ABSTRACT

Cenomanian through Campanian strata of the Kaiparowits Basin in south-central Utah record the eastward migration of the Western Interior foredeep axis as the Sevier Thrust Belt approached from the west. Four, mostly conformable, depositional sequences were produced. With the exception of the lowest sequence, each is divided into four parts distinguishable on the basis of alluvial architecture. Together, the upper three sequences make up a nearly 2 km-thick succession comprised almost exclusively of fluvial deposits. At the base of each of these sequences are relatively thin, restricted sandstone sheets that grade both laterally and vertically into fine-grained deposits. Next are thick intervals of predominantly fine-grained material containing scattered lenses and thin sheets of sandstone. These intervals grade upward into extensive multistoried sandstone sheets that contain very little fine-grained material. Sequences are capped by laterally extensive multistory sheets of gravely sandstone and sandy conglomerate. The lowest sequence is also divisible into four parts but differs from the other three in that it includes significant marine and coastal deposits.

Tectonic and eustatic models based on relationships between alluvial architecture and rates of accommodation production were applied to these sequences in an attempt to determine whether eustatic and tectonic effects could be differentiated from one another in a foredeep basin setting. Locally, both tectonically- and eustatically-controlled base level fluctuations appear to produce similar vertical successions. The key to distinguishing between them seems to lie in regional distribution patterns for the coarse-grained sheets that cap each sequence. In tectonically-controlled sequences, these sheets are predicted to have planar lower and upper boundaries, to become progressively thicker and coarser-grained upward through the section, to thicken toward the thrust belt but not be traceable back to that region, and to step in a progressively basinward direction. In eustatically-controlled sequences, sheets are expected to be, essentially, valley-fill deposits with irregular lower boundaries, to not necessarily show an overall vertical grain-size increase for successive sheets, and the sheets are anticipated to be traceable back to the thrust belt. Deposits could, however, still demonstrate a progressive basinward migration associated with thrust belt advancement.

Upper Cretaceous sequences of the Kaiparowits Basin most closely fit tectonic models, though significant eustatic effects are recorded in the lower two of these sequences.
INTRODUCTION

Recent approaches to fluvial sedimentology include the analysis of three-dimensional geometry and relative abundances of genetically related facies assemblages referred to as fluvial architecture (McKee and Weir, 1953; Allen, 1983; Miall, 1985, 1988; Holbrook, in press) and the application of sequence stratigraphic concepts to coastal fluvial systems (Shanley, 1991; Shanley and McCabe, 1991; Flint, 1993; Puigdefabregas, 1993). A number of computer models have been developed that relate primary architectural characteristics; such as sandbody geometry, sand/mud ratios, and sandbody interconnectedness to eustatic and tectonic controls on the creation and destruction of sediment accommodation space (Allen, 1978; Leeder, 1978; Bridge and Leeder, 1979; Alexander and Leeder, 1987), but application of these models to thick successions of real fluvial strata has been limited. Until recently, sequence stratigraphic models dealt almost exclusively with marine and coastal deposits of passive margin settings. However, there now appears to be a concerted effort to carry these concepts into coastal and marine strata of tectonically active foreland basins (Nummedal and Swift, 1987; Trexler and Nitchman, 1990; Van Wagoner et al., 1990; Shanley, 1991; Shanley and McCabe, 1991; Porter, 1992; Martinsen et al., 1993; Nummedal and Cole, 1993; Ainsworth and Pattison, 1994; Rogers, 1994; Ardevol et al., 2000). The application of sequence stratigraphic concepts to inland fluvial deposits of the foredeep portion of foreland basins is still in the early stages of consideration and is greatly affected by the advancement of new ideas relating thrust loading, basin subsidence, and basin fill patterns for foredeep basins (Blair and Bilodeau, 1988; Heller et al., 1988; Paola, 1988; Jordan and Flemings, 1991; Beaumont et al., 1993; Posamentier and Allen, 1993). The principal objectives of this study were to document major temporal and spatial changes in the architecture of Upper Cretaceous fluvial strata of the Kaiparowits Basin, to determine the applicability of sequence stratigraphic concepts to thick fluvial successions of an active foredeep basin, and to determine a means for differentiating between eustatically- and tectonically-controlled stratal patterns in these successions.

The study area is located in the northern part of the Kaiparowits Basin of south-central Utah (Fig. 1). Detailed measured sections incorporating units as thin as 5 cm were measured through the John Henry and Drip Tank Members of the Straight Cliffs Formation, the Wahweap Formation, and the Kaiparowits Formation between the southern margin of Table Mountain and the towns of Tropic and Escalante in and around an area called The Blues (Fig. 2). Additionally, photomosaics were produced and analyzed to identify architectural patterns in large outcrops. These studies were combined with information from published reports for the Dakota Formation, Tropic Shale, Tibbet Canyon and Smoky Hollow Members of the Straight Cliffs Formation, and the Canaan Peak Formation and reveal a succession of mostly conformable fluvial strata that is over 2 km thick and deposited in well-defined cycles that can be clearly distinguished on the basis of alluvial architecture. Each cycle consists of four parts reflecting predictable changes in fluvial style associated with distinct basin-filling episodes. Though each sequence demonstrates the same general pattern, there are internal differences that reflect the final withdrawal of the Late Cretaceous sea from the Western Interior Basin and the tectonic transition of the study area.
from active Sevier-style deformation west of the basin to Laramide-type deformation east of the basin. Measured sections from the northern Kaiparowits Basin were compared to those published by others (Gregory and Moore, 1931; Gregory, 1950, 1951; Cook, 1957; Lohrengel, 1969; Peterson, 1969; Bowers, 1972; Eaton, 1987, 1991; Goldstrand, 1990a, 1990b; Fillmore, 1991; Schmitt et al., 1991; Shanley, 1991; Tilton, 1991) for the same or equivalent units from surrounding areas; including the southern Kaiparowits Plateau, northern Paunsaugunt Plateau, Pine Valley Mountains, Cedar and Parowan Canyons on the Markugunt Plateau, and the Beaver Dam Mountains near the town of Gunlock to identify regional stratigraphic relations (Fig. 2). Limited field reconnaissance was also performed in most of these surrounding areas to supplement the more detailed study of the northern Kaiparowits Basin.

**Tectonic Setting**

The Kaiparowits Basin is a foredeep basin situated along the western margin of the Cretaceous Western Interior foreland basin (Kauffman and Caldwell, 1993) between the Muddy Mountains, Blue Mountain, and Wah Wah segments of the Sevier thrust belt to the west, the Circle Cliffs Uplift and Monument Upwarp to the east, and the Mogollon Highlands to the south (Fig. 1B). The Sevier thrust belt extends from southern Nevada to northern Canada and constitutes a region of thin-skinned crustal shortening along west-dipping ramp faults (Bally et al., 1966; Armstrong, 1968; Price, 1973; Villien, 1984). The foreland basin developed through isostatic flexural subsidence in response to tectonic events (thrust loading, synorogenic sedimentation, forebulge development) within the thrust belt; therefore, sediment accumulation rates and distribution patterns within the basin are closely tied to the deformational history of the mountain belt (Beaumont, 1981; Jordan, 1981; Lawton, 1983, 1986; Royden and Karner, 1984, Jordan and Alonso, 1987; Jordan et al., 1988; Armstrong and Ward, 1993; Beaumont et al., 1993; McMechan and Thompson, 1993).

