Implications for large-scale sea level change in the Turonian Western Interior Seaway: Evidence from the Codell Sandstone, Colorado

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Implications for large-scale sea level change in the Turonian Western Interior Seaway: Evidence from the Codell Sandstone, Colorado

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ABSTRACT

Middle to Upper Turonian strata of the Cretaceous Western Interior Seaway record evidence of a large-scale sea level change. The Codell Sandstone Member of the Carlile Shale, exposed in the Pueblo, Colorado area, consists of two distinct facies that are interpreted to record this sea level change: an upward–coarsening unit interpreted as distal lower shoreface overlain by a heterolithic unit interpreted as estuarine. $^{87}Sr/^{86}Sr$ ratio analyses show an isotopic excursion within the estuarine facies, which is attributed to freshwater input. The surface separating the two facies is interpreted as a sequence boundary and the base of a 10 meter thick incised valley fill. The time equivalent shoreline (highstand) for the lower shoreface strata of the Codell Sandstone Member is placed between central Kansas and central Missouri, 700 to 1100 km east of the study area. Brackish-water strata of the incised valley fill would require a minimum of 700 km lateral translation of the eastern margin of the Cretaceous Western Interior Seaway during deposition of the Codell Sandstone Member. This westward shift in the eastern shoreline resulted from a sea level fall that could have been as little as 30-60 meters.

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INTRODUCTION

The Middle Turonian Codell Sandstone Member of the Carlile Shale, exposed in the Pueblo, Colorado area, is a complicated stratigraphic succession and represents the terminal unit in the well-studied Greenhorn regressive hemicyclothem of Kauffman (1969). This regressive succession records an overall upward-shallowing depositional facies trend, and the unit was deposited near the axis of the Cretaceous Western Interior Seaway (KWIS). Although originally proposed by Kauffman (1969) to record a nearly complete depositional succession of a third order eustatic fall, the majority of regressive successions, like the Greenhorn hemicyclothem, are now recognized to be an incomplete record of sea level fall, punctuated by sequence boundaries. This paper revisits the Codell Sandstone Member to determine how much of the regressive event is missing, the magnitude of sea level fall, and the extent of strandline migration associated with the fall. This was done through facies interpretation of key stratigraphic sections (outcrop and subsurface) and strontium analysis of the strata bracketing this interval.

The Codell Sandstone Member (figure 1) has not been extensively studied since the mid 1980's to early 1990's (Krutak, 1970; Lowman, 1977; Pinel, 1977; Aulia, 1982; McLane, 1982; McLane, 1983; Pinel, 1983; Glenister and Kauffman, 1985; Caraway, 1990). The Codell Sandstone Member is a complex, commonly heterolithic unit with successions of physical sedimentary structures that are rarely diagnostic of a particular facies. Previous interpretations of the depositional setting range from shoreface through beach deposits, a barrier island complex, and offshore marine bar (Krutak, 1970; Lowman, 1977; Pinel, 1977; Aulia, 1982; McLane, 1982; McLane, 1983; Pinel, 1983; Caraway, 1990).

Broad-scale sea level changes recorded in fine-grained strata in the KWIS have been interpreted as transgressive-regressive cycles (Kauffman, 1969; Kauffman et al., 1977). The Codell Sandstone Member represents the termination of the Greenhorn regressive hemicyclothem (Kauffman, 1969; Glenister and Kauffman, 1985). Shoaling is evident from the upper Fairport Chalky Shale Member of the Carlile Shale through the Codell Sandstone Member. The upper Fairport Chalky Shale Member marks the initiation of terrigenous input and becomes decreasingly calcareous upward. Transition to the overlying Blue Hill Shale Member of the Carlile Shale indicates continued basin filling and westward migration of the eastern margin of the seaway through the progradation of facies, resulting in the shoaling of the basin along the eastern margin of the seaway and the dilution of calcareous material with terrigenous material (Witzke et al., 1983; Ludvigson et al., 1994). The Blue Hill Shale Member coarsens-upward before grading into the overlying Codell Sandstone Member. The Codell Sandstone Member marks the termination of regression (Glenister and Kauffman, 1985; White and Arthur, 2005). Lithology, facies, and physical sedimentary structures change throughout the studied interval and record a transition from deep water deposition with the Fairport Chalky Shale Member to shallow water deposition with the Codell Sandstone Member (figure 2; Kauffman, 1969). Although the hemicycle is interpreted to record a gradual westward migration of the eastern shoreline of the KWIS, the exact position of the shoreline is unknown (Williams and Stelck, 1975; Kauffman et al., 1977). With the exception of the Codell Sandstone Member, all Turonian aged strata in Kansas are either pelagic limestones, or calcareous to non-calcareous shales (Kauffman et al., 1977). In addition, strata of the Codell Sandstone Member in Kansas are interpreted as lower shoreface (Glenister and Kauffman, 1985). The Middle Turonian shorelines are placed east of Wichita, Kansas (Williams and Stelck, 1975).

