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An Evaluation of Relative Sea Level Controls and Fluvial System (Baselevel) Responses in Shallow Marine Through Coastal-Plain Stratigraphy: Sequence Stratigraphy and Facies Analysis of the Tununk Shale and Ferron Sandstone Members of the Mancos Shale, Central Utah

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Executive Summary

This study will evaluate fluvial system responses to relative sea-level (baselevel) change in time-bounded, progradational units of the (Cretaceous) Ferron Sandstone, central Utah. Detailed facies analysis and sequence stratigraphic techniques will be employed to document styles of fluvial and coastal-plain stratigraphy. Four scales of coastal-plain and fluvial facies heterogeneity will be examined by documenting and contrasting facies configurations, associations, and volumes in: (1) discrete channel-belts; (2) geometric arrangements of channel-belts within dicrete progradational events; (3) fluvial and coastal-plain facies between progradational events that occupy distinct geometric positions in a hierarchical stacking pattern; and (4) fluvial and coastal-plain facies in a shelf-margin lowstand and transgressive systems tracts of a Vail-type (Vail *et al.*, 1977a; Van Wagoner *et al.*, 1987) depositional sequence. Similarities in facies characteristics expressed at different scales of facies heterogeneity will facilitate developing key relationships between fluvial system responses to baselevel, slope, alluvial ridge development, and channel avulsion frequency. Similarly, coastal-plain responses to relative sea-level change will be evaluated by documenting lateral variations in sediment aggradation, and the frequency and magnitude of lithology-specific depositional processes. Determining through field studies, the nature of dependency among these variables provides the information necessary to develop second-generation, quantitative forward models (Allen, 1978, 1979; Bridge and Leeder, 1979) of fluvial systems and alluvial stratigraphy.

In a fluvial-dominated coastal-plain setting, styles of coastal-plain and fluvial stratigraphy reflect secondary fluvial system responses to primary eustatic, tectonic subsidence, and sediment supply controls. Eustasy and tectonic movement combine to create or remove space for sediment accumulation. Variations in sediment supply, which may be partly dependent on tectonic and eustatic variables, controls the nature of sedimentary fill. Interactions of these primary controls determine water depth and relative sea level. At our present level of understanding, empirical relationships are required to establish relations between fluvial system responses and relative sea level change. An empirical geomorphic database (e.g., Fisk, 1944, 1947; Hack, 1957; Yatsu, 1955; Bernard, 1962) of contemporary coastal-plain fluvial systems suggests that a relative sea level rise results in baselevel rise and decreased channel slopes which in turn may control alluvial ridge buildup and floodplain topography. Alluvial ridge buildup and flood plain topographic relief controls channel avulsion frequency. If relative sea level controls baselevel which in turn effects alluvial ridge buildup, then a relationship between channel avulsion frequency and relative sea-level exists. This relationship should be expressed at different scales of facies heterogeneity despite changing styles of fluvial and coastal-plain stratigraphy. Assuming that these complex interactions control coastal-plain and fluvial stratigraphy, documenting the similarities and differences in a hierarchy of facies configurations provides a method for evaluating the nature of dependency among these controls.

Extraordinary three-dimensional exposures of shallow marine through coastal-plain strata in the Ferron Sandstone occur along the western margin of the Cretaceous Western Interior foreland basin in central Utah. A regressive maximum of the Cretaceous seaway during Ferron deposition is recorded in a series of discrete progradational units which contain a complete spectrum of shallow marine through coastal-plain facies. These units are arranged in a hierarchy of seaward-stepping, vertically stacked and landward-stepping geometric patterns. The Upper Tununk Shale and Ferron Sandstone Member (*Collignoniceras woolgari* through *Scaphites preventricosus* ammonite zones) correspond to the shelf-margin lowstand through transgressive systems tracts of recent Exxon terminology (Van Wagoner *et al.*, 1987). This lowstand systems tract includes a laterally persistent but locally discontinuous sandstone, overlain by shallow-marine siltstones and silty shales and two seaward-stepping sandstone units. The upper Ferron, transgressive systems tract consists of a landward-stepping arrangement of at least six coal-bearing progradational units.

Field work will be conducted during the summer and fall of 1989 and May and June of 1990. Facies analysis will be accomplished through detailed measurement of vertical sections. Cliff-face photomosaics will serve as a guide in tracing time-significant surfaces including volcanic ash beds. Sequence stratigraphic techniques that proved successful in our previous Ferron studies will be applied in constructing a chronostratigraphic framework. Depositional dip and strike oriented, two-dimensional cross-sections will be prepared integrating measured sections, photomosaics, and subsurface data. Our research accomplishments on the Ferron Sandstone (Gardner, Leverson and Cross, 1987; Leverson and Gardner, 1987; Gardner and Cross, 1989; Gardner, 1989), augurs well for completing this study in a expeditious and cost-effective manner. This study offers potentially significant contributions to Cretaceous paleogeography, coal geology, sedimentology, forward stratigraphic modeling and sequence stratigraphic techniques in foreland basin settings. The target completion date is December, 1991.

Research Significance and Objectives

The fluvial system is the principal sediment conduit to the shoreface and it directly impacts sediment dispersal patterns in more distal, shallow and deep marine facies (Allen, 1965, Wright and Coleman, 1973; Reading, 1978). Consequently, understanding controls on the distribution of coastal-plain, fluvial systems also facilitates an understanding of sediment dispersal in marine facies (Swift, 1968; Reading, 1978). Interactions among primary eustatic, tectonic, and sediment supply variables determine water depth and relative sea level and control the development of coastal-plain and fluvial facies. Despite changing styles of fluvial and coastal-plain stratigraphy, complex interactions among primary and secondary variables should be expressed at all scales of facies heterogeneity. At our present level of understanding, empirical relationships are required to evaluate the nature of dependency among these controls and their effect on the stratigraphic record. The principal objectives of this investigation are to document a hierarchy of fluvial and coastal-plain facies heterogeneity to evaluate the nature of dependency among fluvial system responses (baselevel, slope, alluvial-ridge buildup, and avulsion frequency) to relative sea-level change. The following section discusses in more detail these objectives and outlines key relationships and assumptions related to scales of *facies heterogeneity* and *fluvial system responses* to relative sea level change.

Facies Heterogeneity

Because coastal-plain and fluvial strata contain significant economic coal deposits and hydrocarbon reservoirs, understanding controls of facies heterogeneity underpins successful exploration and development (geologic targeting) strategies. Despite the fact that fluvial and coastal-plain facies form very heterogeneous reservoirs (which directly affects hydrocarbon recovery), there have been surprisingly few attempts at documenting a hierarchy of reservoir and facies heterogeneity. Fuvial system responses to relative sea level change may control the development of cross-bedding dependent directional permeability, channel-belt interconnectedness, reservoir boundaries and baffles, and permeability zonation (Miall, 1985). Four scales of coastal-plain and fluvial facies heterogeneity that will be examined in this study (Fig. 1). These include:

(1) discrete channel-belts; (2) geometric arrangements of channel-belts within dicrete progradational events; (3) fluvial and coastal-plain facies between progradational events that occupy distinct geometric positions in a hierarchical stacking pattern; and (4) fluvial and coastal-plain facies in a shelf-margin lowstand and transgressive systems tracts of a depositional sequence (Vail *et al.*, 1977a; Van Wagoner *et al.*, 1987).

Within a discrete channel-belt, three scales of lithologic and sedimentologic heterogeneity will be examined. The smallest scale features include internal lithologic and mineralogical changes, cross-bed orientations, and grain-size variations and trends within bedform successions These internal changes will be related to larger-order vertical and lateral bedform successions. Bedform successions will be associated with the internal ordering of bounding surfaces in large-scale, three dimensional channel-belt sandstone configurations. Documenting this hierarchy provides a method for characterizing sedimentological responses to depositional processes that occur within a discrete channel-belt . Depositional processes inferred from these facies associations may then be related to fluvial system changes that occur within a single progradational event.

