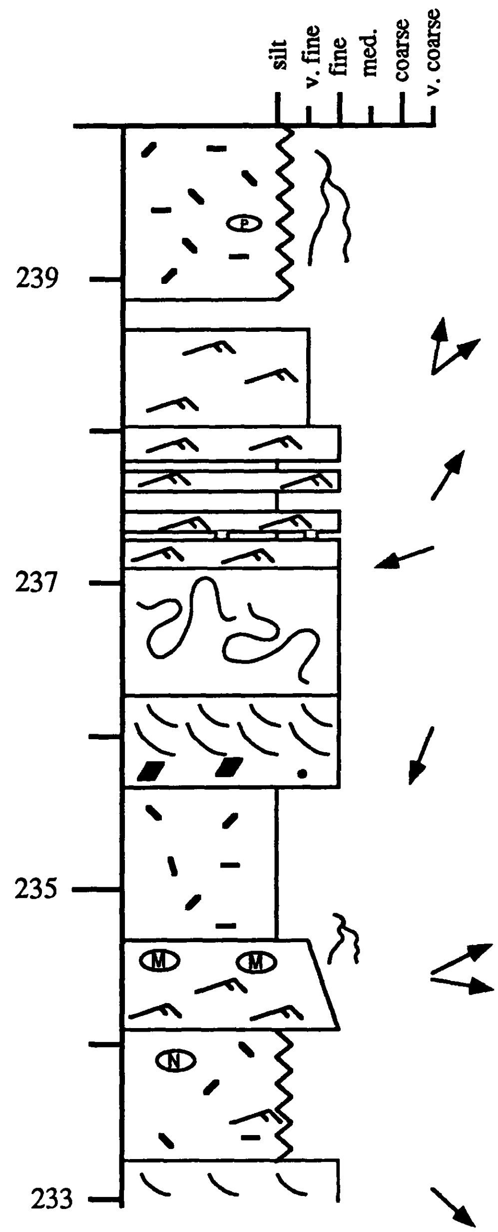
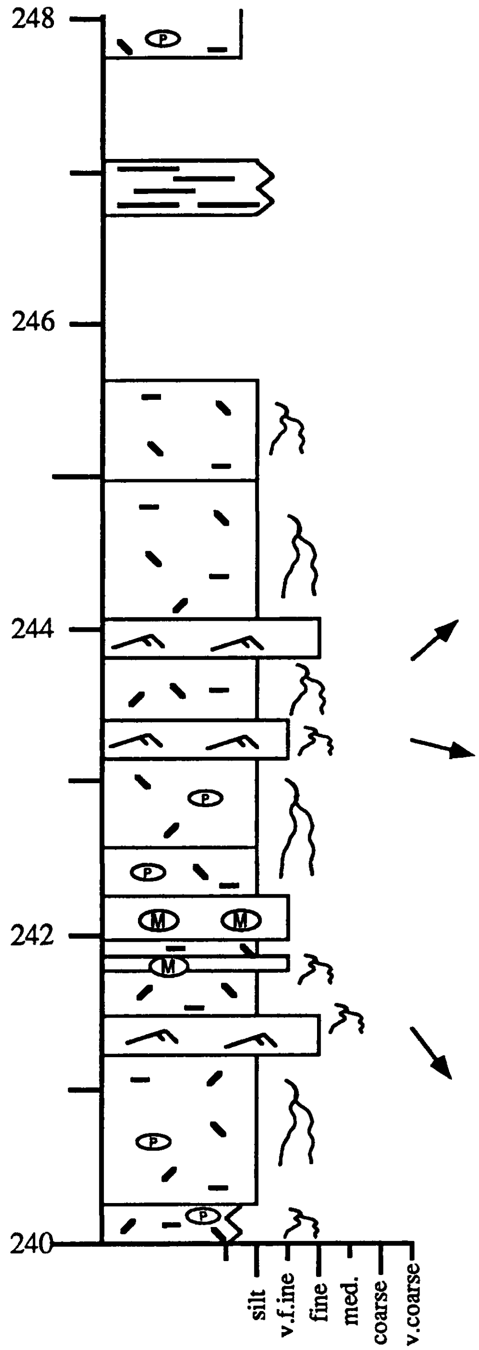
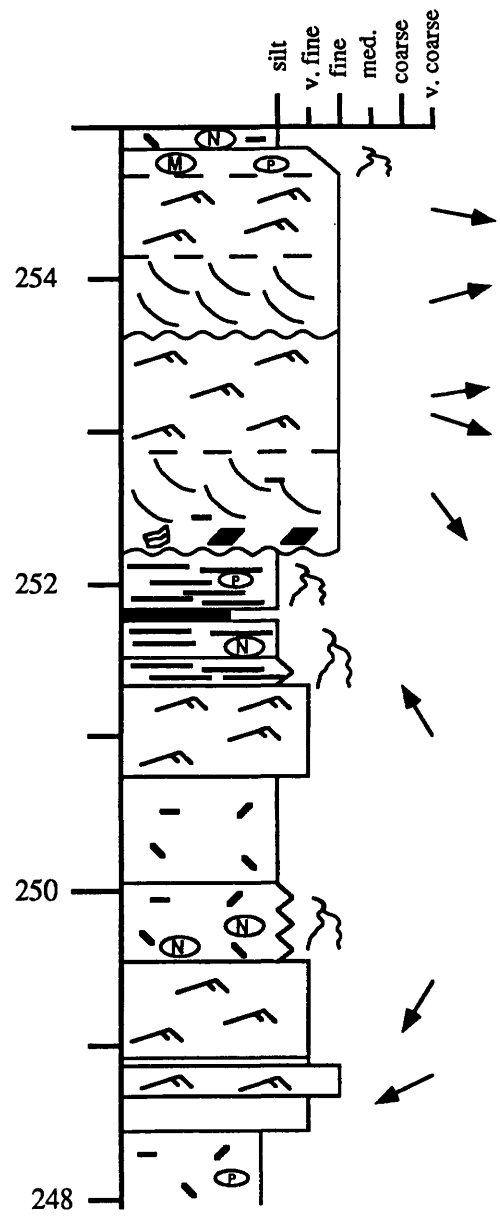