Outcrops of the Codell Sandstone Member near Pueblo, Colorado, have been interpreted as a continuous succession from marginal marine to shoreface deposits based on lithology and facies studies (Krutak, 1970; Pinel, 1977; Aulia, 1982; McLane, 1982). These strata, however, have only been considered in localized context while the magnitude of sea level fall integrated in this study, and shoreline migration, have not been addressed. Although, Kauffman (1969) identified a brackish-water faunal assemblage in the upper part of the Codell Sandstone Member, he did not interpret these facies as overlying a sequence boundary. Krutak (1970) described two distinct facies within the Codell Sandstone Member, displaying upward-shoaling water conditions, interpreted as a continuous succession with multiple and complex lateral facies changes. The upper surface of the Codell Sandstone Member was described by Pinel (1983) as partially lithified by vadose and phreatic carbonate cementation, and potentially representing a period of subaerial erosion. The top of the Codell Sandstone Member is capped by a major regressive event that is represented by a hiatus of two molluscan biozones of Kauffman and Pope (1961). Krutak (1970) interpreted this hiatus as a cessation of deposition, distinguished by a concentration of reworked chordate and invertebrate remains.

A major transgression resulting in the deposition of the Juana Lopez Member of the Carlile Shale signals the termination of the Greenhorn regressive hemicyclothem. The Juana Lopez Member represents the initial transgression of the Niobrara Seaway, known as the Niobrara Transgression (Kauffman et al., 1977; Fisher et al., 1985). McLane (1982) interpreted the Juana Lopez Member as a transgressive episode, distinguished by a transgressive lag of calcareous sandstone and limestone mixed with abraded fossil fragments. This lag deposit is attributed to storm-intensified or storm-generated shelf currents which entrained and winnowed sediment of the upper Codell Sandstone Member (Aulia, 1982). In the study area, this unit is commonly mapped/included with the Codell Sandstone Member, because of its limited thickness (less than 2 m). The Niobrara Formation unconformably overlies the Juana Lopez Member. In places the Juana Lopez Member is missing and the Niobrara Formation unconformably overlies the Codell Sandstone Member.

The KWIS was an epeiric seaway that extended from the Sevier fold and thrust belt in central Utah eastward across Colorado and, at times, across all of Kansas (figure 3). At its western margin, the seaway occupied the Sevier Foreland Basin (SFLB), and to the east, inundated the low lying area of what is informally called the axial basin. Separating the two basins is a structural feature of the SFLB known as the peripheral bulge or forebulge. During times of extreme lowstand conditions, the peripheral bulge may have been exposed subaerially (Kamola and Hoffmeister, 2010; Hoffmeister, 2011). Subaerial exposure along the forebulge designates a complete separation of the seaway into the SFLB and axial seaway. Precedence for subaerial exposure of the forebulge occurs in Alberta and Saskatchewan in correlative strata to the Codell Sandstone Member (Nielsen et al., 2008; Schröder-Adams et al., 2012).

Regional Geology

Regional Extent of the Codell Sandstone

The Codell Sandstone Member of the Carlile Shale was first described by Bass (1926), based on exposures in the valley of the Saline River, southwest of Codell, Ellis County, Kansas (type locality). These exposures crop out almost 500 kilometers east of the study area near the erosional eastern limit of the formation. The easternmost exposures are described as very fine-grained sandstone to thin clayey sandstone (Krutak, 1970; McLane, 1982). The easternmost sections are thought to represent an offshore to offshore transition depositional environment. The

Codell Sandstone Member is traceable through the subsurface to outcrops exposed west of Pueblo, Colorado, at the westernmost depositional limit (figure 4). To the south, the Codell Sandstone Member is traced to Walsenburg, Colorado, and to the north it is traced to Cheyenne, Wyoming. Notably, the Codell Sandstone Member is absent in outcrop and subsurface between Colorado Springs and Denver. Relatively few depositional facies have been described for the Codell Sandstone Member through the mapped extent in western Kansas/eastern Colorado, but complexity increases in south-central Colorado (Krutak, 1970; Hattin, 1975; Kauffman et al., 1977; Glenister and Kauffman, 1985).