Through computer modeling of sediment thicknesses for the Cretaceous Western Interior, Cross and Pilger (1978) have shown a significant change in the nature and distribution of basin subsidence at the beginning of Campanian time. From the Late Albian through the Santonian, basin subsidence was in the form of an elongate linear foredeep trough that ran parallel to the trend of the Sevier thrust belt, bound to the east by a low-level incipient forebulge uplift (Fig. 3A). Subsidence during Campanian and Maastrichtian time produced a more circular subsidence pattern that was centered in Utah, Wyoming, and Colorado (Fig. 3B). They attributed this change to a decrease in the subduction angle for the Farallon Plate, which led to subcrustal loading in the Utah/Wyoming/Colorado region (see also Kauffman, 1977, 1984; Armstrong and Ward, 1993; Kauffman and Caldwell, 1993). This change in the nature of subsidence was accompanied by a shift in active tectonism from thin-skinned thrusting in the Sevier Belt to large-scale uplift of basement cored blocks (Laramide uplifts) within the foreland basin (Cross and Pilger, 1978). Jordan and Alonso (1987) have noted a similar relationship between the modern Nazca plate and Andean tectonics, in which areas landward of steep subduction are characterized by active volcanic arcs and narrow thin-skinned thrust belts; whereas, areas landward of shallow subduction typically consist of broader thrust belts and basement cored uplifted blocks. Major deformation within the Utah portion of the Sevier thrust belt ended during Campanian time, although some movement continued into the Paleocene and possibly the Eocene (Armstrong, 1968; Villien, 1984; Villien and Kligfield, 1986; Armstrong and Ward, 1993; Kauffman and Caldwell, 1993; Monger, 1993).
The Circle Cliffs and Monument uplifts are Laramide structures that developed within the foredeep portion of the foreland basin approximately 75 to 150 km east of the leading edge of the Sevier thrust belt, forming the eastern margin of the study area by latest Cretaceous time. These structures have been active periodically since the late Paleozoic and early Mesozoic and underwent major reactivation with episodic movements during the late Campanian through Paleocene time interval (Armstrong, 1968; Jordan, 1981; Lawton, 1983, 1986; Villien, 1984; Villien and Kligerfeld, 1986). The growth of Laramide structures in the foreland basin had significant effects on sediment dispersal patterns, eventually blocking the path of fluvial systems between the thrust belt and the sea, creating large closed basins dominated by fluvio/lacustrine depositional systems (Lawton, 1983, 1986; Goldstrand, 1990a, 1990b, 1992).

Uplift of the Mogollon Highlands in southern Arizona began in the Late Triassic from subduction-related processes that are not clearly understood. By Late Jurassic and Early Cretaceous it existed as a raised rift margin in association with the initial phase of the opening of the Gulf of Mexico (Bilodeau and Lindberg, 1983). The area continued to be elevated through much of the Late Cretaceous, shedding sediment northward into southern Utah (Eaton et al., 1988).

Eustatic Sea Level Fluctuations

Upper Cretaceous strata of the Kaiparowits Basin have been correlated to large-scale fluctuations in relative sea level associated with the Greenhorn, Niobrara, Clagget, and Bearpaw cyclothsms of Kauffman (1977, 1985) (Fig. 4), which, in turn, have been tied to the global cycle chart of Haq et al. (1987; see also Kauffman and Caldwell, 1993). Strata of the Greenhorn Cyclothem include the upper part of the Dakota Formation, Tropic Shale, and Tibbet Canyon and Smoky Hollow Members of the Straight Cliffs Formation (Peterson and Kirk, 1977; Molenaar, 1983; Eaton et al., 1988). The John Henry and Drip Tank Members of the Straight Cliffs Formation were deposited during the transgressive and regressive phases, respectively, of the Niobrara Cyclothem (Peterson and Kirk, 1977; Molenaar, 1983; Eaton et al., 1988). The Wahweap Formation would broadly correspond in time to the Clagget Cyclothem and the Kaiparowits Formation to the Bearpaw Cyclothem, but physical evidence for these relationships has not been found (Eaton et al., 1988), due, in part, to the erosion of possible marine equivalent strata east of the Kaiparowits Basin. Additionally, these units have been dated as Middle and Late Campanian (Peterson, 1969; Bowers, 1972; Eaton, 1987, 1991), and reactivation of Laramide structures to the east may have isolated the Kaiparowits Basin from eustatic effects before these units were deposited. This is almost certainly the case for the Late Campanian Kaiparowits Formation.

SEQUENCES IN THE NORTHERN KAIPAROWITS BASIN

Upper Cretaceous strata of the northern Kaiparowits Basin consist of four tectonically-generated second-order sequences with significant eustatic influence overprinted onto the lowest two. The succession records relatively continuous deposition at varying rates in the axial portion of the foredeep basin associated with episodic tectonic activity and eastward migration of the Sevier thrust belt. Each sequence consists of an overall coarsening-upward pattern divisible into four parts that reflect predictable changes in fluvial style associated with distinct basin-filling episodes (Figs. 5, 6). The presence of the same four basic parts in each cycle, regardless of
whether or not eustatic influences are present, strongly argues for a primary tectonic control on
the development of these stratal patterns. Each cycle is interpreted to have begun with the onset
of active tectonism in the Sevier thrust belt. This led to rapid basin subsidence and the
development of highly aggradational fluvial systems dominated by thick intervals of fine-grained
sediment in the upper three sequences and by marine deposits in the lowest sequence. As
tectonism decreased, so did rates of basin subsidence, allowing the basin to fill and produce an
upward-coarsening succession dominated by fluvial deposition. Each sequence is capped
abruptly by a coarse-grained sheet associated with relatively slow subsidence rates representing
times of tectonic quiescence. Eustatic effects are restricted to more distal portions of the
foredeep basin and are, therefore, expressed only in the lower two sequences. As the thrust belt
migrated closer to the location of the Kaiparowits Basin, the relative impact of eustatic processes
diminished and the overall succession shows an upward transition from more distal to more
proximal foredeep conditions (Fig. 7).

The basal sequence includes the Dakota Formation, Tropic Shale, and the Tibbet Canyon
and Smoky Hollow Members of the Straight Cliffs Formation. This sequence appears to have
been highly influenced by eustatic processes and most likely represents deposition within the
distal axial zone of the foredeep basin (Little, 1995). The next sequence, made up of the John
Henry and Drip Tank Members of the Straight Cliffs Formation, demonstrates a transition from
combined eustatic and tectonic affects in the lower part to wholly tectonic influences in the upper
part and formed near the boundary between the distal and proximal axial zones. The next
sequence, contained entirely within the Wahweap Formation, and the upper sequence, comprised
of the Kaiparowits and Canaan Peak Formations, are entirely of tectonic origin. The Wahweap
and Kaiparowits Formations were deposited within the proximal axial zone, and the Canaan Peak
Formation is a syntectonic conglomerate deposited in the thrust belt zone. An angular
unconformity near the top of the succession records tilting and deposition of syntectonic
conglomerates as the Sevier thrust belt approached the Kaiparowits Basin from the west.
Additional tectonic influence was contributed by the development of Laramide foreland uplifts to
the east of the Kaiparowits Basin during deposition of the uppermost sequence.

General Nature of Fluvial Sequences

Each sequence consists of a coarsening-upward succession divisible into four parts (Fig.
6). With the exception of the basal sequence, the boundary between sequences is marked by an
abrupt vertical shift from thick, laterally extensive multistoried fluvial sheets dominated by
gravelly sandstone and sandy conglomerate below to relatively thin, laterally restricted sheets of
fine-grained sandstone interbedded with equally thick intervals of mudstone and siltstone above.
The boundary between sequences is sharp, but conformable. Scouring equal to the thickness of a
single channel deposit or less is typically present on the boundary and is believed to be the result
of normal fluvial processes and not due to entrenchment associated with a significant lowering of
base level. The lower boundary of the basal sequence is a major regional unconformity overlain
by fluvial conglomerates and sandstones.

The basal part of the upper three sequences is made up of laterally restricted sandstone
sheets. These sheets may or may not show overlapping relationships and consist primarily of
trough cross-bedded fine- to medium-grained sandstone at the bottom, grading upward to fine- or
very fine-grained wavy and parallel laminated sandstone at the top. Interbedded mudstones are
sandy and silty at their base and contain scattered thin sandstones throughout. These thin
sandstones pinch out laterally over relatively short distances. The entire unit rests sharply, but
conformably, on a relatively planar surface capping the underlying sequence. These deposits are interpreted as having been formed by meandering stream systems under conditions of slow to moderate rates of accommodation space production. The John Henry Member, at the base of the upper Straight Cliffs sequence, contains considerable evidence of marine influence, including brackish water fossils and features suggestive of tidal processes (Shanley, 1991; Shanley and McCabe, 1991).