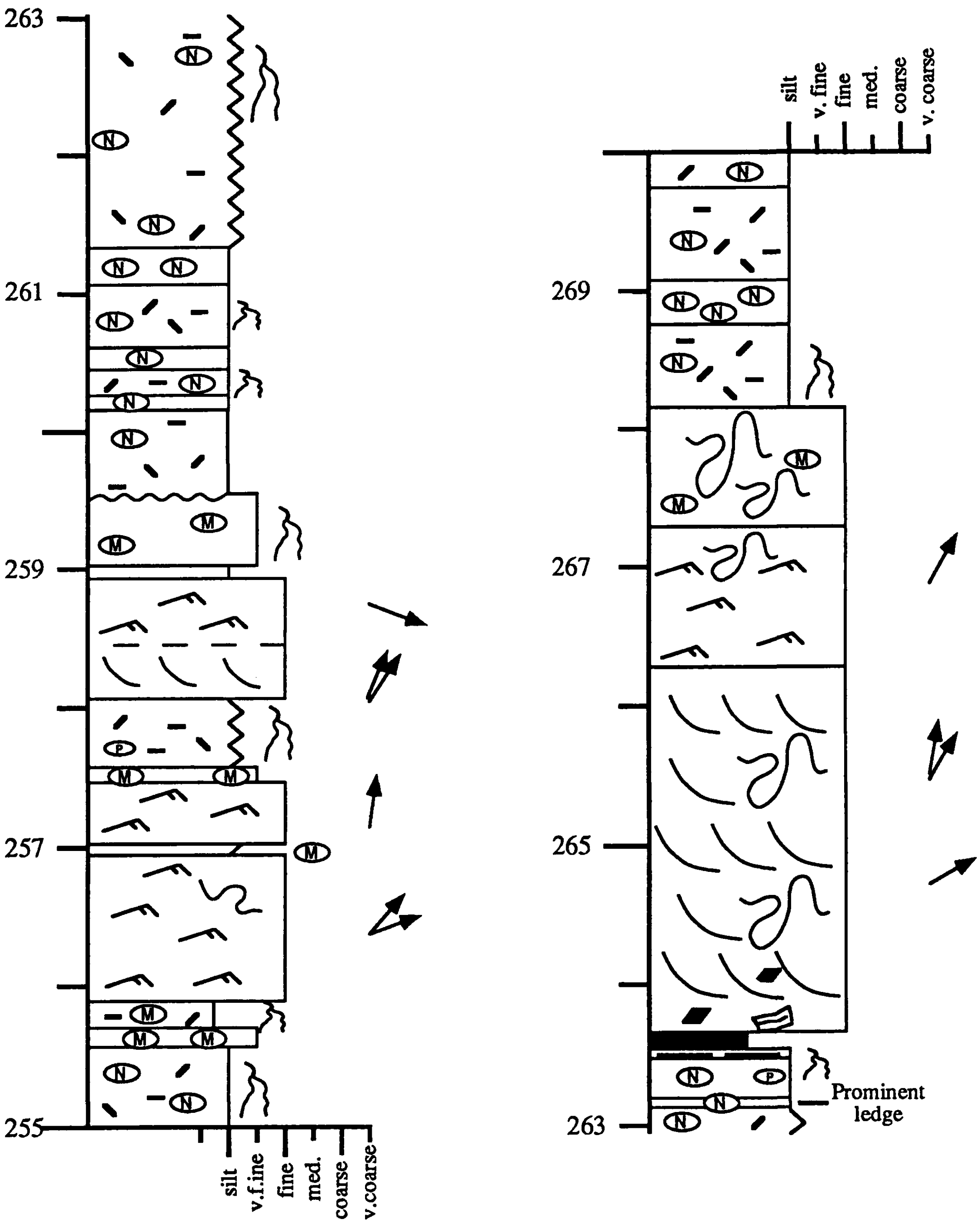


Tibbet Canyon #1 (17-22)