FACIES DESCRIPTIONS AND INTERPRETATIONS

The study area contains 4 distinct depositional facies: facies 1 is in the upper Blue Hill Shale Member, facies 2 occurs in the basal exposures of the Codell Sandstone Member, facies 3 occurs in the upper exposure of the Codell Sandstone Member and is subdivided into 4 subfacies to reflect complexity, and facies 4 is found within the Juana Lopez Member. Facies are interpreted from the detailed description of five measured sections and one core (USGS Portland #1, Fremont County, Colorado) in the Pueblo area (figure 5). Grain size is described according to the "American/Canadian Stratigraphic" (Amstrat) grain size card and the Phi scale.

Facies 1 - Blue Hill Shale Member Facies

This facies description is based on the upper 5 meters of exposed Blue Hill Shale Member. The basal Blue Hill Shale Member is poorly exposed in most of the measured sections. The upper part of this facies is typically a poorly laminated, weakly fissile, non-calcareous shale that exhibits an upward increase in silt and sand. The upper 5 meters of this facies is a silty to sandy shale. Coarser sand grains are dispersed throughout the shale; discreet beds of sand and silt are not seen. In outcrop, the Blue Hill Shale Member appears to be amalgamated by bioturbation (bioturbation index of 4-5). Roots, body fossils, and carbonaceous material are absent. The Blue Hill Shale Member-Codell Sandstone Member contact is gradational. Transition to the overlying facies is interpreted where the sand and silt content becomes greater than the mud content. Physical sedimentary structures are not observed in outcrop, but in core include millimeter-scale discontinuous sand stringers and wave-ripple laminae in the upper part of the Blue Hill Shale Member. These continue upward into the overlying facies.

This facies is the distal-most facies in the study area. Where sand grains are dispersed in the shale, the upper Blue Hill Shale Member represents an offshore depositional environment. This interpretation is similar to that of Glenister and Kauffman (1985). Where discreet sand laminae were observed in core, burrowing was more limited, perhaps indicating a stressed environment. The Blue Hill Shale Member grades into the overlying Codell Sandstone Member, where sand/silt content dominates mud content. This gradational change from the Blue Hill Shale Member to the Codell Sandstone Member is attributed to progradation of facies.

Facies 2 - Lower Codell Sandstone Member Facies

This facies is found at the base of the Codell Sandstone Member where it gradationally overlies the Blue Hill Shale Member. This facies consists of two upward-coarsening intervals. The first interval coarsens upward from silty sandstone (4.5 ϕ) at the basal contact with the Blue Hill Shale Member to fine grained sandstone (2.5 ϕ). The second coarsening-upward interval overlies this and initiates with very-fine-lower grained sandstone (3.75 ϕ) to very-fine-upper grained silty sandstone (3.25 ϕ) near the top of the facies. The base of this facies is poorly bedded and poorly exposed. It appears generally bioturbated in outcrop, while in core, this interval is heavily burrowed locally with discontinuous wave-ripple laminae. Grain size increases upward to a maximum grain size of fine-lower (2.75 ϕ) to very-fine-upper (3.25 ϕ) near the top of the facies. The facies shows an upward increase in sorting from the base to the top of the interval. Bioturbation decreases upward to the point where individual traces are easily identifiable. Traces observed include *Chondrites, Cylindrichnus, Ophiomorpha, Rhizochorallium, Teichichnus,* and *Thalassinoides* (figure 6 A-B). The upper portion of this facies contains well-defined beds of sandstone, 20-40 centimeters thick, interbedded with silty-shale, 20-50 centimeters thick; sandstone beds have sharp lower contacts and grade upward into silty-shale. Millimeter-scale mud drapes and centimeter-scale (less than 2 cm) lenticular bedding occur randomly throughout the facies. These sandstone beds pinch and swell, and contain low-angle laminae that give beds a synformal and antiformal appearance similar to hummocky cross stratification. A sharp contact separates facies 2 from overlying strata of facies 3.