The middle part of the upper three sequences is made up of laterally discontinuous ribbon or single-story sheet sandstones entirely encased in mudstone. Sandstones typically are trough cross-bedded at the bottom, becoming more wavy or parallel laminated toward the top. In some sheet-like bodies lateral accretion surfaces have been identified. Narrow, multistory sandstones generally do not contain evidence of lateral accretion, except for scroll bars on the upper surface of the capping story. Contacts between sandstones and underlying mudstones are sharp and erosional. Rounded mud clasts a few millimeters to several centimeters in diameter are common near the base of these sandstones, and larger, generally elongate, mud clasts up to several decimeters long occur near the base of some units. Gastropods, bivalves, vertebrate bone fragments, dinosaur teeth, and turtle shell fragments may be locally abundant at the base of these units. Upper contacts between sandstones and encasing mudstones are typically sharp, but conformable. The lower part of the mudstone units is generally silty or sandy and may be flaser-bedded. Thin sandstones dominated by ripple and small-scale trough cross-stratification are scattered throughout the mudstone facies. These sandstones have planar contacts and pinch out abruptly within the mudstone. Thick intervals of finely-interbedded thin mudstones and sandstones are also common. Occasionally, these intervals can be traced laterally to the margins of one of the lens or sheet sandstones. Bivalves are abundant at the base of some thin sandstone beds and the lower part of the John Henry Member contains thin coals and carbonaceous shales. The contact between the middle and basal parts of a sequence is gradational. Deposition occurred primarily within anastomosing and meandering fluvial systems under conditions of high accommodation production. In the basal sequence, this interval is dominated by thin-bedded marine mudstones of the Tropic Shale overlying highly aggradational fluvial and coastal deposits of the middle and upper Dakota Formation.

The upper parts of these sequences consist of laterally-extensive, multistoried sheet sandstones. Mudstone facies are generally thin and discontinuous or not present. Lower storys are typically finer-grained than upper storys and consist mostly of trough cross-bedded sandstone. Trough cross-bedding may or may not grade upward into wavy and parallel laminations. Occasionally, lateral accretion surfaces can be seen in the lower storys. Upper storys typically consist of coarser sandstone and are trough to planar cross-bedded. Boundaries between storys are sharp and commonly display some erosional relief. The finer-grained, trough cross-bedded sandstones with lateral accretion surfaces were formed by meandering streams. Coarse-grained, trough to planar cross-bedded sandstones without lateral accretion surfaces were deposited mostly in sandy braided systems. These units most likely represent a normal regression as the basin filled during a slowing in the production of accommodation space.

The capping part of each sequence is dominated by laterally extensive, multistoried sheets of trough and planar cross-stratified gravely sandstone and sandy conglomerate. The tops of all storys within the sheet are sharp and show erosional relief of a few meters. The basal contact for the capping unit is sharp, but conformable, except for the Canaan Peak Formation, which consists of a cobble conglomerate at the base and locally overlies the Kaiparowits Formation with an angular unconformity. The capping parts of the sequences represent
deposition by sandy to gravely braided streams during a period of slow accommodation production.

**SEQUENCE STRATIGRAPHIC MODELS FOR THE KAIPAROWITS BASIN**

Because basin subsidence and eustatic sea level rise each create an increase in accommodation space, it can be difficult to distinguish between these two influences from studies of a single locality, such as the northern Kaiparowits Basin (Fig. 8). However, when data from surrounding areas are included, a much clearer picture as to depositional controls emerges. Four depositional sequences are found in Upper Cretaceous strata of the Kaiparowits Basin and record the eastward migration of the basin axis through the area.

These sequences were deposited in the axial and proximal portions of a foredeep basin, and, as such, depositional sequences would be expected to be controlled primarily by tectonic influences. However, these units have also been correlated to large scale fluctuations in eustatic sea level associated with the Greenhorn, Niobrara, Clagget, and Bearpaw cyclothem of Kauffman (1977, 1985; Kauffman and Caldwell, 1993). In reality, the relative contribution of eustatic and tectonic processes changes upward through the section. Greenhorn strata were not included as part of the field study, but from published reports (Peterson, 1969; Molenaar, 1983; Eaton, 1987; Gustason, 1989; Bobb, 1991; Shanley, 1991; Leithold, 1994), the affects of eustasy and tectonics appear to have been equally important. This may be the result of a young foredeep basin that was still relatively wide and shallow with a relatively low-lying sediment source area, allowing greater influence by eustatic sea level changes. Eustatic controls diminish somewhat for strata of the Niobrara cycle, but are still important, especially in the southeastern part of the basin. Eustasy probably was not an important factor in the development of the Clagget and Bearpaw age strata of the Kaiparowits Basin. By this time, the basin was close to the thrust belt, and eustatic affects were restricted to areas east of the Kaiparowits Basin, such as the Henry and Uinta Basins.

**Eustatic Models**

To transport gravel into the foredeep basin, a surface gradient must be maintained basinward from the thrust belt (Paola, 1988; Flemings and Jordan, 1989). Such a gradient would be unlikely during episodes of active thrusting due to a rapid increase in subsidence rates adjacent to the thrust belt, which rotates the earlier depositional surface toward the thrust belt. Because the Kaiparowits cycles do contain coarse deposits and because of the apparent correlation of these cycles to eustatic sea level fluctuations, models have been developed that attempt to account for the stratigraphic patterns seen in these sequences. Therefore, for this discussion, it is assumed that subsidence is continuous during a given eustatic cycle, that sedimentation rates are sufficient to keep the proximal portion of the foredeep basin filled, and that eustatic effects are expressed entirely across the basin to the thrust belt. Such a situation is unlikely in well-developed foredeep basins, but would be necessary to produce the required depositional slope by eustatically controlled base level fluctuations alone and would most closely be achieved during times of tectonic quiescence and during the early history of the foredeep basin. Under these conditions, a eustatic sea level rise would shift facies toward the thrust belt into areas already experiencing high production rates of accommodation space, adding to the rate of alluvial aggradation. A subsequent lowering of eustatic sea level would then decrease the rate at which accommodation space is produced in these areas, resulting in a basinward progradation
of the fluvial system, or possibly incision, depending on the relative rates of eustatic fall and basin subsidence. Alluvial architectural patterns would be controlled by rates and directions of base level change which could be predicted by vertical position within the sequence (Fig. 9). The overall succession would consist mostly of conformable sequences exhibiting alternating aggradational and progradational patterns (Mutti and Sgavetti; 1987; Jordan and Flemings, 1991).

Lowstand Deposits

A base level lowstand in foredeep basin continental deposits is characterized by either stream entrenchment and sediment bypass, producing an irregular regional unconformity (Fig. 9a), or more likely, a basinward progradation of the fluvial system, depositing laterally extensive sandy and gravely sheets with conformable and possibly intertonguing lower contacts (Fig. 9b). In the case of incision, a thin lowstand fluvial deposit similar in character to the progradational sheets, but with incised valley-fill geometry, might be preserved above the unconformity as base level begins to rise. In either case, preserved overbank sediment is minimal due to extensive lateral migration and floodplain reworking.

Early (Slow) Base Level Rise

As base level begins to rise, sand sheets become storied. Streams continue to migrate back and forth, stacking one coarse-grained sheet upon another, resulting in minor aggradation. There may be discontinuous lenses of fine-grained overbank deposits preserved, but channel deposits continue to dominate the sequence.