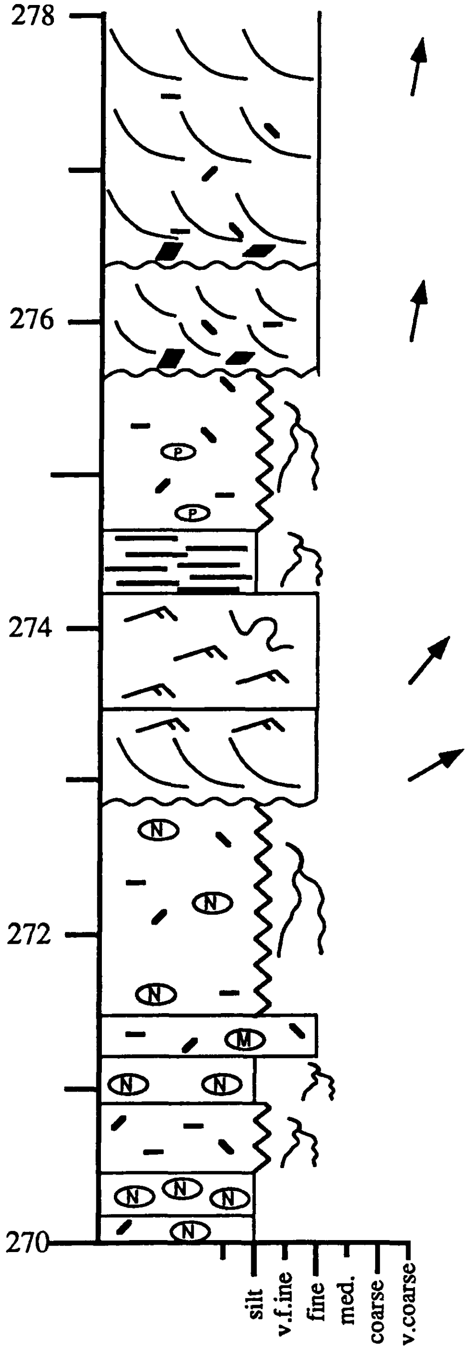


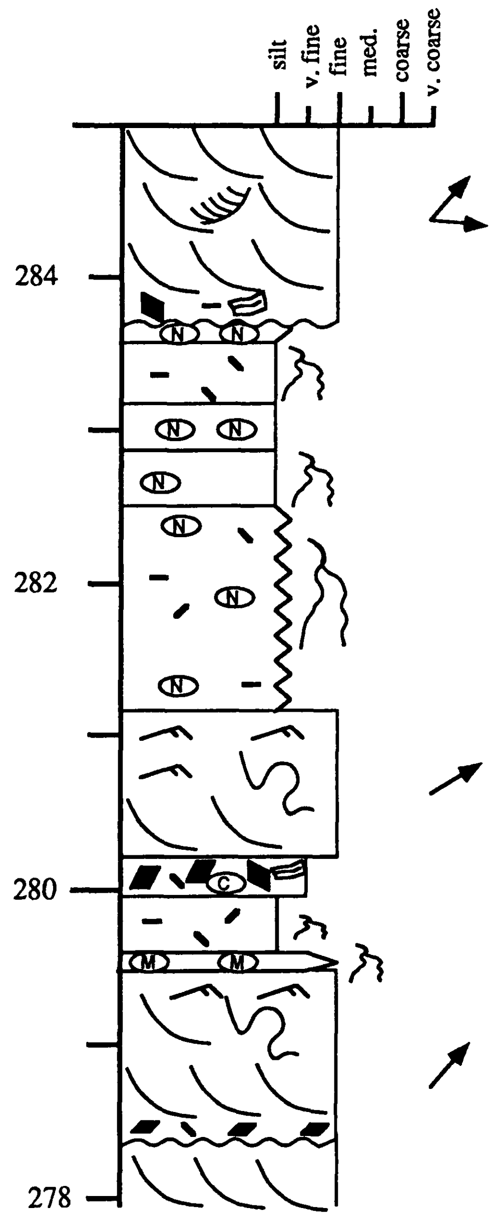


Tibbet Canyon #1 (18-22)