Within a single progradational event (parasequence of VanWagoner et al., 1987; fourth-order cycle of Ryer, 1983), vertical and lateral changes in the facies architecture of channel-belt sandstones and equivalent coastal-plain strata will be documented to identify and separate component regressive and transgressive half-cycles. Repetitive and systematic changes in styles of fluvial and coastal-plain stratigraphy coupled with correlative and consistent changes at facies boundaries will be used to identify time-significant surfaces. These surfaces will be used to connect a broad spectrum of shallow marine through coastal-plain facies, that although lithologically diverse are genetically related by their equivalence in time. Gardner, Leverson, and Cross (1987) and Gardner (1989) demonstrated that time-significant surfaces in the Ferron Sandstone are represented in offshore marine facies by condensed sections, in shallow-marine facies by flooding surfaces produced by deepening and landward shift of facies, and in coastal-plain facies by surfaces that separate sand-poor lithologies from sand-rich lithologies (Fig. 2). Regionally correlative volcanic ash beds, and a refined biostratigraphic framework will be used to corroborate these correlations. Characterizing facies associations that record regressive and transgressive (relative sea level) changes within a discrete progradational event will facilitate identifying time-significant surfaces and the construction of a chronostratigraphic framework. Changes in these baselevel sensitive facies-associations between multiple progradational events can then be used to evaluate longer-term fluvial system responses to baselevel and relative sea-level change.

Contrasting changes among facies geometries, associations, and sediment volumes of multiple progradational units that occupy distinct geometric positions in the Ferron hierarchical stacking pattern (part of Kauffman's (1977) Greenhorn and Niobrara Cyclothems and Vail et al.'s (1977a) third-order cycle) can be used to evaluate primary eustatic, tectonic, and sediment supply controls of stratigraphic architecture. In the Ferron, transgressive systems tract, Gardner, Leverson and Cross (1987) used the area between the landward and seaward pinchout of shoreface sandstones plus the thickness of sandstone in shallow marine and coastal-plain facies tracts to document total sandstone volumes in progradational units representing each of the geometric positions in the Ferron stacking pattern (Fig. 3). They demonstrated that in a seaward-stepping unit the shallow marine-coastal-plain sandstone volume ratio is 3:1. In the vertically-stacked unit the volume ratio is 2:1, and in the landward-stepping unit the volume ratio is 1:1. Total sediment volumes expressed as absolute ratios are equal in forward and backstepping units but are doubled in the vertically-stacked unit. These results demonstrate that systematic sediment volume partitioning in shallow marine and coastal-plain facies tracts is related to the geometric position of discrete progradational events in the hierarchical stacking pattern. These geometric and volumetric relationships are controlled by systematic and predictable shifts in sediment accommodation that is controlled by primary eustatic, tectonic and sediment supply variables. Changing styles of coastal-plain and fluvial stratigraphy that accompany sediment volume changes must reflect secondary fluvial system responses to these primary controls.

The interaction of primary eustatic, tectonic, and sediment supply variables results in systematic changes in sediment accommodation space. Changes in sediment accommodation space are recorded by changes in genetically-related facies associations of depositional systems (Fisher and McGowen, 1967; Fisher, 1969; Brown, 1969; Frazier, 1974; among others). Three end-member depositional sytems constitute a depositional sequence (Vail, 1977a) and are related to relative sea level changes by the Exxon group (Van Wagoner etal., 1987). The lowstand systems tract corresponds to the highest rate of relative sea level fall, whereas the transgressive, and highstand systems tracts correspond to successively increased rates of relative sea level rise. A case example of fluvial and coastal-plain facies architecture in foreland basin, lowstand and highstand systems tracts is presently absent. This study will compare systematic changes in different scales of baselevel sensitive fluvial and coastal-plain facies associations contained in depositional sequence systems tracts. This will provide the documentation necessary for characterizing coastal-plain and fluvial stratigraphy in a foreland basin, shelf-margin lowstand and highstand systems tracts (Fig. 4). This will facilitate evaluating fluvial system responses to baselevel and relative sea level change, and provides a reference for comparison with systems tracts in other similar and diverse depositional regimes. Ultimately, such comparisons will determine whether Ferron styles of coastal-plain and fluvial stratigraphy are representative of sedimentary responses to primary and secondary controls in a foreland basin setting.

Fluvial System Responses

An empirical geomorphic database (e.g., Fisk, 1944, 1947; Hack, 1957; Yatsu, 1955; Bernard, 1963) of contemporary coastal-plain fluvial systems suggests that a relative sea level rise results in baselevel rise and decreased channel slopes. Fisk (1944, 1947) demonstrated that during the late Wisconsin glacial maximum, the Mississippi river formed a wide and deep alluvial valley which, during the subsequent post-Wisconsin sea-level rise, filled with alluvium. Valley incision is related to baselevel fall and increased slopes, whereas alluviation is related to baselevel rise and decreased slopes. Allen (1965, citing Fisk 1944, 1947 and Bernard et al., 1962) suggested that rising base level, which led to thick alluviation in the Mississippi and other Gulf Coast streams, is manifested in lower stream gradients, decreased sediment loads and increased floodplain relief.

Inasmuch as relative sea level change controls nearshore fluvial system baselevel and slope adjustments, these adjustments may in turn control alluvial ridge buildup. Fisk (1944, 1947) noted that in response to the Holocene sea-level rise, the modern Mississippi river has built at least five alluvial ridges along meander belts up to 50 miles apart. With the exception of this citation, there is little evidence directly relating baselevel and slope adjustments to alluvial ridge buildup. Therefore, developing empirical relationships between these variables requires examining facies that makeup an alluvial ridge. These facies include the channel belt, channel levees, crevasse splays, and abandoned channel fills. In examining the effects of isostatic readjustment in high latitudes (analogous to base level fall) on channel morphologies, Allen (1965) noted a lack of levee development in the Yukon river (observed by Eardley, 1938). Conversely, well developed levees are observed in Gulf Coast streams (Bernard et al., 1962) and are related to tectonic subsidence and sea-level rise (the combined effect results in baselevel rise). In evaluating slope controls on channel sinuosity, Leopold and Wolman (1957) demonstrated that a decreased channel slope (baselevel rise) resulted in an increased channel sinuosity. Increased channel sinuosity results in increased channel cutoffs and more clay plugs. As the number of clay plugs increase, potential bank stability of channels increases and the channel belt becomes more restricted. This effect enhances vertical sediment aggradation near the alluvial ridge. These empirical relationships suggest that baselevel rise and decreased channel slopes may result in increased alluvial ridge buildup.

Because a river seeks the lowest topographic position in the floodplain, there is a direct relationship between alluvial ridge buildup and channel avulsion frequency (Allen, 1978). The greater the ridge height, the greater the probability and frequency of channel avulsion. Over the span of geologic time-frames, sea level and related base level changes could control channel avulsion frequency through changes in floodplain topographic relief. Schumm (1956) reported that as channel slopes increase, stream channels become more closely spaced and are relatively stable and laterally restricted. Although lateral bank migration increases during a slope increase, the time scale of bank migration (meandering) is small compared to channel avulsion (Allen, [illegible] This implies that channel avulsion, which is at a minimum during an increase in channel [illegible] is still the dominant channel migration mechanism during baselevel fall.

Quantitative models that explore fluvial system controls of alluvial stratigraphy are restricted to Leeder (1977), Allen (1978, 1979), and Bridge and Leeder (1979). Allen (1978) developed a simple, quantitative model to examine the connectedness of channel sandbodies over time periods of 10^5-10^6 yrs. This model assumes that: (1) subsidence is uniform and steady; (2) each time-step initiates with a channel avulsion; and (3) overbank and channel sandbody thickness is proportional to subsidence and avulsion period, with sandstone thickness also controlled by channel depth. Sediment compact is ignored. Channel-shifting is partly random and based on random-number tables and rules for avoidance of older, relief forming sandbodies. Model results indicate that channel sandbodies are unconnected in coastal-plain successions containing greater than 50% of overbank fines, while the degree of connectedness increases as the proportion of sandbodies increases above 50%.

Bridge and Leeder (1979) developed a two-dimensional, quantitative model that assumes linear changes in four independent variables: (1) laterally variable aggradation, (2) compaction of fine sediment, (3) tectonic movement at floodplain margins, and (4) channel avulsion. In this model, each time-step initiates with channel avulsion, while other input variables in the system respond independently (e.g. changes in sediment aggradation are independent of changes in channel avulsion frequency). This pioneering model provides the only means of systematically evaluating factors that control sediment distribution patterns in fluvial systems. However, as with Allen's model, they realized there are several shortcomings in this approach. These include the assumptions: (1) that input variables are independent; (2) that responses to processes are linear; (3) that channel avulsion frequency is constant; (4) that lithologic variability in the flood-plain is simplified; and (5) the lack of calibration of model output with actual data from ancient alluvial successions.

Background and Previous Work

The following discussion provides a summary of previous work related to this study. A brief history of geologic investigations of the Ferron Sandstone in central Utah is followed by a lithostratigraphic summary of Middle Turonian to Coniacian strata in Castle Valley. The regional sequence stratigraphic framework for this interval and the tectonic setting of this region are outlined.