Moderate Base Level Rise

An increase in the rate of base level rise causes sheets to become less extensive laterally due to a shorter migration time at a given base level. Channels no longer are able to rework their entire flood plains, and the amount of preserved overbank sediment greatly increases. Greater preservation of overbank deposits results in enhanced channel stability and development of a meandering channel pattern. As channels become stabilized, the degree of lateral migration decreases while vertical stacking may increase, producing narrow, multistoried sandbodies encased in mudstone. Channel migration becomes more a result of avulsion than lateral erosion/accretion. These deposits show increasingly significant rates of vertical aggradation, principally within overbank facies.

Rapid Base Level Rise

Continued increase in rates of base level rise result in very rapid aggradation, producing anastomosed stream patterns in which isolated sandbodies are encased in mudstone. Lateral erosion/accretion becomes insignificant and migration is almost exclusively a result of avulsion. Overbank deposits dominate the sequence.
Transgressive Deposits

Rates of base level rise might become such that the fluvial system cannot provide enough sediment to fill the available space, resulting in a marine transgression. This would be marked by a transgressive disconformity as the surface of the fluvial deposits is reworked by advancing wave base. Thin transgressive coastal deposits may overlie the fluvial deposits. Slightly more inland, fluvial deposits might include features indicative of tidal influence (Shanley, 1991; Shanley and McCabe, 1991). Alluvial aggradation would shift landward to some location where rates of sediment input are balanced with rates of base level rise.

Highstand Deposits

Highstand deposits are characterized by laterally-restricted sand sheets at the base with abundant associated overbank sediments, grading upward to laterally-extensive, possibly multistoried sand sheets with little preserved overbank material. This succession is produced as available accommodation space becomes filled during a base level highstand and the rate of eustatic rise slows and then turns to a eustatic fall. Depending upon the relative rates of basin subsidence and eustatic base level fall, the upper boundary of the highstand deposits could be either a type 1 or a type 2 sequence boundary.

Tectonic Models

Traditionally, the progradation of coarse clastic deposits into foredeep basins has been related to active movement within the adjacent thrust belt (Armstrong and Oriel, 1965; Wilchko and Dorr, 1983). This concept implies that source area uplift and associated basin subsidence result in greater relief between the source area and the basin, leading to higher erosion rates and therefore the widespread distribution of coarse-grained deposits. This idea has been challenged in recent years by a number of authors on the basis that the lag time between uplift and new sediment production is much greater than the lag time between uplift and basin subsidence, and therefore, the asymmetrical nature of a foredeep basin would result in the trapping of coarse sediment adjacent to the thrust belt (Heller et al., 1988; Steidtmann and Schmitt, 1988; Flemings and Jordan, 1989). This has led to the development of new models that associate very coarse deposits located in a narrow belt adjacent to the thrust front to active thrusting (synorogenic conglomerates) and widespread coarse clastic sheets to a basinward shift in accommodation potential following the cessation of tectonic movement as the thrust load is eroded and rebounds and the load is shifted basinward in the form of sediment loading. On a local scale, tectonically-controlled sequences are similar to eustatically-controlled sequences, and in many cases, it may not be possible to distinguish between the two without regional information.

Isostatic Rebound Model

One explanation for the reworking of syntectonic deposits during times of tectonic quiescence considers the role of isostatic adjustment in elevating the basin following the cessation of major tectonic activity as continued erosion decreases the thrust belt load. This is the two-phase model proposed by Heller et al. (1988) (Fig. 10).
**Phase 1: Active Tectonism:** Uplift within the thrust belt leads to geologically instantaneous basin subsidence, and therefore a rise in relative base level (Fig. 10A). Near the thrust belt, coarse conglomerates are deposited, but are confined to a narrow strip along the active front. Farther basinward, an abrupt vertical change from relatively coarse-grained sediment to much finer sediment occurs in response to a rise in base level and trapping of coarse-grained sediment near to the thrust belt. Fluvial systems respond to the growth in accommodation space with rapid aggradation, producing deposits dominated by fine-grained sediment. Sandstones are confined to isolated lenses or thin sheets scattered throughout the finer sediment. As tectonic activity slows, accommodation space is produced at a much lower rate, leading to a coarsening-upward sequence dominated by multistoried sand sheets at the top.

**Phase 2: Tectonic Quiescence:** Erosion within the thrust belt leads to isostatic rebound of the thrust belt and areas of the basin adjacent to it (Fig. 10B). In response, synorogenic deposits are reworked and redistributed basinward. The result is a lowering of relative base level and deposition of a widespread clastic sheet into the basin. These sheets correlate to unconformities formed within the synorogenic deposits.

**Blind Thrust Model**

The blind thrust model is similar to the isostatic rebound model in that episodes of active tectonism are separated by periods of tectonic quiescence. The principal difference between these two models lies in the processes operating during the tectonically "quiet" phase and the amount of erosion that takes place within the earlier synorogenic deposits during this phase. Forward breaking thrust belts develop through formation of new thrusts in front of the old. The new thrust begins in the subsurface along a decollement surface and propagates basinward and upward from the decollement, leading to uplift in front of the older thrust belt (Fig. 11). As in the isostatic rebound model, synorogenic sediments are reworked and deposited farther basinward. In the blind thrust model, however, uplift may be sufficient to entirely rework the synorogenic deposits, leaving a record of only finer-grained deposition adjacent to the thrust belt. The reworked sediments would then be carried basinward, resulting in coarse clastic sheets in the basin that might have no coarse-grained equivalent in the area of the thrust belt.

**DIFFERENTIATING BETWEEN TECTONIC AND EUSTATIC MODELS**

Foredeep basins are created by flexural subsidence of the lithosphere beneath and in front of a tectonic load associated with thrust faulting, folding, and synorogenic sedimentation. As such, tectonic activity exerts the primary control on foredeep basin geometry and stratigraphic patterns. In proximal portions of the basin, subsidence and sedimentation rates are generally sufficient to preclude any significant influence by eustatic sea level variations. However, decreasing subsidence and lower sedimentation rates permit eustatic sea level fluctuations to strongly affect and even dominate depositional patterns away from the thrust belt. The stratigraphy of the Western Interior foredeep basin is represented by thick intervals of continental strata near the thrust belt that thin basinward and grade into shoreline sandstones at their distal ends, eventually pinching out into thick accumulations of marine mudstone. Thickness, aerial distribution, and composition of these continental facies together with timing relationships to dated thrusting events and eustatic sea level curves appear to be useful in determining the relative impact of tectonic and eustatic processes in the development of foredeep basin sequences.
Distribution and Geometry of Coarse Clastic Deposits

**Eustatic Models**

In a eustatically dominated sequence, coarse clastic deposits represent eustatic lowstands and may develop as either widespread progradational sheets or discontinuous valley fills. Progradational sheets form during a lowering of sea level in a setting where the rates of basin subsidence remain equal to or greater than the rates of sea level fall. Accommodation space continues to be generated in landward areas, but at a slower pace, allowing coarse sediment to be transported to more distant parts of the basin. These deposits would form continuous sheets from the thrust belt into the basin that become progressively finer-grained basinward due to selective deposition of the largest particles and particle breakdown by weathering processes. A widespread clastic deposit associated with lowstand progradation would, therefore, constitute part of a thick conformable succession of coarse conglomerate near the thrust belt that thins and grades basinward into a sheet of sandy conglomerate and gravelly sandstone bound conformably above and below by relatively thick intervals of finer-grained fluvial deposits (Fig. 12A). The lower contact will step progressively basinward during a period of base level lowering and then step landward as base level subsequently rises.

Valley fill deposits form in settings where the rate of sea level fall is greater than the rate of subsidence, leading to channel incision and development of an irregular erosional surface. As base level subsequently rises, accommodation space is created in progressively more landward areas, trapping coarse sediment within the incised channels. Therefore, valley fill deposits develop a number of time-equivalent, laterally discontinuous linear or ribbon-shaped bodies of backstepping gravelly deposits that grade landward into thick successions of unconformity bound conglomerate beds (Fig. 12B). A sheet-like geometry would form only if the valleys became completely filled and streams then spread sediment over surfaces separating adjacent valleys (Fig. 13). Incision can also be produced by tectonic uplift, but in many cases may be distinguished from a eustatic fall by angular discordance between the eroded units and the valley fill deposit. Reflecting the relative direction of base level movement, lowstand progradational sheets would tend to coarsen upward as the rate of space creation diminished and finer-grained sediments were transported through the system; whereas, the valley fill deposit would fine upward as accommodation potential increased.