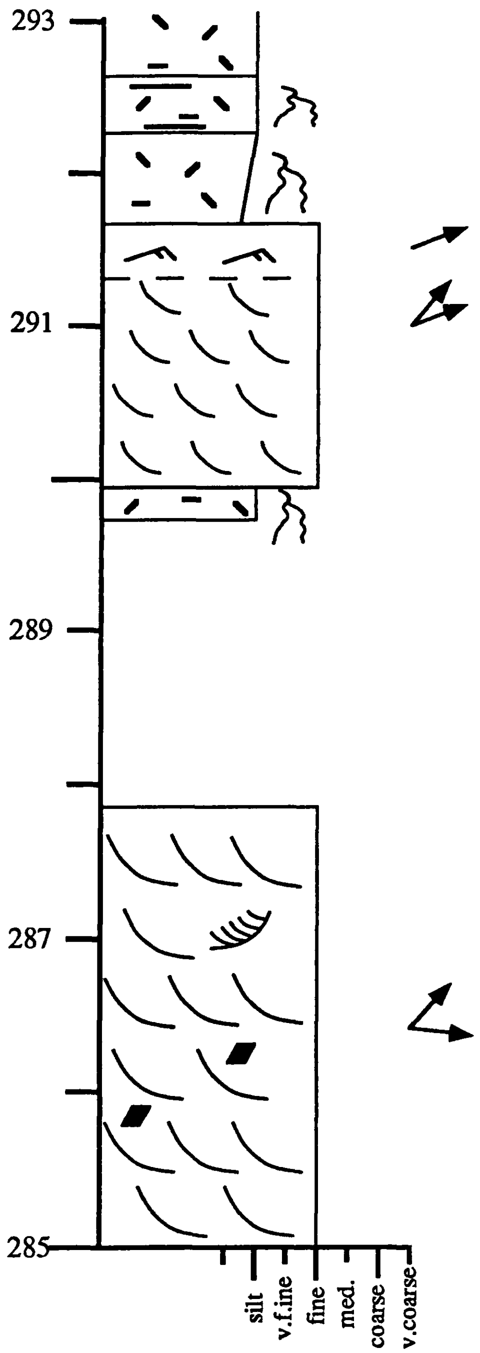


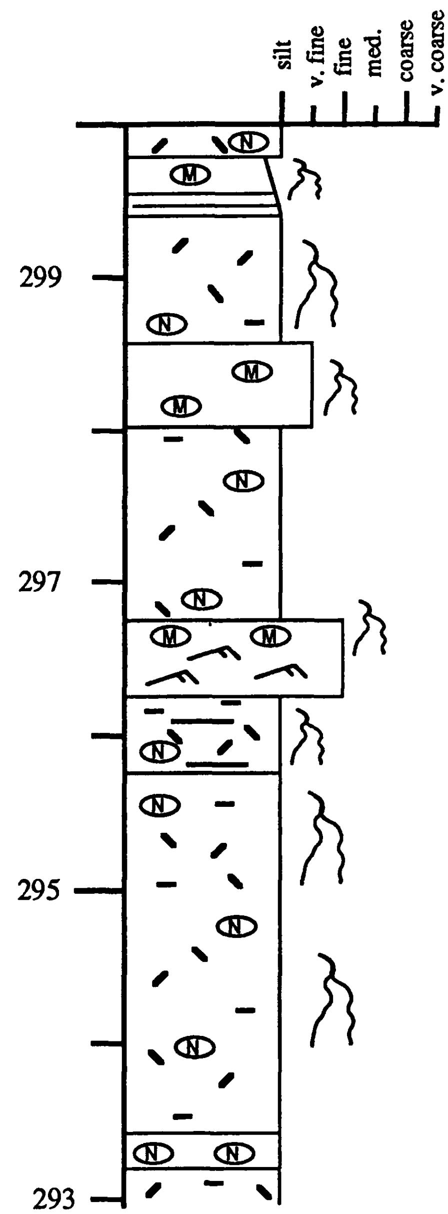
Tibbet Canyon #1 (19-22)