The upward increase in sand content and grain size is indicative of prograding facies and upward shoaling. Isolated wave-ripples at the base of the succession indicate limited wave energy or deeper water conditions. Wave energy increases upward as indicated by the presence of hummocky cross stratification (HCS). HCS beds are interpreted as a result of large-scale oscillatory currents, which are typically associated with storm events, and occur solely in the lower shoreface depositional environment (Harms et al., 1975; Dott and Bourgeois, 1982; Southard et al., 1990). HCS beds develop below fair-weather wave base, but in water depths shallow enough for wave orbits to become strong and large while remaining symmetrical (Dott and Bourgeois, 1982). This commonly produces bedsets of sandy synformal and antiformal bed forms with low-angle stratified foresets, interbedded by burrowed fine grained sediment. In the distal lower shoreface, HCS beds are commonly thin (10's of cm) and interbedded with burrowed fine grain material and gradually thicken and amalgamate in more proximal settings (Dott and Bourgeois, 1982). Observations from the lower Codell Sandstone Member show that the depositional environment was shallow enough to form HCS bedding, but deep enough that these beds did not thicken and amalgamate. Strata exhibited in this facies of the lower Codell Sandstone Member are consistent of the distal lower shoreface environment (Dott and Bourgeois, 1982).

Facies 3 - Upper Codell Sandstone Member Facies: Bioturbated Facies, Sandstone Beds with Heterolithic Interbeds Facies, Channelized Facies, Upward-Coarsening Facies

Facies 3 is subdivided into 4 subfacies: subfacies 3.1 is a bioturbated silty-sandstone, subfacies 3.2 is contains sandstone beds and heterolithic siltstone to shale interbeds, subfacies 3.3 is a channelized sandstone, subfacies 3.4 is an upward-coarsening sandstone succession. The subfacies are included together under the heading of facies 3 to represent their vertical relationship with one another in a stratigraphic context.

Subfacies 3.1 - Bioturbated facies

Subfacies 3.1 is heavily burrowed (bioturbation index of 3-4) sandstone. Some individual burrows are easily identifiable and other burrows are nondescript or overprinted (figure 6 C). Unidentified sand filled burrows range from horizontal to vertical, and are up to 20 centimeters in length. Horizontal backfilled burrows on the scale of 1 centimeter in diameter are common throughout the subfacies. Bioturbation obscures most physical sedimentary structures. However, relict crossbeds up to 20 to 30 centimeters thick are recognized. The intense bioturbation results in a mottled and friable appearance to the outcrop, which in general is poorly bedded. Grain size varies from very-fine-upper (3.25 ϕ) to fine-upper (2.25 ϕ), and the subfacies is moderately sorted. Wispy wave-ripple laminae and discontinuous silty to organic laminae account for the majority of physical sedimentary structures observed. A variety of traces were identified, including *Chondrites, Cylindrichnus, Ophiomorpha, Rhizochorallium, Teichichnus,* and *Thalassinoides.* The most abundant traces are *Ophiomorpha and Thalassinoides.* This subfacies accounts for a large portion of each measured section (up to 8 meters in multiple locations). Horizons of calcareous concretions, up to 40 by 40 centimeters in size, commonly occur within this subfacies.

This subfacies is interpreted to be deposited in a low energy protected environment that was dominated by biogenic activity. Limited wave energy is evident by the presence of discontinuous wispy wave-ripple laminae. Intervals of decreased energy also occurred, which allowed for deposition of discontinuous silty to organic laminae. The trace fossil assemblage indicates marine influence. *Chondrites, Rhizochorallium,* and *Teichichnus* are feeding traces that indicate the sediment was rich in organic detritus. This further supports a lower energy setting in which organic material could settle out of the water column.

Subfacies 3.2 – Sandstone beds with heterolithic interbeds facies

This subfacies is laterally variable in character across the outcrop. It contains beds of sandstone and heterolithic beds. It is comprised of up to 30-60 centimeter thick sandstone beds, interbedded with laterally discontinuous beds of siltstone to shale that are up to 10 centimeters thick. Horizontally, sandstone bedsets thin and become more heterolitihic with the addition and of siltstone beds. Locally heterolithic strata are inclined. Inclined surfaces dip at a low angle (less than 5 degrees) and extend across the outcrop face. Sandstone beds contain either planar to low-angle laminations, wave-rippled to flaser-bedded laminae, wave-modified current-ripple laminae (up to 5 cm), or are heavily burrowed. Runzelmarken are locally evident at the contact between sandstone and siltstone beds. Sandstones are moderately to well sorted and range from very-fine-upper (3.25 ϕ) to fine (2.50 ϕ). The lower contact of sandstone beds commonly is accentuated by the presence of millimeter-scale rip-up clasts composed of mudstone, while the upper surface of beds is marked with wave-ripples. *Thalassinoides* and *Ophiomorpha* are the dominant traces; *Rhizochorallium* and *Teichichnus* also occur (figure 6 D-F).