Ferron Geologic History

In Castle Valley, Lupton (1916) named exposures of interbedded clastic and coal-bearing strata in the Mancos Formation the Ferron Sandstone Member, and developed a classification for Ferron coal beds that is still used today. Katich (1954) and Davis (1954) divided the Ferron into a lower unit lacking coal and an upper coal-bearing unit. Katich (1951) documented a north-northeast transport direction for the southerly derived and westward thickening upper coal-bearing unit. Hale and Van De Graaf (1964) in preparing regional paleogeographic maps for Cretaceous strata in northeastern Utah formalized the "somewhat arbitrarily" defined Vernal Delta as the older and northerly derived unit. Hale (1972) named the younger southerly derived coal-bearing deltaic sequence the Last Chance Delta.

Cotter (1975a, 1975b) recognized two distinct and unrelated depositional systems from outcrops in Castle Valley. Corroborating earlier work, he related the lower unit to the northern sourced "Vernal Delta" and the upper coal-bearing unit to the southwestern sourced "Last Chance Delta." He described the lower unit as being deposited along a low energy coastal zone (Cotter, 1975b) and interpreted the upper unit as a high constructive lobate delta (Cotter, 1975a). In a paleohydraulic study of fluvial systems in the upper coal-bearing unit, Cotter (1971) proposed that Ferron streams drained an area of 6,000 to 8,000 mi^2, were 200 miles long, highly sinuous, suspended load systems, with discharges ranging from 6,000 to 7,000 ft ^{3}/s.

In a series of papers, Ryer (1980a,b; 1981a,b; 1982, 1983) used surface and subsurface data to examine upper coal-bearing strata associated with the Emery coalfield. Ryer (1981) interpreted these strata as a fluvial-dominated deltaic depositional system. He described the stacking pattern for five "fourth order" deltaic cycles, each associated with a major coal zone. This relationship formed the basis for an empirical predictive model for coal distribution. This model states that the thickest coals occur in a shore parallel, 10 km belt extending landward from the observed landward pinchout of delta-front sandstones. In a subsequent paper relating Cretaceous coal distributions in Utah to sea level change, Ryer (1983) suggested that the transgressive maximum of Vail's (1977a) third order cycle, corresponds to the vertical stacking of fourth-order cycles. He demonstrated that maximum coal development occurred during the vertical stacking of fourth-order cycles. Lawrence (1982) demonstrated a similar relationship for the Adaville Formation in southwestern Wyoming. Ryer's vertically stacked, fourth-order cycles would correspond to the transgressive systems tract.

Biostratigraphy

Biostratigraphic data constrain the timing of initation and termination of progradational events, and the age of component systems tracts and unconformities that encompass Middle Turonian to Coniacian time. The upper Tununk Shale and Ferron Sandstone Member (Fig. 4) encompass the *Colliginoniceras woolgari* through *Scaphites preventricosus* ammoniod biozones and *Inoceramus labiatus* through *Inoceramus deformis* inoceramid biozones (Cobban, 1976, Kauffman and others, 1976, Merewether and Cobban, 1986; Kauffman and Colloms, personal communication, 1989). Argon-argon radiometric dates from volcanic ash beds tied to ammonite biozones indicate that this interval spans from 93.5 to 91.0 Ma ± 400,000 yrs (Kauffman and Colloms, personal communication, 1989). Therefore, Ferron strata accumulated over a period of roughly 2.1 million years. Progradation of Ferron strandline sequences from their western, landward initiation to their eastward, seaward termination is recorded by six ammonite and nine mixed ammonite-scaphites biozones and occurred during a period of approximately 1.6 Ma (based on collections of *Colliginoniceras woolgari* through *Scaphites whitfieldi* by Ryer (1983) and Cobban (1976) from Ferron Sandstone along the 76.5 mi (122 km) trend from Salina to Price).

In central Utah, Ryer (1983) collected the ammonite *Colliginoniceras woolgari* from a sandstone unit in the upper part of the Allen Valley Shale (Tununk Shale) near Salina, Utah, and the inoceramid *M. dresdensis labiatoidiformis* (*Scaphites preventricosus*) at the Ferron Sandstone-Bluegate Shale contact near Emery, Utah. South of Emery along the Coal Cliffs, Katich (1954, p. 46) collected the ammonite *Colliginoniceras woolgari* from the upper Tununk Shale member. Along the northeast edge of Castle Valley near the town of Farhnam, Cobban (1976) collected the ammonite *Prinocyclus hyatti* from the lower Ferron, Clawson and Washboard units. At the top of the Ferron, he collected inoceramidae, scaphites, oysters, and ammonites from the zone of *Prinocyclus wyomingensis*. Cobban (1976) reported that Hale (1972) collected specimens typical of *Scaphites warreni* (*Prinocyclus wyomingensis*) from the top of the Ferron near Castledale. *Scaphites whitfieldi* (one biozone younger) were collected from the top of the Ferron near the towns of Price and Ferron. However, the collections from the town of Ferron, Utah may reflect a transgressive lag deposit because *Prinocyclus wyomingensis* and *I. preplexus* were also collected from this horizon. South of Emery, near Ivie Creek, Forrester (cited in Cobban, 1976) collected *Scaphites preventricosus* from limestone concretions one hundred feet above the Ferron.

Sequence Stratigraphic Framework

Preliminary field results from the Ferron and Kaiparowits projects (Gardner and Cross, 1989; Shanley and McCabe, 1989) and available literature (Weimer, 1960; Peterson and Ryder, 1975; Kauffman, 1977; Ryer and Lovekin, 1986; Merewether and Cobban, 1986; Eaton and others, 1986) on contemporaneous strata in Utah, Wyoming, and Colorado, suggests that the upper Tununk Shale and Ferron Sandstone Member correspond to the lowstand through transgressive systems tracts of recent Exxon terminology (VanWagoner *et al.*, 1987). In this scheme, the upper Tununk Shale and Clawson and Washboard units of the lower Ferron would constitute the lowstand systems tract; whereas coal-bearing units of the upper Ferron would correspond to the transgressive systems tract; and the overlying upper Mancos Shale and Bluegate Shale Member would represent the marine shelf facies within a highstand systems tract. This stratigraphy suggests that along the active western margin of the Cretaceous Western Interior foreland basin, the composite Ferron and Bluegate Shale Members constitute a Vail-type seismic or depositional sequence (Vail, 1977a,b). Along depositional strike variations in thicknesses, progradational geometries, and stacking patterns (Fig. 5) suggest that during Ferron deposition, central Utah recorded the highest subsidence rates in Utah (Ryer and McPhillips, 1983). Consequently, this region contains the most complete record of lowstand through highstand systems tracts.

Biostratigraphic evidence (Cobban, 1976; Kauffman and others, 1976; Kauffman, 1977; Merewether and Cobban, 1986), suggests that basinward equivalents to the foreland flank, lowstand systems-tract (the lower Ferron) are the unconformity-bounded Unnamed Member (Emigrant Gap Member) of the Frontier Formation in Wyoming, and Codell Sandstone in Colorado. The basinward equivalents to the foreland flank, transgressive systems-tract (the upper Ferron) are the Wall Creek Member of the Frontier Sandstone in Wyoming, and Juana Lopez Member of the Carlile Shale in Colorado.

Tectonic Setting

Along the western margin of the Western Interior Cretaceous seaway, the Sevier orogenic belt (Armstrong,1968; Allmendinger,and Jordan, 1981) provided a source for clastic sediments shed eastward into an evolving foreland basin. The foreland basin formed in response to progressive thrust-induced lithospheric loading resulting in a pronounced foreland trough adjacent to the thrust sheet (Jordan, 1981; Cross, 1986). In central Utah, thrusting was initiated in Latest Albian time (100 Ma) along the Pavant 1 thrust sheet and was followed by a second episode of thrusting during (82 Ma) lower Campanian time along the Pavant 2 thrust sheet (Villien and Kligfield, 1986). Fleming and Jordan (1987) demonstrated that the foreland basin wavelength increases during and after thrust motion, while the initation of a subsequent thrust cycle results in a pronounced decrease in basin wavelength. If true, Ferron deposition occurred between thrust cycles and during a period of foreland basin expansion. Tectonic subsidence influences on depositional patterns are indicated by west and southwestward thickening of the Tununk Shale and Ferron Sandstone Members (Ryer and McPhillips, 1983) .