Tibbet Canyon #1 (20-22)





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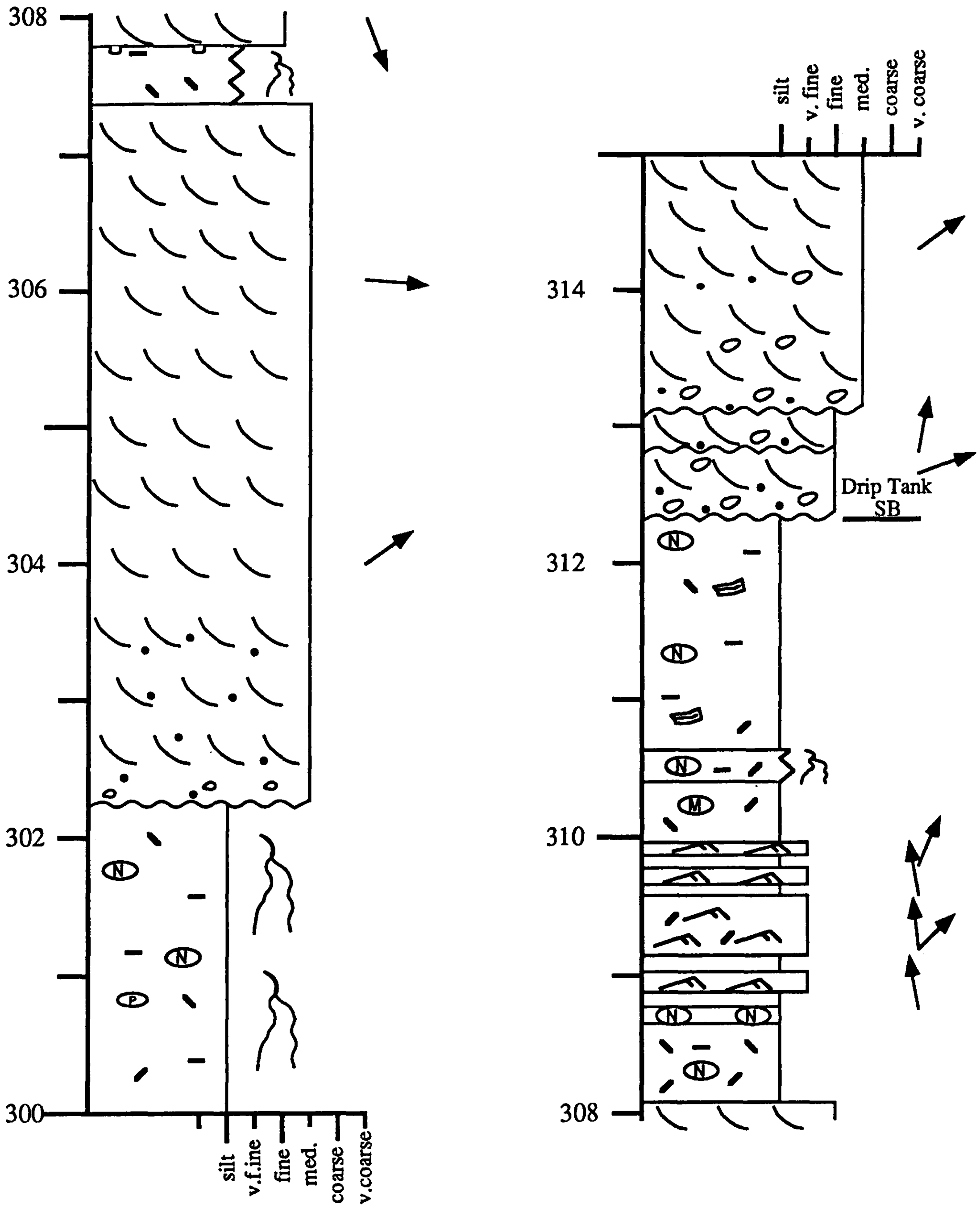

Tibbet Canyon #1 (22-22)