**Tectonic Models**

According to both the isostatic rebound and blind thrust models, coarse synorogenic conglomerates are reworked from areas of the foredeep basin proximal to the thrust belt and then redistributed into the basin as coarse clastic sheets during periods of post-orogenic quiescence (Figs. 12C, 12D). Isostatic rebound would necessarily leave a portion of the original synorogenic deposit near the thrust belt, unless the amount of rebound were greater than the amount of original subsidence, which is highly unlikely. This would lead to a thick succession of unconformity bound conglomeratic bodies near the thrust belt and widespread gravelly sheets farther basinward with the potential for little or no physical connection between the two. Isostatic rebound and fault propagation both lead to a lowering of base level ahead of the advancing clastic deposit. Redistribution of coarse clastics over this surface will produce a
sheet-like rock body similar to that of a eustatic lowstand progradational sheet, but with sharper lower contacts (Fig. 13). The lower contact would most likely show some scouring associated with fluvial channel migration, but probably would not appear as a major unconformity. Time-wise, the gravely sheets would correlate to the unconformities separating syntectonic conglomerates.

The blind thrust model provides a mechanism for generating much higher amounts of uplift through the development of a new thrust sheet in front of the old. The syntectonic deposit could potentially be reworked entirely, leaving little or no record of the original conglomerate. This would result in a coarse clastic sheet which is not physically connected to the thrust belt, but which instead correlates to an unconformity in finer-grained deposits of that area. Successive sheets in either model should step basinward and become progressively coarser-grained as the axis of subsidence shifts basinward through subsequent thrusting events.

**Kaiparowits Basin**

Eaton and Nations (1991) have produced a restored cross-section for Upper Cretaceous strata in southwestern and south-central Utah (Fig. 14). This cross-section shows that most coarse-grained units in the Kaiparowits Basin; including the Calico Bed, the Drip Tank Member, the capping sandstone member of the Wahweap Formation, and the Canaan Peak Formation, are not traceable back to the thrust belt. Additionally, conglomeratic units of the Kaiparowits Basin show a basinward stepping trend through time, and each successive sheet is coarser-grained and thicker than the previous. These relations suggest that coarse-grained clastic units capping the stratigraphic sequences of the Kaiparowits Basin are primarily the result of the development and initial movement on thrust faults to the west.

Coarse clastic deposits in the Kaiparowits Basin are in the form of laterally extensive sheets with sharp lower and upper boundaries. The basal contacts are typically scoured, and have been interpreted by some workers as major unconformities (Shanley, 1991; Shanley and McCabe, 1991), but the planar nature of the contacts, a lack of angular discordance between units above and below, and lack of evidence for major gaps in time suggest that the scouring is related to normal fluvial processes operating during deposition of the gravel sheets. Additionally, the coarse clastic deposits of the Kaiparowits Basin all thicken to the northwest toward the thrust belt. The sheet-like geometry of these deposits could be used to support either a eustatic lowstand progradation or postorogenic quiescence; however, the sharp lower contacts favor the tectonic interpretation. If the lowstand sea level remained fixed at one elevation for a long period of time and there were no additional subsidence during this period of time, it would be possible to form a sharp contact at the base of the lowstand progradational sheet through repeated channel migration across the area. However, that would require that aggradation take place during the subsequent transgression rather than during the lowstand. Transgressive deposits for most basins are typically thin and transgression shifts the focus of fluvial sedimentation landward. The units capping sequences in the Kaiparowits Basin all prograde far into the basin, and, with the exception of the Calico Bed, all reach thicknesses in excess of 100 m. The Calico Bed can be as thick as 50 m (Bobb, 1991). Sharp lower contacts, great thicknesses, and widespread basinward distribution all support simultaneous progradation and aggradation during periods of slow basin subsidence.
Paleocurrent Orientation

In asymmetrical basins, fluvial channels migrate toward the location of maximum subsidence (Alexander and Leeder, 1987). Crustal loading by thrust faults depresses the lithosphere immediately adjacent to the thrust front, creating a linear trough. Major drainage systems then flow parallel to the thrust front along the axis of maximum subsidence. During periods of tectonic quiescence and relatively slow subsidence, it may be possible for the proximal portion of the foredeep basin to become overfilled, producing a basinward gradient and permitting streams to flow away from the thrust belt. Such a gradient would likely exist if space creation were dominated by eustatic processes. Therefore, eustatic dominance would most likely be characterized by overfilled basins with fluvial systems that flow away from the thrust belt; whereas, tectonic dominance would be shown by thrust parallel fluvial systems. In a tectonically generated sequence, subsidence rates could remain high enough during the postorogenic portion of the cycle to prevent overfilling and maintain the axial system. In the Kaiparowits Basin, Gustason (1989) reported alternating episodes of thrust parallel and thrust perpendicular flowing fluvial systems for the Dakota Formation and related this to alternating intervals of tectonic activity and quiescence respectively. For the units involved in the upper Straight Cliffs through Kaiparowits Formations, no such pattern was found. Rather, streams flowed predominantly to the northeast throughout the section, again suggesting tectonic dominance in their formation.

Timing

Thick stratigraphic sequences for the Kaiparowits Basin have been broadly correlated in time to the second-order eustatic cycles of Kauffman (1977, 1985; Kauffman and Caldwell, 1993) (Fig. 4); yet, these sequences are interpreted here to have been driven primarily, and for Clagget and Bearpaw equivalents entirely, by tectonic processes. A similar relationship was noted by Villien (1984) for age-equivalent strata in the Wasatch Plateau and San Rafael Swell areas, where he correlated thrusting events from the Sevier orogenic belt to both the foredeep stratigraphic record and the eustatic sea level curve for the Cretaceous Western Interior Basin. He found that in central Utah, both transgressions and synorogenic conglomerates correlate to episodes of active thrusting; whereas, regressions and widespread clastic sheets correspond to periods of postorogenic quiescence (Fig. 15). These findings are in agreement with those of Kauffman (1984, 1985) for Cretaceous age strata from the Utah-Arizona and Wyoming-Montana-Idaho regions of the Western Interior, in which episodes of thrust emplacement, basin subsidence, and explosive volcanism have been tied to rises in base level and coastal transgression; whereas, tectonic quiescence corresponds to base level fall and coastal regression (Fig. 16). Additionally, these events have been tied to global seafloor spreading rates and eustatic cycles (Kauffman, 1984, 1985; Kauffman and Caldwell, 1993). Thus, it appears that development of accommodation space in the distal foredeep basin by tectonic and eustatic processes and in the proximal portion of the basin by tectonic processes alone should be related in time. Correlations with specific thrusting events have not been made for continental strata of the Kaiparowits Basin; however, it appears that several of the thrust faults affecting central Utah are the same as those impacting the Kaiparowits region, such as the Wah Wah/Mineral Range/Canyon Range system and the Blue Mountain/Pavant system (Fig. 1B).
DESCRIPTION AND INTERPRETATION OF SEQUENCES IN THE NORTHERN KAIPAROWITS BASIN

Dakota/Tropic/Lower Straight Cliffs Sequence (Late Cenomanian - Middle Turonian)