Tectonic subsidence patterns along an active margin of a foreland basin (Jordan, 1981; Villien and Kligfield, 1986; Cross, 1986) are different than in a passive margin setting (Pitman, 1978). Therefore, stratal architectures and geometries within unconformity-bounded sequences (Vail, 1977a) may also be different. Because subsidence rates are higher along the active margin of a foreland basin than in more basinward position, conformable sequences restricted to the active margin of a foreland basin correlate basinward to unconformity-bounded equivalents. This is a geographically opposite configuration of sequences developed on a passive margin. Notable exceptions occur along the southern margin in the Henry Mountains and Kaiparowits Plateau, where reported unconformities (Peterson and Ryder, 1975; Peterson, 1979a,b) at the top of the transgressive systems tracts have no basinward equivalents. The presence of this unconformity may represent a transgressive surface of erosion, separating the transgressive and highstand systems tracts, that is accentuated in this region by a relative decrease in subsidence rates.

Methodology

The bulk of the field work will be conducted along the Coal Cliffs where the Ferron Sandstone is three-dimensionally exposed as a continuous 60 km long cliff face oriented subparallel to depositional dip. Additional exposures of the Ferron occur in a series of tributary canyons that approximate depositional strike. The Emery coalfield (Doelling, 1972) less than three miles from the Coal Cliffs, contains an extensive subsurface database (Fig. 6).

Facies analysis will be conducted through detailed measurement of vertical sections. This will determine the nature of facies and facies transitions in progradational units. Facies described from measured sections will be calibrated to subsurface geophysical well logs and core descriptions to define three-dimensional facies distributions. Cliff-face photomosaics will be constructed to laterally trace facies associations and physically correlate volcanic ash beds and time-significant surfaces. These correlations will be extended as far seaward and landward as physically possible.

Two-dimensional cross-sections and time-bounded facies maps will be prepared to document lateral and vertical facies geometries and distributions. The purpose of the mapping phase is to define three-dimensional coal and channel-belt geometries. The stratigraphic position of channel sandbodies in depositional units will be compared with the distribution of coals and other fine-grained, vertical accretion deposits. Empirical relationships between the geographic position of channels and floodplain mires at discrete time-steps may shed light on whether Ferron peat swamps represent raised or low-lying mires. Sediment volumes within time-bounded units will be calculated to evaluate sediment partitioning in a broader spectrum of facies tracts than previously investigated.

Field investigations will emphasize the following areas:

1) Facies analysis will be conducted using existing photomosaics of the Ferron to identify selected sites where facies changes at critical facies transition boundaries and time-significant surfaces require further examination. For example, additional documentation is needed on the vertical and lateral distribution and character of abandoned channel-fill deposits. Presently, coeval channel-belts in three time-bounded units have been identified and correlated. Selected detailed measured sections will be used to document down-channel changes in facies occurrences and geometries in these channel belts. Upstream and downstream changes in facies volume partitioning, facies associations and fluvial architectures will be documented to evaluate the landward-directed rate of upstream baselevel influence on fluvial architectures in coeval channel-belts
2) Sequence stratigraphic correlations based solely on the recognition of time-significant surfaces will be corroborated by physically tracing volcanic ash beds. Although, Ryer and others (1980) demonstrated that volcanic ash beds in one coal bed can be correlated to laterally equivalent shoreface deposits, this empirical relationship requires further documentation in other progradational units to unequivocally establish its validity. Because the underlying Tununk Shale and its equivalents to the north and south are better exposed than the overlying Bluegate Shale, this offshore marine shale will be measured to identify regionally correlative volcanic ash beds that will serve as a datum, and to obtain macro-fossil samples.
3) As previously discussed, the Clawson and Washboard Units in the lower Ferron represent a lowstand systems tract. Cliff-face photomosaics from the southwestern outcrop belt, indicate

that these two units are separated by a toplap unconformity. Excellent clinoform geometries are exposed in shoreface sandstones of these units. Stapor and Adams (1988) suggested that delta morphologies change from gilbert-type deltas in the southwest to river-dominated deltas further to the east near Emery, Utah The toplap unconformity surfaces and facies changes that occur along clinoform surfaces and the nature of coastal-plain and fluvial facies will be documented.

4) In Castle Valley, the ammonite zone *Colliginoniceras woolgari* occurs in a laterally persistent sandstone horizon in the upper Tununk Shale. The lithology of the Tununk changes from shale to silty shale at this contact (Occian and Poelchau, 1985). This same ammonite zone occurs above a regional unconformity in Wyoming, Colorado and Utah (Merewether and Cobban, 1986) but this unconformity is absent in Castle Valley and along depositional-strike, in Utah (Walton, 1944; Maoine, 1971; Peterson and Ryder, 1975; Peterson, 1969a,b). In place of an unconformity the first sandstone above the Dakota Formation along the western margin of the foreland basin in Utah occurs at or near *Colliginoniceras woolgari* . These relationships suggest that this ammonite zone coincides with the position of a depositional sequence boundary that marks the lower boundary of the Ferron lowstand systems tract. Ammonite collections from the landward initation and seaward termination of sandstone in Castle Valley (Ryer and McPhillips, 1983; Cobban, 1976) suggest that the duration of the Ferron lowstand systems tract is 1.6 Ma. Collections from the top of the Ferron near Emery, Utah imply that the duration of the transgressive systems tract is .5 Ma. If true, these ages indicate that the duration of the lowstand systems tract is slightly more than three times greater than the highstand systems tract. The nature of the basal lowstand sandstone and other stratigraphic relationships in the lowstand systems tract requires further investigation before facies relationships in the lowstand systems tract can be compared with better documented facies relationships in the transgressive systems tract.

5) The southern outcrop belt provides an excellent opportunity to examine fluvial architectures thirty miles landward of the pinchout of contemporaneous shoreface sandstones. Previous work (Gardner, 1989) has documented fluvial sandstone geometries a maximum of fifteen

miles landward of the shoreface pinchout. Additional detailed measured sections, will double the empirical database of fluvial and coastal-plain strata. More proximal changes in fluvial architectures will be documented to determine if westward thickening in the Tununk and Ferron Sandstone is recorded by changing styles of fluvial architecture. Cliff-face photomosaics will facilitate physically tracing discrete channel sandstones in this area.

6) A chronostratigraphic framework will be constructed to determine the depositional history of Ferron peat mires. Most coal originates either as peats in raised mires or in low lying mires well removed from active clastic environments (McCabe, 1984). Because coal seams formed in low lying peat mires and associated clastic facies cannot coexist, when vertically juxtaposed these facies must be separated by a significant hiatus (McCabe, 1987). Therefore, an empirical relationship between the position of laterally-equivalent channel belts and peat mires can be used to predict where seam splits and coal bed thinning is likely to occur. Coal in slightly younger strata in the Kaiparowits Plateau has been interpreted as forming in raised mires (McCabe and Shanley, 1988). Coals facies in the Ferron will be compared with coal facies in the Kaiparowits to determine if this interpretation has broader applicability.

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Schedule of Work

May 6-June 2, 1989: 27 days field work, southwestern Coal Cliffs, Utah .

June 5-June 15, 1989: 11 days field work, northeastern Coal Cliffs area, Utah.

July 12-August 11, 1989: 30 days field work, eastern San Rafael Swell and Waterpocket Fold, Henry Mountain Basin, Utah

August 13-August 23, 1989: 11 days field work, Uinta Basin, Thistle,

September 7-September 22, 1989: 15 days field work, Waterpocket Fold, Henry Mountain Basin, Utah

October 1-5, 1989: Fluvial Conference, Barcelona, Spain

October 9-October 31, 1989: 22 days field work, southwestern flank of Uinta Mountains

November 1989: Volumetric Paper-draft; Correlations paper-outline

December 1989: Foreign Language test; Correlations paper-draft

January-May, 1990: Spring 89/90 academic semester, acquire well logs, construct base map, correlate data, define mappable units, complete facies maps

May 15-June 10, 1990: 26 days field work, Coal Cliffs, and Uinta Mountains area, Henry Mountain Basin, Utah.

June, 1990: Complete correlation paper

July, 1990: Begin fluvial architecture paper

August, 1990: Draft fluvial architecture paper, fieldwork drafting

September-December, 1990: Fall 90 /91 academic semester, oral and written comprehensive exam, minor completed

January-May, 1991: Spring 90/91 academic semester; Course work completed during Spring 90/91 academic semester,

May-December, 1991: Draft and final report.

December, 1991: graduation.