In core, this subfacies appears more heterolithic than in outcrop. Sandstone beds up to 10 centimeters thick are interbedded with siltstone beds which average 5 centimeters or less in thickness, but can be up to 10 centimeters thick. Millimeter-scale clay and silt drapes also occur. Sandstones are very-fine-upper (3.25 ϕ) to fine-lower (2.75 ϕ) and exhibit low-angle laminae. Wave-rippled laminae, some with mud drapes, flaser-bedded laminae, and load structures are common through the interval. Sandstones are commonly burrowed with *Teichichnus*, *Thalassinoides*, and *Ophiomorpha*. *Asterosoma*, *Cylindrictnus*, and *Rhizochorallium* traces are also present within sandstone beds.

The heterolithic character of this subfacies is interpreted to reflect tidal influence (Shanley et al., 1992; Greb and Archer, 1995). This facies records an alternation in energy during deposition of sandstone beds, which reflect higher energy conditions, in contrast to siltstone/shale beds, which indicate a low energy depositional setting. These alternating energy conditions are common in tidally influenced environments and can produce the lateral variability exhibited in this subfacies. The presence of flaser bedding is suggestive of tidal processes.

Millimeter-scale rip-up clasts could indicate proximity to the intertidal zone, sourced by intertidal muds. Rip-up clasts derived from intertidal muds would be fragile and unlikely to survive extended transport. Laterally inclined surfaces are interpreted as lateral accretion surfaces. Their presence indicates that these strata are channel-fill deposits. Wave energy is consistent throughout deposition of the sandstone as seen through the presence of wave-ripple laminae. These channel-fill deposits were subjected to both tidal and wave conditions.

Subfacies 3.3 - Channelized facies

The basal contact of this subfacies is a sharp, locally scoured, surface accentuated by centimeter-scale shell fragments and millimeter-scale rip-up clasts. Locally, sole marks (10-20 cm), gutter casts, and load structures occur along this surface. This subfacies is characterized by sandstone bedsets with complex compound stratification. Beds occur stacked, or isolated, encased in fine-lower (2.75 ϕ) to fine-upper (2.25 ϕ) sandstone and siltstone (4.5 ϕ). Sedimentary structures include planar beds, low-angle bedding, planar-tabular cross stratification, and wave-modified current-ripples. Internal scour and fill structures occur, and are up to 15 centimeters in relief and up to 2 meters wide, and are defined by millimeter-scale rip-up clasts. Beds show rapid lateral transitions between structures. Most beds are wave rippled at their upper surface. Beds can be separated by organic rich, siltstone interbeds up to 10 centimeters in thickness. Locally, beds exhibit lateral shingling which is traced across the outcrop exposure (over 50 meters). Sandstones are well-sorted, with grain size ranging from fine-lower (2.75 ϕ) to fine-upper (2.25 ϕ), which is the largest grain size observed in the Codell Sandstone Member. Traces are limited to *Ophiomorpha* up to 1–1.5 centimeter diameter with well-defined wall structures, and which are both vertical and tangential to bedding. *Thalassinoides* are concentrated at the contact between sandstone and siltstone beds.

This subfacies is interpreted as channelized sandstone with siltstone interbeds. Shell fragments at the basal contact designate proximity to the marine environment. Rip-up clasts indicate a local source of mud chips, perhaps intertidal or flood plain in origin. Complex compound stratification, found throughout this subfacies, are composite structures which indicate a range of depositional processes which occurred over short distances. Complex compound stratification has been described as a tidal indicator by Shanley et al. (1992). Most tidal channels have a sinuous geometry, and the beds which exhibit lateral shingling are interpreted as lateral accretion deposits from point bar deposition within tidally influenced channels. Wave-ripple laminae at the upper surface of individual beds indicate wave energy within this channelized subfacies. The presence of *Ophiomorpha* and *Thalassinoides* are interpreted as marine indicators. The summation of these attributes favor a tidally-influenced channel fill deposit for this channelized subfacies.