The Dakota/Tropic/Lower Straight Cliffs sequence (Fig. 17) is the basal Cretaceous foredeep sequence of the northern Kaiparowits Basin and corresponds to the second-order Greenhorn cyclothem of Kauffman (1977, 1985). These units were not included as part of this field study, but have been discussed by others (Peterson, 1969; Molenaar, 1983; Ryer, 1983; Eaton, 1987; Gustason, 1989; Bobb, 1991; Shanley, 1991; Leithold, 1994) and record a major transgression and regression following initial tilting and scouring of Upper Jurassic strata. The Jurassic units were incised, forming valleys up to 50 m deep and 10 km wide, and then backfilled with gravely braided stream deposits of the lower member of the Dakota Formation as base level subsequently rose. Once the incised valleys were filled, streams spread out over the area between valley cuts forming a broad braidedplain. Rates of relative base level rise increased during deposition of the middle member of the Dakota Formation, leading to the formation of highly aggradational meandering and anastomosing streams dominated by floodplain deposition. The upper member of the Dakota Formation consists of backstepping parasequences deposited in various sand-dominated coastal environments and contains a number of marine flooding surfaces marked by transgressive lag deposits. The Tropic Shale represents the greatest incursion of the Cretaceous sea into the Western Interior Basin, extending perhaps as far west as the eastern flank of the Pine Valley Mountains (Eaton, pers. Comm., 1992). This was followed by a gradual withdrawal of the sea as manifest by regressive coastal deposits of the Tibbet Canyon Member and overlying fluvial deposits of the Smoky Hollow Member of the Straight Cliffs Formation. The sequence is capped by the basal part of the Calico Bed. The basal Calico Bed consists of multistoried gravely braided stream deposits and records very slow rates of aggradation.

Both tectonics and eustasy played important roles in the development of this sequence. The cycle began with the uplift and tilting of Upper Jurassic strata, leading to channel incision and the development of an angular unconformity between these units and the Dakota Formation, possibly recording initial movements in the Sevier thrust belt and early development of the foredeep basin (Gustason, 1989; Fillmore, 1991). The influence of tectonics can also be seen by a large increase in the thickness of all units toward the thrust belt, indicating higher subsidence rates landward. The basin axis was located approximately 100 km to the west of the Kaiparowits Basin (Leithold, 1994), and this cycle represents deposition in the distal axial zone. Gustason (1989) has documented paleocurrent patterns in the Dakota Formation that flow parallel to the thrust belt during times of high sediment accumulation and away from the thrust belt when sediment accumulation rates are lower, consistent with alternating episodes of basin subsidence and filling respectively. An investigation by Merewether and Cobban (1986) has revealed depositional patterns suggestive of forebulge uplift and erosion in northeastern Utah and northwestern Colorado during this time period, also indicative of active basin tectonics (Jordan and Flemings, 1991). A significant eustatic component is suggested by backfilling patterns in paleovalleys of the lower Dakota Formation that produced ribbonlike conglomerate bodies traceable from the basin to the thrust belt (Hintze, 1986; Gustason, 1989; Fillmore, 1991), the presence of widespread Milankovitch-type cycles in correlative marine units to the north and east (Sageman, 1985; Elder, 1991; Leithold, 1994), and time equivalent transgressive/regressive
cycles for the Dakota Formation in other regions, such as the San Juan Basin (Aubrey, 1989) and the Denver Basin (Weimer, 1983).

The sequence is capped by the lower part of the Calico Bed. Bobb (1991) considers the lower Calico Bed to be a lowstand deposit associated with decreased subsidence rates during a period of post-thrusting quiescence in the Sevier orogenic belt. Tectonic quiescence in the lower Calico Bed is suggested by the presence of coarse conglomerate and a sheet geometry (Bobb, 1991). As discussed above, a basinward gradient from the thrust belt is essential to the progradation of coarse-grained sedimentary deposits. During times of tectonic activity, such a gradient is unlikely as space is created most rapidly adjacent to the thrust belt, trapping coarse-grained sediment in that region. During tectonic quiescence, slower subsidence rates lead to basin filling and progradation of coarse clastic sediments. Additional evidence for tectonics comes from the lack of a coarse-grained equivalent in the area adjacent to the thrust belt.

Deposits consisting mostly of fine- to medium-grained sandstone containing only rare occurrences of very thin conglomerate have been described for the Iron Springs Formation in the Gunlock area of southwestern Utah (Hintze, 1986; Fillmore, 1991). The first occurrence of conglomerates within the Iron Springs Formation is about 30 km to the east in the Pine Valley Mountains (Eaton and Nations, 1991) and has been correlated to the Calico Bed (Bobb, 1991; Eaton and Nations, 1991). Bobb (1991) believes that the lower Calico Bed represents reworked synorogenic deposits associated with postorogenic isostatic rebound. The complete lack of conglomerate adjacent to the thrust belt would argue instead for the blind thrust model.

**John Henry/Drip Tank Sequence (Middle Coniacian - Early Campanian)**

The John Henry/Drip Tank sequence records deposition near the boundary between the proximal and distal axial zones and a transition from combined tectonic and eustatic affects in the lower part to solely tectonic influence at the top. In the northern Kaiparowits Basin, this sequence is made up entirely of fluvial deposits that grade eastward into shoreline and marine units (Peterson, 1969; Vaninetti, 1979; Eaton, 1987; Bobb, 1991; Shanley, 1991; Shanley and McCabe, 1991). The basal part of the John Henry/Drip Tank sequence is actually the upper part of the Calico Bed, located at the top of the Smoky Hollow Member. This sequence has been correlated to the second-order Niobrara Cyclothem of Kauffman (1977, 1985) and sandbody geometry, sandbody interconnectedness, and sandstone/mudstone ratios demonstrate an overall increase in aggradation rates from the upper Calico Bed through the middle part of the John Henry Member followed by a decrease in aggradational rates for the upper John Henry Member and the Drip Tank Member. The upper Calico Bed gradationally overlies the gravely braided stream deposits of the lower Calico Bed and consists of meandering channel belt sandstones and floodplain deposits (Bobb, 1991). These are overlain sharply, but conformably by laterally restricted single and multistory sandstone sheets and finer-grained strata of the lower John Henry Member (Fig. 18A/28), which are in turn overlain gradationally by isolated lenses and single-story sand sheets encased in a dominantly fine-grained succession deposited by anastomosed and meandering streams of the middle part of the member (Fig. 18B). The middle John Henry grades upward into laterally discontinuous sheet sandstones and associated floodplain deposits of meandering stream origin. Multistoried sheet sandstones deposited by meandering and sandy braided streams constitute the upper part of the member (Fig. 18C). The sequence is capped abruptly by extensive multistoried sheets of sandy and gravely braided stream deposits of the Drip Tank Member (Fig. 18D).
Bobb (1991) considers the upper part of the Calico Bed to represent an early eustatic sea level rise. The sharp contact between the Calico Bed and the John Henry Member demonstrates an abrupt increase in aggradation, probably associated with renewed tectonic activity in the Sevier thrust belt. The combination of high subsidence rates and rapid eustatic base level rise lead to high aggradational rates for the middle John Henry Member, recorded by isolated channel sand bodies in a dominantly fine-grained succession. The sequence then gradually coarsened upward as subsidence and aggradation rates decreased, leading to an increase in sandstone/mudstone ratios and sandbody interconnectedness. This same succession is shown by a major transgressive/regressive cycle in equivalent coastal and marine strata in the eastern part of the basin. In the marine section, the increased aggradation rates associated with renewed tectonic activity is marked by a 0.15 - 0.3 m-thick quartzite cobble conglomerate that separates fluvial deposits of the Smoky Hollow Member below from shoreline and marine deposits of the John Henry Member above (Peterson, 1969; Bobb, 1991; Shanley, 1991; Shanley and McCabe, 1991). This has been interpreted by Bobb (1991), Shanley (1991), and Shanley and McCabe (1991) as a transgressive lag deposit. Peterson (1969) has noted a slight angular discordance along this boundary, which may also be related to renewed tectonic activity as the underlying strata were simultaneously tilted and transgressed. The transgressive lag is overlain by hummocky cross-bedded sandstone, which in turn is overlain by marine mudstones and sandstones of the lower John Henry Member (Bobb, 1991; Shanley, 1991; Shanley and McCabe, 1991). Shanley (1991) has called this the first marine flooding surface or transgressive surface of his Calico sequence. The upward-coarsening recorded in the fluvial section is shown by a succession of retrogradational, aggradational, and finally progradational parasequence stacking patterns related to an initial increase and then progressive decrease in accommodation potential (Shanley, 1991; Shanley and McCabe, 1991). Some marine influence has been recorded in the fluvial succession as well. Beds containing brackish water fossils have been identified from the lower part of the John Henry Member at Pardner and Henderson Canyons in the northwestern part of the basin (Eaton, 1987) and are postulated to correspond to marine maximum flooding surfaces and condensed sections of equivalent marine deposits to the east (Shanley, 1991; Shanley and McCabe, 1991). The close association of conformable fluvial deposits and a dominantly coastal and marine section suggests deposition near to the equilibrium point separating the proximal and distal axial zones.