Coursework

Course	Credits	Grade
Spring 86		
#GE 611 Advanced Stratigraphy	3	A
Fall 86		
GE 504 Integrated Exploration	3	A
^GC 528 Geochemistry, Petro. Source Bed Evaluation		A
#GE 621 Hydrodynamics and Clastic Facies Analysis	3	A
HM 221 Spanish 1	NC	
Spring 87		
#GE 607 Graduate Seminar	1	A
^GP 558 Seismic Data Interpretation		A
GE 507 (CU) Advanced Sedimentology	3	A
GE 653 (CU) Fluvial Mechanics and Sediment Transport	NC	
Spring 88		
#GE 608 Graduate Seminar	1	A
*ME 504 Economic Eval. and Investment Dec. Methods	3	A
GE 631 Special Topic: Stratigraphy Seminar	1	A
#GE 605 Advanced Structure/ Tectonics	3	A
Fall 88		
#GE 511 History of Geologic Concepts	3	A
GE 559 (CU) Carbonate Diagenesis	3	A
GE 631 Special Topic: Stratigraphy Seminar	1	A
Spring 89		
GE 631 (CU) Sandstone Petrology	3	
GE 504 Seminar: Reservoir Heterogeneity	3	
GE 631 Special Topic: Stratigraphy Seminar	1	
Fall 89		
Foreign Language Test		
Spring 90		
*PE 422 Economic Evaluation of Oil and Gas Operations	3	
GE 631 Diagenesis	3	
GE 631 Special Topic: Stratigraphy Seminar	1	
GE 609 Advanced Petroleum Geology	3	
Fall 90		
*ME 580 Exploration Economics	3	
*ME 568 Applied Economic Decision Analysis	3	
GE 610 Basin Analysis	3	
Oral and Written Comprehensive Exam		
Spring 91		
GE 467 Hydrogeology	3	
ME 550 Numerical Analysis	3	
Fall 91		
Graduation		

Coursework Summary

Geology (major)	50
*Mineral Economics (minor)	12
Total	62

Coursework Key

#--comprehensive course *--minor course ^--deficiency course

NC--Course taken for no credit (official audit)

Hierarchy of Facies Heterogeneity

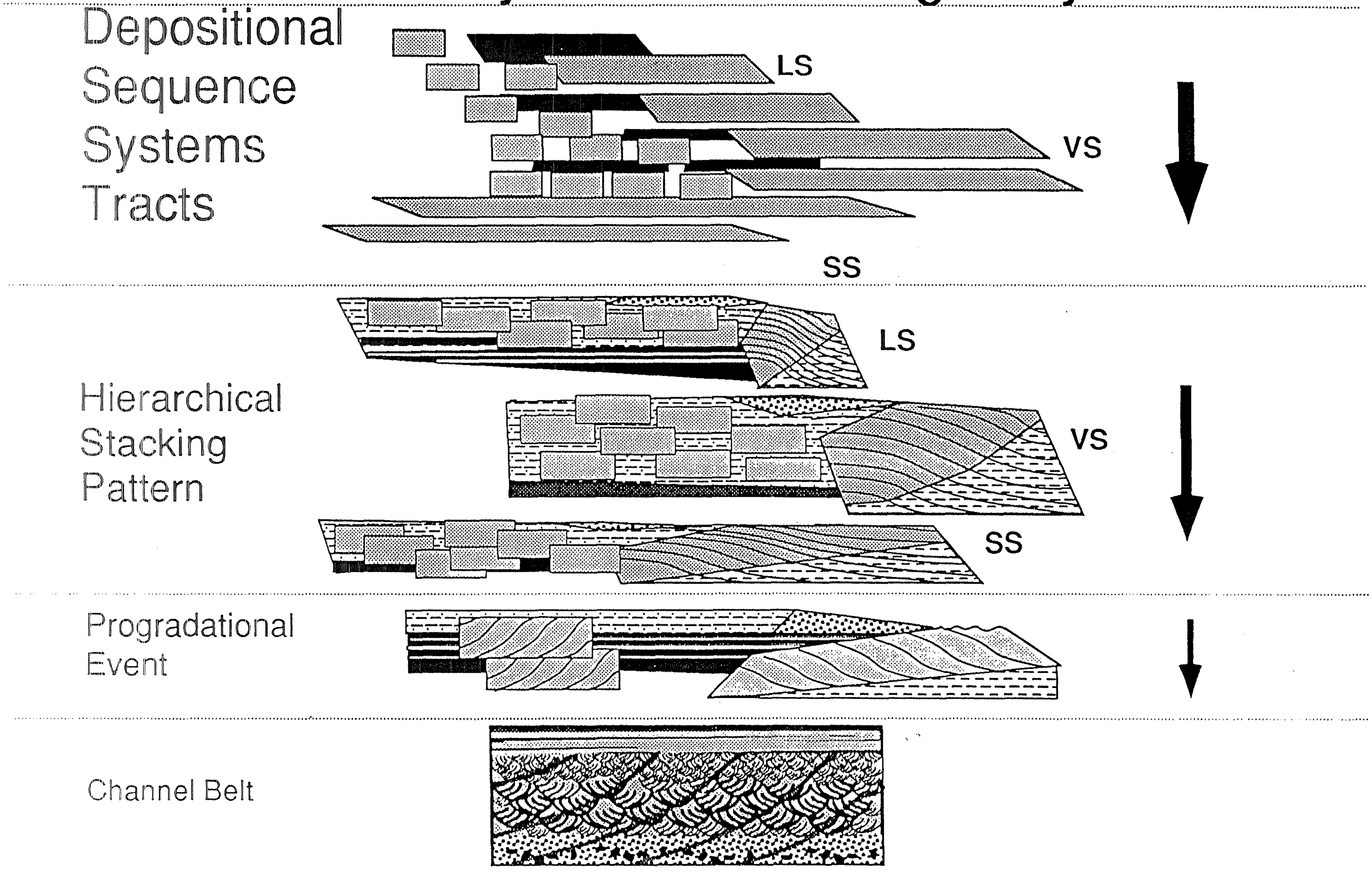
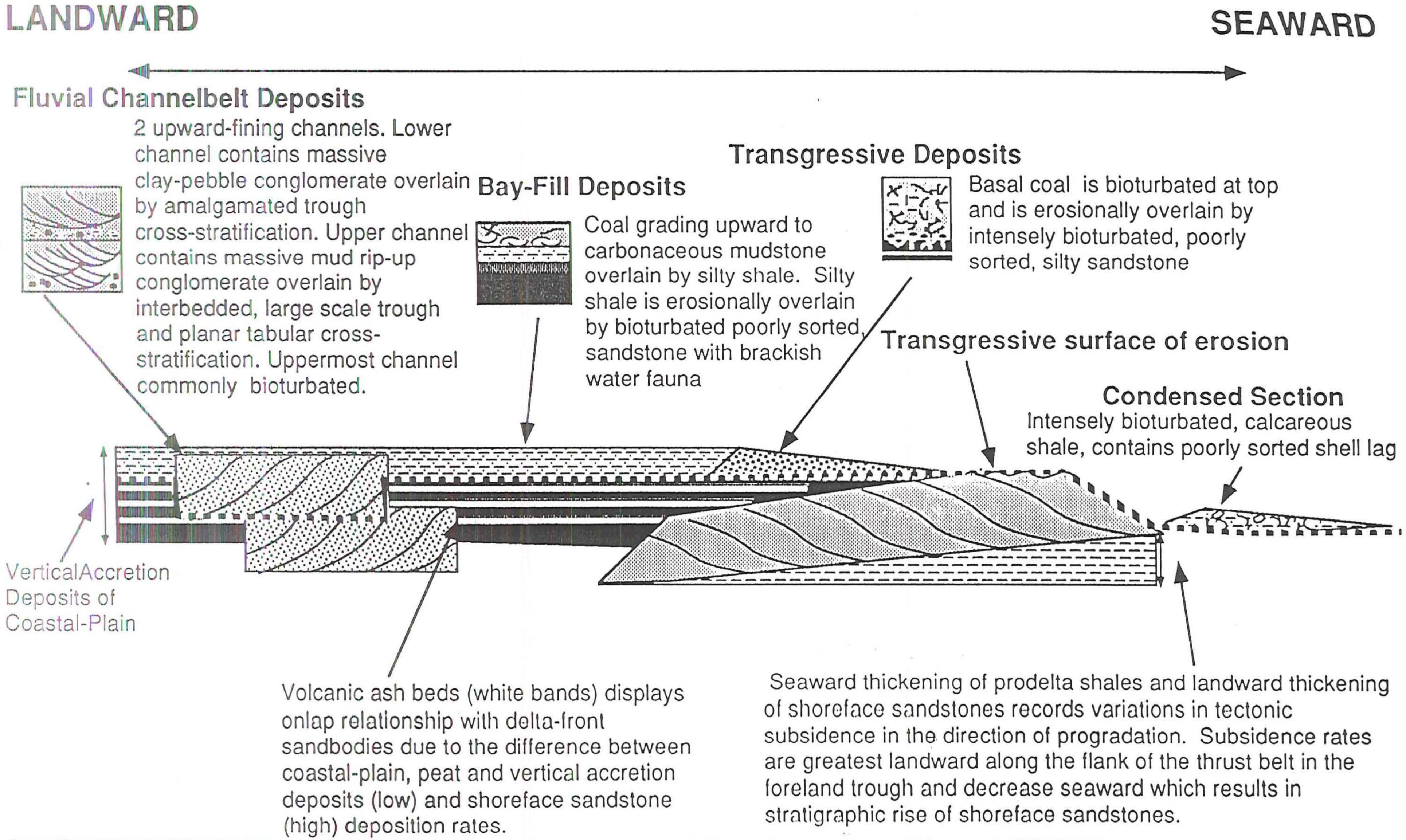