Subfacies 3.4 – Upward-coarsening facies

This subfacies exhibits an upward-coarsening sandstone profile from fine-lower (2.75 ϕ) at the base to fine-upper (2.25 ϕ) at the top. Bedding surfaces are laterally consistent across the outcrop. Well-defined 15-20 centimeter thick wedge-shaped cross stratified sandstone beds form bedsets up to 60 centimeters thick. Sandstone bedsets are separated by bioturbated siltstone beds up to 5 centimeters thick. Beds thicken upward from 15 centimeters near the base to 40 centimeters towards top to form bedsets up to 1 meter thick. Locally, rip-up clasts and abraded shell material, including *Inoceramus* fragments, mark the lower surface of individual beds. Most sandstone beds are wave rippled at their upper surface; some ripples are mud-draped.

This subfacies is interpreted as a deltaic environment. The upward-coarsening profile, and the thickening of beds upsection, indicates progradation. The lack of wave-form structures in this subfacies would indicate that the delta prograded into a protected setting, where wave energy was absent.

Facies 4 - Juana Lopez Member Facies

This facies averages one meter in thickness. The basal contact of this facies is sharp and overlain by a .3-.5 meter thick skeletal grainstone replete with rip-up clasts and centimeter-scale abraded shell material. This is overlain by a clean, medium grained (1.75ϕ) sandstone with abraded shell material, cemented with sparry calcite cement. The sandstone is dominated by planar-tabular crossbeds up to 20-30 centimeters thick. No trace fossils were observed in this facies. This facies comprises the Juana Lopez Member in the study area and is not present in all sections. Variations in facies thickness may reflect erosional relief, or micro-paleotopography on the top of the Codell Sandstone Member, or the variation in thickness may be caused by subsequent erosion of deposits associated with transgression of the overlying Niobrara Formation.

The facies is a higher energy deposit than the underlying strata of the Codell Sandstone Member. The sharp basal contact represents an erosional event overlain by the migration of large-scale 2-D megaripples. The lower contact of this facies marks the initial transgression of the Niobrara Seaway (Kauffman, 1977). Regionally, the base of this facies is interpreted as transgressive lag of chert pebbles, shark's teeth, bone fragments, and abraded shell material

(Krutak, 1970, Aulia, 1982; McLane, 1982; Pinel, 1983). The lower contact is described as a regional ravinement surface along an unconformity marked by missing faunal zones (Trexler, 1967; Lowman, 1977; Pinel, 1983; Caraway, 1990). Transgressive lags form by the removal, reworking, and winnowing of sediment (Nummedal, 1990; Riemersma and Chan, 1991). It is not unusual for most, if not all, of a deposit to be removed by the ravinement process (Fischer, 1961; Swift, 1968). That sediment too coarse to be removed by the ravinement process forms the transgressive lag. A lag deposit of one meter, as seen in the Juana Lopez Member, represents the winnowing of a substantially thicker deposit. The original thickness of the Juana Lopez Member cannot be determined. The Juana Lopez Member is interpreted to have formed as a transgressive barform. This interpretation is favored due to the presence of an erosional basal contact overlain by planar-tabular crossbedded sandstone.

STRONTIUM ISOTOPIC SIGNATURE

Samples for strontium isotope analysis were collected from the Codell Sandstone Member and Juana Lopez Member, from both the USGS Portland # 1 core and the Calle del Fuente outcrop. Thin sections were analyzed using cathodoluminescence to determine the degree of diagenetic alteration. Samples chosen for analysis were deemed unaltered diagenetically along with some altered samples as a reference. Samples for the strontium isotope analysis were milled directly from unaltered shell material. Analysis was performed to determine whether the Codell Sandstone Member incised valley strata was subject to freshwater input. Samples were dissolved in 3.5 N HNO_3. Strontium was separated using ion-exchange columns filled with strontium-spec resin at the University of Kansas Isotope Geochemistry Laboratories. Samples were analyzed on the Sector 54 Thermal Ionization Mass Spectrometer (TIMS) in the same laboratory. Isotopic fractionation was corrected using $^{86}Sr/^{88}Sr = 0.1194$ and an exponential correction. Isotope ratios were adjusted to correspond to a value of 0.710248 on NBS987 for $^{87}Sr/^{86}Sr$ (external precision was 3ppm on ratio on standards during the duration of analyses) to be consistent with the McArthur and others (2001) normalization.