Additional evidence for a combined eustatic and tectonic influence comes from regional correlation patterns. The Niobrara cyclothem has been well documented throughout the Western Interior Basin (Kauffman, 1977, 1985), and similar transgressive/regressive patterns have been described from correlative strata in surrounding areas, such as the San Rafael Swell (Ryer and McPhillips, 1983; Gardner, 1991), the Henry Mountains (Peterson and Ryder, 1975; Peterson et al., 1980), and Black Mesa Basin (Franczyk, 1988; Kirkland, 1991), suggesting a strong eustatic component. Tectonic influence is demonstrated by a significant thickening of both the Calico Bed and the John Henry Member toward the thrust belt (Peterson, 1969; Vaninetti, 1979; Eaton, 1987, 1991; Bobb, 1991; Shanley, 1991) and a basinward transition from a conformable lower boundary within the Calico Bed in the northern Kaiparowits basin to an erosional lower boundary at the base of the correlative upper sandstone member of the Toreva Formation in the more distal Black Mesa Basin (Franczyk, 1988; Bobb, 1991), each indicating increasing basin subsidence toward the thrust belt.

The Drip Tank Member at the top of the sequence is a coarse-grained postorogenic sheet. The basal contact with the John Henry Member is sharp and conformable, and has been
described by some workers as intertonguing (Peterson, 1969; Vaninetti, 1979; Eaton, 1987, 1991; Bobb, 1991). The Drip Tank Member actually consists of a number of thinner coarse-grained sheets separated by planar contacts and is easily recognized throughout the Kaiparowits Basin, but is not found beyond this region. It thickens significantly toward the thrust belt (Peterson, 1969; Vaninetti, 1979; Eaton, 1987, 1991), but does not have a coarse-grained equivalent in the vicinity of the thrust belt. Based on these criteria, it has been interpreted as a coarse-elastic sheet associated with isostatic rebound or, more likely, new thrust propagation during a period of tectonic quiescence.

**Wahweap Sequence (Middle Campanian)**

The Wahweap Formation is found only in the Kaiparowits Basin and is entirely of continental origin. Based primarily on stratigraphic position and lithologic character, Peterson and Ryder (1975), Peterson et al. (1980), and Eaton (1987, 1990) have correlated the lower, middle, and upper members of the Wahweap Formation to the Masuk Formation of the Henry Basin and the capping sandstone member to the Tarantula Mesa Sandstone of the Henry Basin and the Castlegate Sandstone of the Book Cliffs, where marine transgressive/regressive deposits associated with the Clagget cyclothem of Kauffman (1977, 1985) have been identified. A sharp, but conformable contact separates the Wahweap Formation from the underlying Drip Tank Member and signals an abrupt increase in aggradation. The lower member of the Wahweap consists of meandering stream deposits in the form of laterally restricted single- and multistoried sheets of sandstone interbedded with moderate amounts of mudstone (Fig. 19A). These grade rapidly upward into the middle member, which is similar in character, but sandstones are thinner and the middle member as a whole contains a much higher percentage of fine-grained deposits (19B). The middle member in turn grades into the upper member, which is dominated by extensive multistoried sandstone sheets (Fig. 19C). Lower sheets are fine- to medium-grained at the base and contain abundant trough cross-stratification and distinct lateral accretion surfaces. Upper sheets are coarser grained, and planar cross-stratification is the dominant structure. Deposition took place within meandering streams for the lower sheets and sandy braided streams for upper sheets. The Wahweap Formation is capped by a multistoried sheet of gravely sandstone and sandy conglomerate deposited by gravely braided streams (Fig. 19D). The basal contact of the capping sandstone member is sharp, but conformable.

Though basinward, age-equivalent strata can be tied to the Clagget cyclothem, eustasy probably did not play a major role in the development of the Wahweap sequence. The nearest evidence for marine influence comes from the northern Henry Mountains where Eaton (1987, 1990) documents two localities containing possible evidence of minor tidal influence. At one locality, a single thin sandstone bed containing *Thalassinoides* burrows and flat-topped symmetrical ripples was found. The other locality includes a single 70 cm-thick bed that is rippled laminated and contains fossil wood fragments. Wahweap deposition most likely took place in the proximal axial zone and began with thrust induced subsidence, leading to a sudden increase in accommodation space as recorded by the sharp contact with the underlying Drip Tank Member. Subsidence rates continued to increase from the lower to the middle member and are manifest by increased aggradation rates. The sequence then gradually coarsens upward from the middle through the upper member, reflecting slowing subsidence and lower aggradation rates. Tectonic dominance is suggested by a basinward thinning of the Wahweap Formation (Eaton, 1987, 1991), proximity to the thrust belt, lack of marine influence, and the nature of the capping
sandstone member. The capping sandstone member consists of several laterally persistent sheets of gravely sandstone and sandy conglomerate. It does not have a coarse-grained equivalent in the vicinity of the thrust belt; it is restricted in distribution to the Kaiparowits Basin; it is coarser-grained than the earlier postorogenic Drip Tank Member; it steps basinward of the Drip Tank Member as would be expected from an advancing thrust belt, and it has been correlated to the Castlegate Sandstone, which in turn has been determined as postorogenic by Villien (1984) and Villien and Kligfield (1986).

**Kaiparowits/Canaan Peak Sequence (Late Campanian - Maastrichtian?)**

The Kaiparowits/Canaan Peak sequence exhibits the same overall pattern of fining-up and then coarsening-up found in each of the lower sequences, but also includes some features that are distinct. These differences may signal major reactivation and growth of Laramide structures to the east of the Kaiparowits Basin. The initial history for this sequence is similar to that of the others. A sharp, conformable contact between interbedded sandstones and mudstones of the lower Kaiparowits Formation and the gravely capping sandstone member of the Wahweap Formation signals renewed movement in the Sevier orogenic belt, leading to higher rates of subsidence and aggradation in the Kaiparowits Basin (Fig. 20A). These grade upward into isolated channel sandstones and single-storied sandstone sheets encased in thick intervals of mudstone representing deposition by anastomosing and highly aggradational meandering streams of the middle Kaiparowits Formation (Fig. 20B). This part of the Kaiparowits/Canaan Peak sequence is much thicker than it is in the other sequences, contains a much higher proportion of preserved fine-grained deposits, and sandbodies are narrower and more multistoried.

Accompanying the transition between the lower and middle parts of the Kaiparowits Formation is a change in sandstone composition, showing an abrupt increase in the relative abundance of feldspar. A similar relationship has been noted by Lawton (1983, 1986) and Franczyk et al. (1990) for strata of the southern Uinta Basin. Based on changes in sandstone composition and paleodrainage patterns, Lawton (1983, 1986) and Franczyk et al. (1990) have suggested that Upper Cretaceous fluvial systems in central Utah originally flowed to the east and southeast away from the Sevier highlands and later flowed to the northeast subparallel to these highlands. During this later time interval, these systems possibly drained areas in Arizona, Nevada, and California and may have passed through the Kaiparowits region (Lawton, 1983, 1986; Goldstrand, 1992). Accompanying the change in drainage patterns, they document a coarsening-upward trend in fluvial depositional patterns and a change in sandstone composition, showing an upward increase in the abundance of feldspar and volcanic rock fragments. They believe that these changes mark an eastward migration of tectonism from the Sevier thrust belt into the foreland basin and indicate the onset and development of foreland uplifts, including the San Rafael Swell and possibly the Circle Cliffs uplift and Monument upwarp.