Figure 1. Levels of coastal-plain and fluvial facies heterogeneity to be examined in this study. Similarities in facies characteristics expressed at different levels of facies heterogeneity may facilitate developing key relatiohships between fluvial system responses to relative sea level change.



Fluvial Channelbelt Deposits

2 upward-fining channels. Lower channel contains massive clay-pebble conglomerate overlain by amalgamated trough cross-stratification. Upper channel contains massive mud rip-up conglomerate overlain by interbedded, large scale trough and planar tabular cross-stratification. Uppermost channel commonly bioturbated.

Bay-Fill Deposits

Coal grading upward to carbonaceous mudstone overlain by silty shale. Silty shale is erosionally overlain by bioturbated poorly sorted sandstone with brackish water fauna

Transgressive Deposits

Basal coal is bioturbated at top and is erosionally overlain by intensely bioturbated, poorly sorted, silty sandstone

Transgressive surface of erosion

Condensed Section

Intensely bioturbated, calcareous shale, contains poorly sorted shell lag

VerticalAccretion Deposits of Coastal-Plain

Volcanic ash beds (white bands) displays onlap relationship with delta-front sandbodies due to the difference between coastal-plain, peat and vertical accretion deposits (low) and shoreface sandstone (high) deposition rates.

Seaward thickening of prodelta shales and landward thickening of shoreface sandstones records variations in tectonic subsidence in the direction of progradation. Subsidence rates are greatest landward along the flank of the thrust belt in the foreland trough and decrease seaward which results in stratigraphic rise of shoreface sandstones.

Figure 2. Schematic diagram illustrating the correlation of time-significant surfaces from offshore marine through coastal-plain facies tracts of a single progradational event. Stippled line represents a time-line separating the regressive half-cycle from the transgressive half-cycle. Diagram is based on outcrop data from landward-stepping progradational unit in the Ferron Sandstone near Emery, Utah. Volcanic ash bed relationships were first demonstrated by Ryer and others (1980).

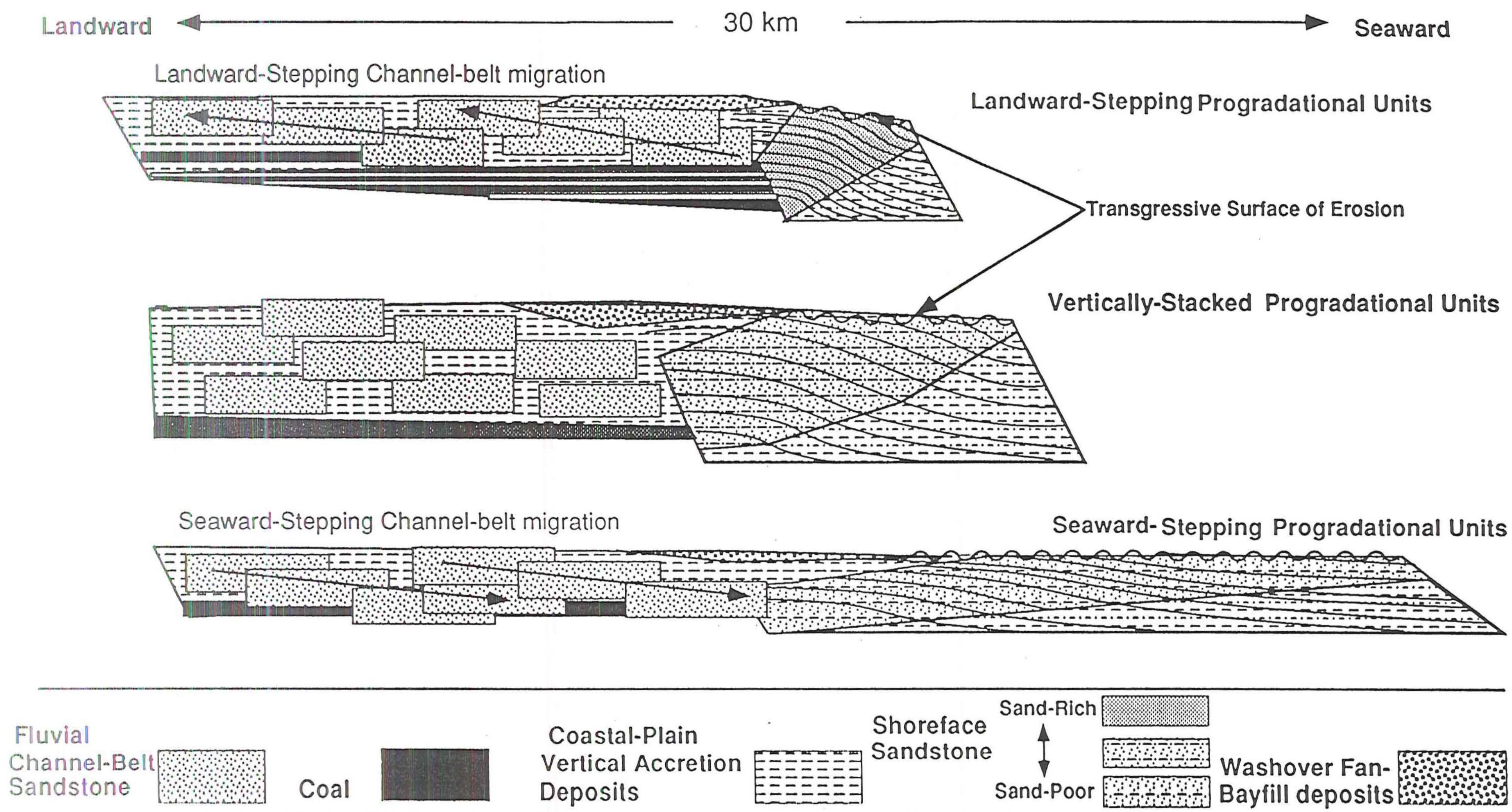


Figure 3. Styles of shallow marine through coastal-plain facies architecture in progradational units that occupy the different geometric configurations that form a hierarchical stacking pattern in the Ferron Sandstone. In seaward-stepping units, channel-belts exhibit a seaward-stepping geometry. Sand-shale ratios are high, facies diversity is low, and channel-belts are highly interconnected. Seaward-stepping shoreface sandstones are thin, laterally extensive, mud-rich and display a high facies diversity. In landward-stepping progradational units, channel-belts exhibit a landward-stepping geometry. Sand-shale ratios are low, facies diversity is high, multiple coal seams are developed and channel-belts are vertically-stacked but poorly interconnected. Landward-stepping shoreface sandstones are thick, laterally restricted, mud-poor and exhibit low facies diversity. Clinoform geometries schematically depict time increments of progradation. Facies tract sediment volume partitioning is expressed as a ratio of shoreface to coastal-plain sandstone. This ratio in seaward-stepping units is 3:1; in vertically stacked units is 2:1; and in landward-stepping units is 1:1. Total sediment volumes are equal in seaward- and landward-stepping units but are doubled in vertically-stacked units.