The majority of the samples record an $^{87}Sr/^{86}Sr$ ratio that is slightly elevated from normal marine deposition (table 1; McArthur et al., 2001). The values collected range from 0.707331 to 0.707377. Normal marine values for this time frame, 90.98 Ma to 90.43 Ma, range from 0.707310 to .0707288 (McArthur et al., 2001).

Two of the samples show an excursion that is interpreted to be consistent with a freshwater input signature based on the guidelines of McArthur and others (1994) and Sessa and others (2012). The "K_C 1" sample was collected from the Codell Sandstone Member (facies 3.4), just below the Codell Sandstone Member-Juana Lopez Member contact at the Calle del Fuente outcrop, and had a signature of 0.707899. This value is higher than is expected in a normal marine setting, but is not high enough for a fluvial signature. "K_C 1" is interpreted to represent a brackish-water setting following the guidelines established by McArthur and others (1994). Sample "E099-276.8" was collected from the USGS Portland # 1 core in the interpreted facies 3.1. With an $^{87}Sr/^{86}Sr$ ratio of 0.708936, sample "E099-276.8" is substantially above what is considered to be a normal marine signature for this time period. This value is consistent with ratios recorded from fluvial sources (McArthur et al., 1994; Sessa et al., 2012). Sample "E099-276.8" however was deemed to be diagenetically altered. Dean and Arthur (1998) suggested that samples from this interval in the Niobrara Formation retain their original strontium values despite appearing diagenetically altered under cathodoluminescence. This theory is consistent with the normal marine value recorded, 0.707331, from sample "E099-260.6", another diagenetically altered sample.

STRATIGRAPHIC CONTEXT

Sequence Stratigraphy

Facies were correlated using the base of the Niobrara Formation as a stratigraphic datum (figure 7). The distal lower shoreface facies (facies 2 - Lower Codell Sandstone Member Facies) records two progradational successions separated by a flooding event. These are interpreted as parasequences, which are progradationally stacked. This interpretation is based on the observation that the deepest water deposits of the overlying parasequence are shallower than the deepest water deposits of the basal parasequence. These parasequences are separated by a parasequence boundary, which can be correlated throughout the measured sections. Deposits of these parasequences represent distal facies near the seaward extent of the storm-wave base. The distal lower shoreface facies of the lower Codell Sandstone Member and the Blue Hill Shale Member (facies 1) are interpreted to be part of the highstand systems tract.

Correlation of facies 3 and its relationship to the underlying facies 1 and 2 allows all facies to be placed in stratigraphic context. Facies 3, with subfacies 3.1-3.4, preserves the complex interaction between tidal, channelized, low-energy facies, and deltaic facies, and represents a complicated depositional environment. The lower contact of these facies successions is an erosional contact and is interpreted as a regional erosion surface. Locally this surface is marked with a lag of abraded shell material and rip-up clasts. This surface overlies distal lower shoreface deposits (facies 2). The juxtaposition of this complex succession with that of distal lower shoreface facies is interpreted to define a regional surface of base-level fall (figure 8) resulting in a basinward shift in facies. Truncated hummocky cross-stratified beds are evidence of incision along the proposed sequence boundary. The surface of incision marks the development of an incised valley. The incised valley fill is recognized by the facies association of subfacies 3.1-3.4, overlying distal lower shoreface deposits. The proposed sequence boundary marks the change from highstand to lowstand conditions. Truncation of distal lower shoreface deposits occurred during a sea level fall, which carved an incised valley, the base of which is seen as sequence boundary 1 on figure 7. As sea level rose the incised valley was flooded, producing an estuarine setting and resulting in the deposition of facies 3. The subfacies 3.1-3.4 succession is interpreted as the shelf expression of the lowstand systems tract. An estuarine interpretation for facies 3 is supported by observations purported by previous studies in this region (i.e. Krutak, 1970; McLane, 1982; Pinel, 1983). Estuary systems are heterogeneous and are difficult to fit to any specific model (Brownridge and Moslow, 1991; Dalrymple et al., 1992; Allen and Posamentier, 1993); their interpretation is tied to stratigraphic juxtaposition as well as facies associations.

The tidally dominated estuarine model of Dalrymple and others (1992) is divided into three distinct parts: a marine- and tidal-influenced lower estuary where tidal sand bars and upper-flow-regime sand flats dominate, a salt- and freshwater tidal mixing zone in the middle estuary, and a fluvial dominated upper estuary. The model of Dalrymple and others (1992) serves as a basic guide in determining depositional position (lower, middle, or upper estuary) within the estuary based on influence of tide, wave, and fluvial processes.