In contrast to central Utah, paleodrainage patterns in the Kaiparowits basin do not show a significant change in flow direction coincident with the increase in feldspar. Paleocurrent directions indicate a predominantly northeasterly flow throughout the formation. The middle part of the Kaiparowits Formation grades upward into multistory sheet sandstones with only moderate amounts of mudstone in the upper Kaiparowits Formation (Fig. 20C). These were deposited by meandering streams under conditions of slowing aggradation. The sequence is capped by the Canaan Peak Formation, which consists of a very thick, multistoried sheet of very
coarse conglomerate deposited by braided streams (Fig. 20D). Whereas, the contact between the upper and capping parts of the other sequences is conformable, the contact between the Kaiparowits and Canaan Peak Formations forms an angular unconformity, indicating uplift and tilting before deposition of the Canaan Peak and a transition from the proximal axial zone to the thrust belt zone.

CONCLUSIONS

Upper Cretaceous sequences of the Kaiparowits Basin most closely fit the blind thrust tectonic model and developed in association with the eastward advance of the Sevier thrust belt and adjacent foredeep basin based on the following evidence: 1) Coarse-grained units thicken toward the thrust belt but are not traceable back to that region; 2) Coarse clastic deposits are thick with sharp, planar lower and upper contacts and have a sheet geometry; 3) Coarse clastic units show a basinward stepping trend through time, and each successive sheet is coarser-grained and thicker than the previous sheet; 4) Paleocurrent orientations indicate a predominantly northeasterly flow throughout the section, suggesting asymmetric basin subsidence parallel to the thrust front; 5) Transgressions and synorogenic conglomerates in the Uinta Basin of central Utah have been correlated to episodes of active thrusting; whereas, regressions and widespread clastic wedges correspond to periods of postorogenic quiescence. Several of the thrust faults affecting central Utah are the same as those affecting the Kaiparowits region, suggesting a similar relationship; and 6) Significant influence by marine processes diminishes upward through the Upper Cretaceous succession of the Kaiparowits Basin.

REFERENCES CITED


FIGURE CAPTIONS

1. The Kaiparowits Basin was located along the western edge of the Cretaceous Western Interior Basin (A) between the Sevier thrust belt to the west and Laramide uplifts to the east (B).

2. Index map showing the location of major Upper Cretaceous outcrops in southwestern and south-central Utah.

3. Isopach maps show a change in basin subsidence patterns from an elongate foredeep trough parallel to the Sevier thrust belt during the Late Albian through Santonian time interval (A) to a circular pattern centered in Utah, Wyoming, and Colorado during the Campanian and Maastrichtian. Units represent sediment thickness in kilometers. From Cross and Pilger, 1978.


5. Upper Cretaceous strata of the northern Kaiparowits Basin consist of four depositional sequences, each of which can be divided into four parts. The three uppermost sequences are shown in this photomosaic with sequence boundaries marked by solid lines. Dashed lines show the contacts between parts of a sequence. Ksj, Ksjm, and Ksju refer to the lower, middle, and upper parts of the John Henry Member. Ksd shows the Drip Drip Tank Member. Kwl, Kwm, Kwu, and Kwc mark the lower, middle, upper, and capping sandstone members of the Wahweap Formation. The lower, middle, and upper parts of the Kaiparowits Formation are indicated by Kkl, Kkm, and Kku. Kc shows the location of the Canaan Peak Formation. Units belonging to Sequence 1 (Dakota Formation, Tropic Shale, and the Tibbet Canyon and Smoky Hollow Members of the Straight Cliffs Formation) are not shown in the photograph. Numbers 1 through 4 indicate the relative position of a unit within a sequence. The general characteristics of these sequences are shown in Fig. 6.

6. General nature of fluvial sequences in the northern Kaiparowits Basin (A) and relationship of specific sequences to formal lithostratigraphic units (B). Each sequence is divided into a basal, middle, upper, and capping part (indicated by the numbers 1 through 4 respectively) distinguished by architectural characteristics that reflect fluvial style and the rate of base level rise.

7. Foredeep basins can be divided into four zones, each exhibiting distinct stratigraphic successions related to tectonic subsidence and eustatic sea-level fluctuations. These are, from the thrust belt basinward, the Thrust Belt Zone, Proximal Axial Zone, Distal Axial Zone, and Forebulge Zone. Each zone will migrate basinward in response to the advancing thrust front.

8. Basin subsidence and eustatic sea-level fluctuations each affect the production of accommodation space and can produce similar vertical sequences for a given locality. This diagram shows the general nature of fluvial sequences in the northern Kaiparowits Basin and the application of the eustatic and tectonic models discussed in the text.

9. Predicted response of fluvial system architecture to a eustatic sea level rise. Channel-belt geometry and the relative abundance of channel-belt and overbank deposits are highly influenced by the rate of base-level rise. A) An incised valley geometry forms at the base of the sequence when the preceding sea-level fall is more rapid than the rate of basin subsidence. B) A progradational sheet geometry results when the sea-level fall is slower than basin subsidence rates.
10. Isostatic rebound model. A) Thrusting leads to basin subsidence and deposition of coarse clastic sediment immediately adjacent to the thrust belt. B) Isostatic rebound during tectonic quiescence results in reworking of a part of the coarse sediment, producing a clastic sheet further basinward. Modified from Heller et al. (1988).

11. Blind thrust model. A) Active thrusting causes basin subsidence in front of the thrust belt. B) The basin is uplifted and previous deposits are reworked in response to the development of a blind thrust.

12. Models for distribution of coarse clastic sheets in foredeep basins by eustatic and tectonic processes. A) Progradational sheets form during a lowering of sea level when rates of basin subsidence remain equal to or are greater than rates of sea level fall, producing continuous clastic sheets that are conformable near the thrust belt and thin basinward. B) Valley fill deposits are produced when the rate of sea level fall is greater than the rate of subsidence, forming discontinuous sand and gravel bodies that grade landward into unconformity-bound conglomerates. C) Isostatic rebound during tectonic quiescence leads to basinward reworking of a portion of previously deposited coarse clastics. D) Blind thrust development during tectonic quiescence has the potential to rework all proximal coarse clastic deposits.

13. A) Lowstand progradational sheets have a tabular geometry and coarsen upward as base-level falls. A thin finer-grained interval may form at the top during a subsequent base-level rise. Lower contacts are gradational. Tectonically redistributed postorogenic sheets are similar in geometry to lowstand progradational sheets, but lower contacts are sharp and may show some scouring. B) Valley fill deposits have incised lower contacts forming valleys that must be filled before coarse-grained sediment can spread across wide areas. Valley fill deposits fine upward in response to a rising base-level.

14. Coarse clastic deposits that are prominent in the Kaiparowits Basin are either absent or are poorly developed in areas adjacent to the thrust belt (Gunlock area). Additionally, these wedges step basinward and become progressively thicker and coarser upward. Modified from Eaton and Nations (1991).

15. In central Utah synorogenic conglomerates have been correlated to eustatic transgressions and widespread clastic sheets have been tied to eustatic regressions. Arrows indicate the end of thrusting for specific thrust faults west of the Wasatch Plateau. Modified from Villien and Kligfield (1986).


18. Photomosaics of the John Henry and Drip Tank Members of the Straight Cliffs Formation showing characteristics of the basal, middle, upper, and capping parts of sequence 2.

19. Photomosaics of the Wahweap Formation showing characteristics of the basal, middle, upper, and capping parts of sequence 3.

20. Photomosaics of the Kaiparowits and Canaan Peak Formations showing characteristics of the basal, middle, upper, and capping parts of sequence 4.