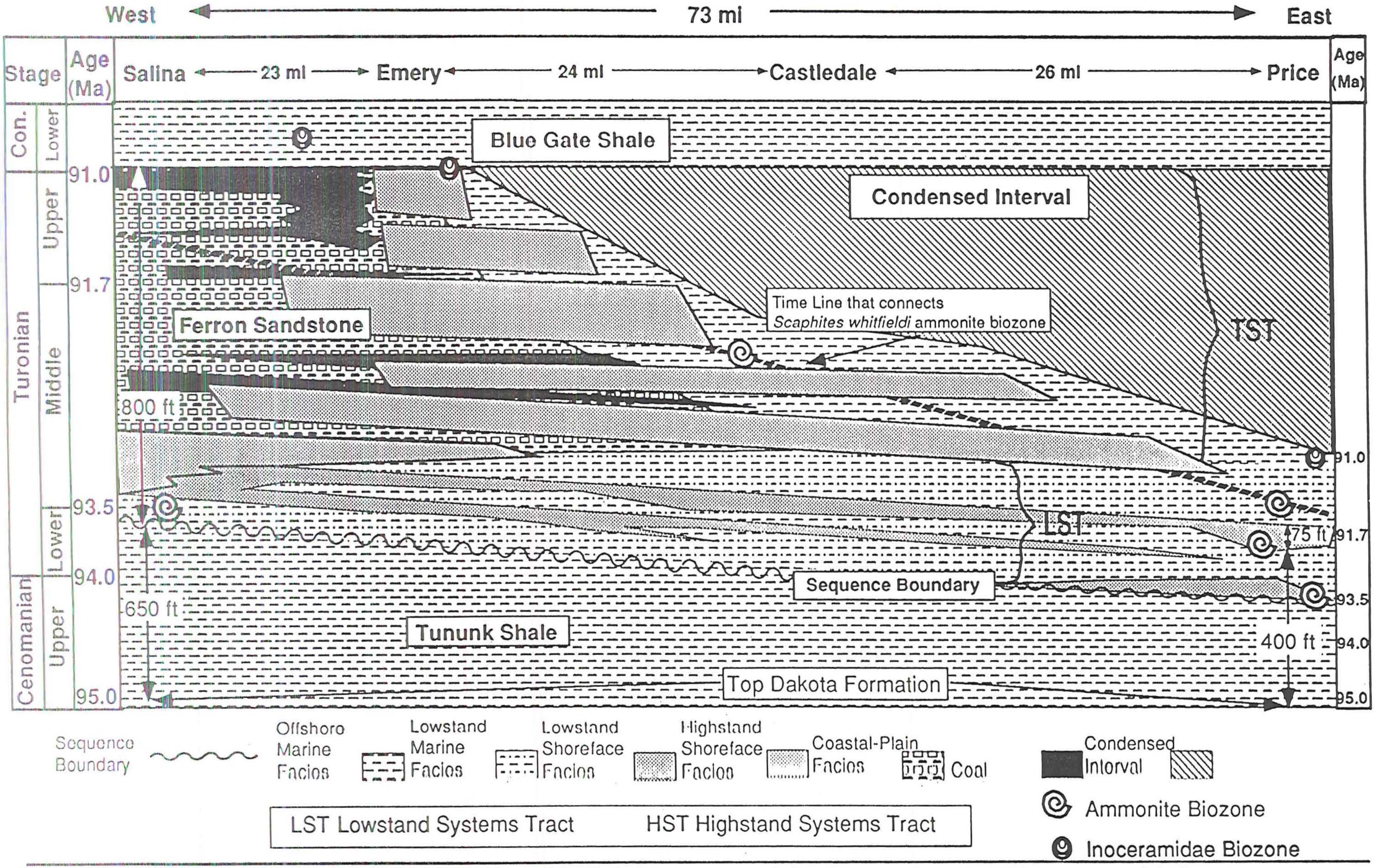


Figure 4. Diagrammatic cross-section from Salina, Utah to Price, Utah showing progradational geometries and stacking patterns of the lowstand and highstand systems tracts in the Ferron Sandstone. The thickness of the Ferron at the landward initation and seaward termination of progradation is scaled to time on the vertical axes of cross section. In contrast to the progradational geometries of the highstand systems, the enigmatic progradational geometries in the lowstand systems tract represent deposition out of the plane of the cross section. The basinward condensation of time lines illustrated by the occurrence of *Scaphites Whitfieldi,* reflects depositional-dip thickness changes due to decreased tectonic subsidence in a basinward direction. Coal-bearing strata are restricted to the highstand systems tract. Diagram based on a synthesis of available literature (Cobban, 1975; Cotter, 1976a,b; Ryer, 1981; Ryer and McPhillips, 1983; Occian and Poelchau, 1985; Kirchbaum, personal communication, 1989) and field results from central Utah.

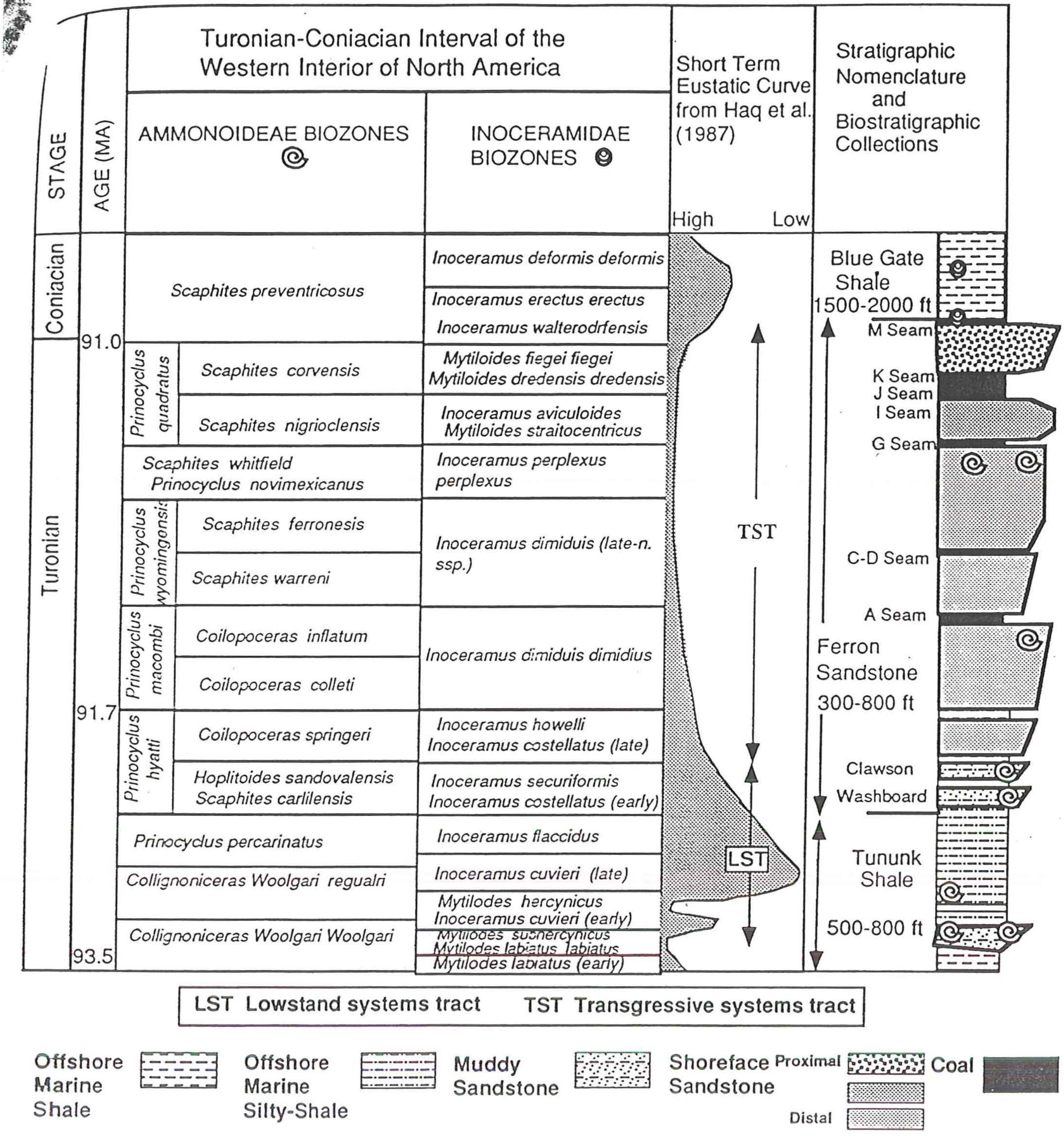


Figure 5. Biostratigraphic chart for the Ferron Sandstone in central Utah (unpublished data from Kauffman and Collom, 1989). Stratigraphic chart shows informal stratigraphic nomenclature and fossil collections from Castle Valley. Haq et al.'s eustatic curve (1987) is approximated from ammonite biozones. Radiometric ages on this chart are based on argon-argon dates from Western Interior volcanic ash beds. These dates do not correspond with potassium-argon dates from Haq et al.'s eustatic sea level chart.

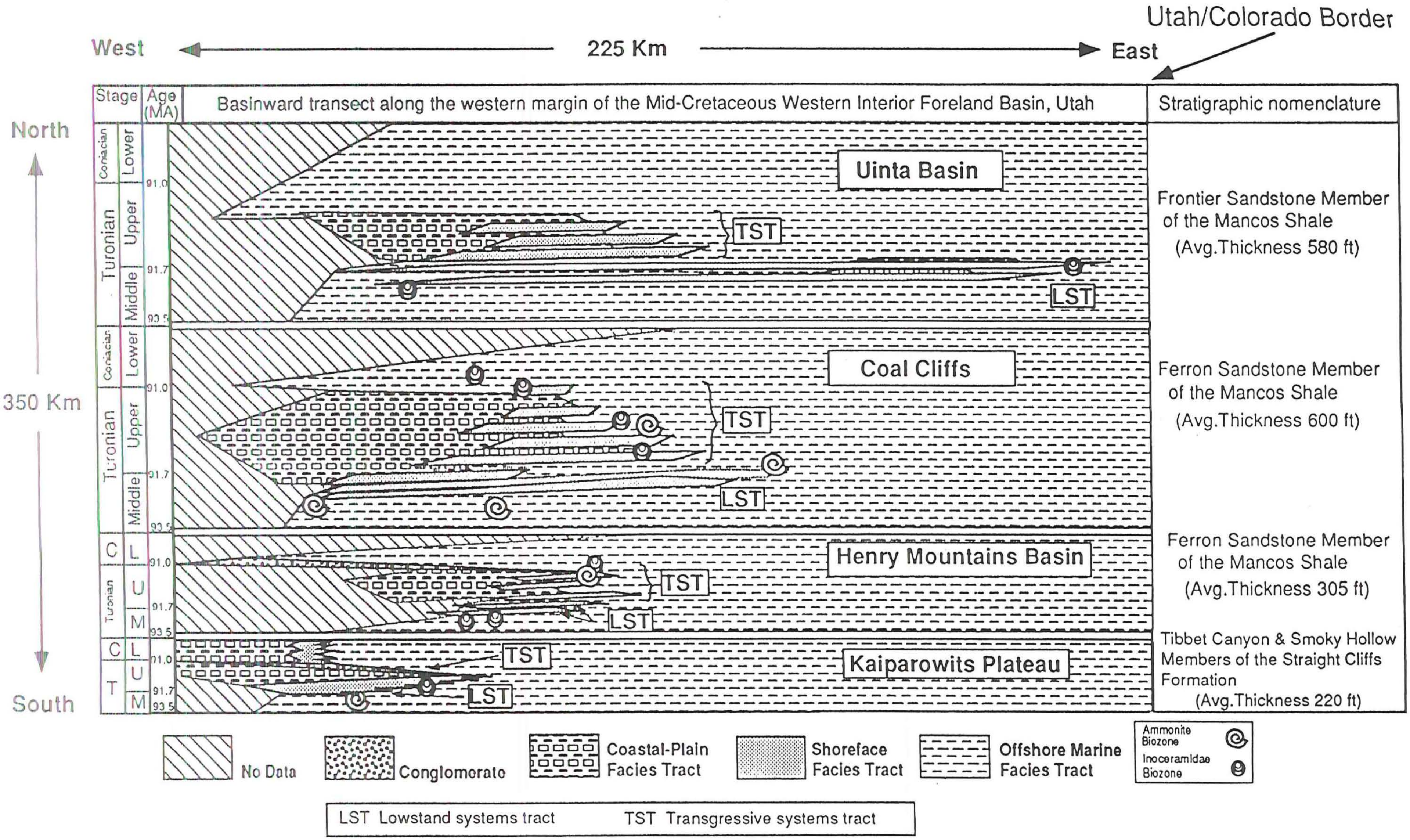


Figure 6. Diagrammatic cross sections across Utah showing successive south to north along-strike changes in thicknesses, progradational geometrics, and stacking patterns of Middle Turonian to Coniacian strandline sequences. Biostratigraphic data constrains the initation and termination of progradation along this transect. Vertical axis represents equal time intervals scaled to average thicknesses in each of the four regions depicted on the basinward cross-sections. Diagram based on a synthesis of available literature and field results from central Utah.

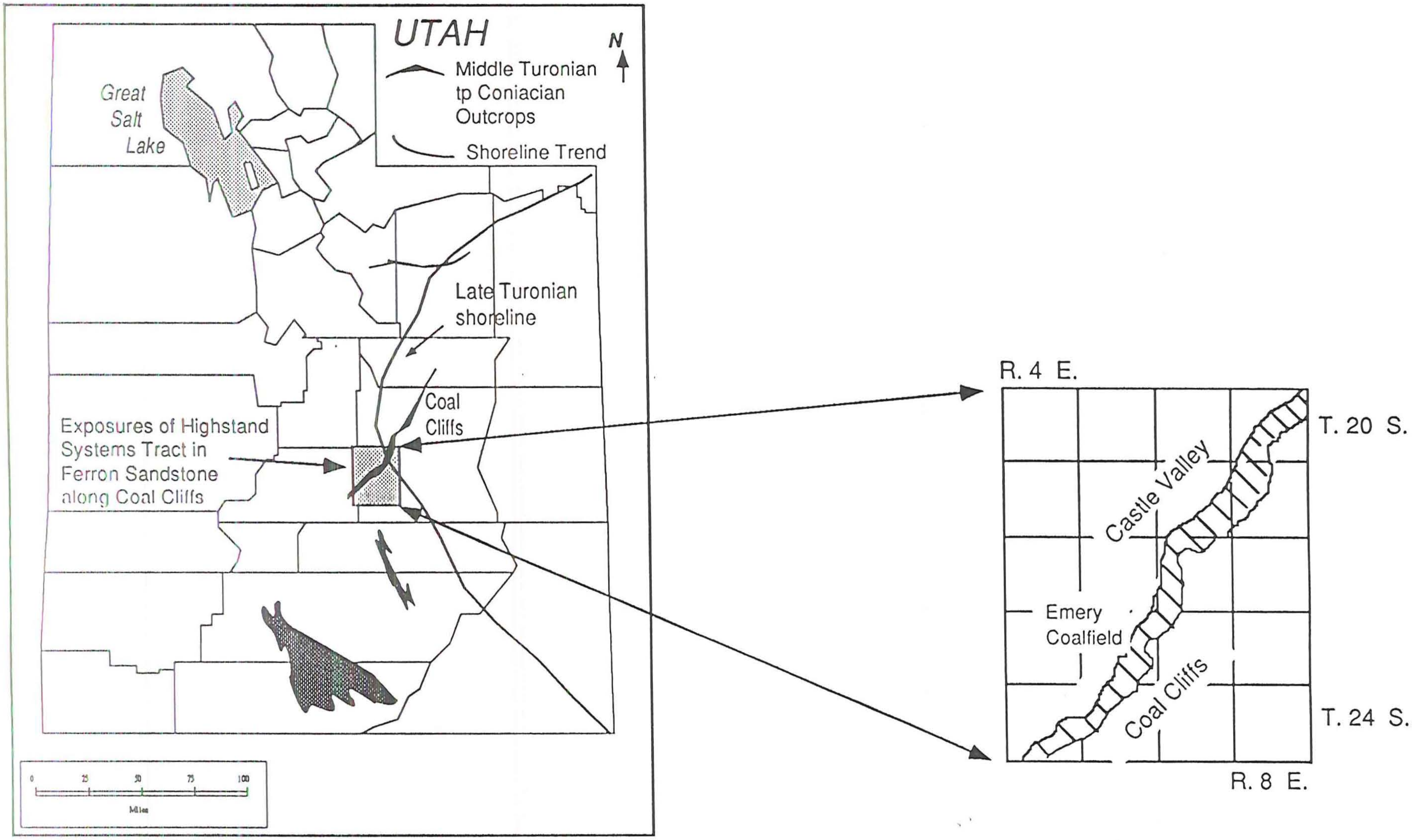


Figure 7. Index map of the state of Utah showing principal exposures of Ferron Fluvial facies to be investigated in this study. The shoreline trace is taken from diagrammatic reconstruction of the paleogeography of Utah during late Turonian time (Ryer and McPhillips, 1983).