The intricate vertical and lateral facies relationships within the Codell Sandstone Member are best explained when placed in an estuarine facies/incised valley system. Bioturbation in subfacies 3.1 is interpreted to occur in a protected area within the tidal mixing zone of the middle estuary or possibly lower estuary. The middle estuary consists of fine-grained sand and mud interbeds that are dominated by tidal processes; bioturbation may disrupt and mix interbeds beyond recognition. Bioturbation is commonly used as a salinity change indicator from marine- to brackish- to fresh-water; such as a fresh- and saltwater tidal mixing zone of an estuary (Howard and Frey, 1975). Subfacies 3.2 is interpreted to occur in a setting similar to the middle estuarine heterolithic channel facies outlined by Greb and Martino (2005). The heterolithic channel facies is identified by scour-based, burrowed to weakly-bioturbated, inclined heterolithic strata (Greb and Martino, 2005). Subfacies 3.2 shows sharp- to gradational-based heterolithic strata that are burrowed and locally inclined. Subfacies 3.3 is interpreted to occur in a mixture of both middle estuarine and upper estuarine facies. The upper estuarine channel facies of Greb and Martino (2005) is characterized by planar crossbeds that are locally interbedded with flaser- to lenticular-bedded sandstones. The presence of planar beds, low-angle bedding, planar-tabular cross stratification, and wave-modified current-ripples in association with lateral accretion in subfacies 3.3 is interpreted to indicate fluvial influence similar to the upper estuarine channel facies. However, wave-rippled surfaces found in this subfacies indicate that tidal and wave processes are still present. These processes in a channelized setting may indicate a large tidal range or a weak fluvial input. Subfacies 3.4 is interpreted to have prograded into a protected portion of the upper estuary producing a deltaic succession analogous to a lagoon- or bay-head delta. An upward-coarsening profile and the thickening of beds upsection indicate a progradational event similar to a deltaic complex. This subfacies is included in the incised valley fill due to its stratigraphic relationship to the other outcrops and the presence of brackish water indicating strontium isotopes.

The estuarine valley fill of the Codell Sandstone Member is overlain by a second regional erosion surface (sequence boundary 2 on figure 7). Sequence boundary 2 has been described by previous researchers (Trexler, 1967; Kauffman et al., 1977; Mclane, 1983; Pinel, 1983; Krutak, 1996). Glenister and Kauffman (1985) interpreted this surface as a subaerial erosion event and described the presence of tree roots along this horizon. This surface is interpreted to record a fall in base-level and exhibits erosional relief of one meter within the study area and two meters regionally (Krutak, 1996). This surface is overlain by a transgressive surface that formed during a subsequent base-level rise (Aulia, 1982; McLane, 1982). The Juana Lopez Member is thought to represent a transgressive systems tract. It is underlain by lowstand deposits in the Codell Sandstone Member and overlain by a flooding surface. This flooding surface initiates a return to highstand conditions with the deposition of the Fort Hays Member of the Niobrara Formation.

Incised Valley

The Codell Sandstone Member displays a laterally varying thickness, which has previously been attributed to seafloor topographic variations in the depositional area (Krutak, 1970; Pinel, 1977; McLane, 1982; Aulia, 1982). These topographic variations were interpreted to be responsible for the juxtaposition of marginal marine (lagoon) deposits with that of lower shoreface and middle shoreface deposits (Krutak, 1970; McLane, 1982). Krutak (1991) later reinterpreted the upper facies of the Codell Sandstone Member as marine sandstone in a scour depression, or valley. However, a sequence boundary has not previously been designated.

Other large scour surfaces are described in the Codell Sandstone Member and time equivalent strata in northern Colorado and Wyoming (Kennedy, 1983; Weimer and Sonnenberg, 1983; McGookey et al., 1972; Larue, 1995). These units include the upper Sage Breaks Member, the middle Turner Sandstone Member, and the lower Pool Creek Member; all are members of the Carlile Shale. The Sage Breaks Member is the top unit of the Carlile Shale and is unconformable overlain by the Niobrara Formation. In Codell Sandstone Member and Juana Lopez Member time equivalent strata of Wyoming, Larue (1995) described multiple northward deepening incised valleys along the Niobrara Formation-Carlile Shale contact and within the Carlile Shale. These valleys have a common trend to the NNW and are incised up to 46 meters. The incised valleys described by Larue (1995) are thought to have formed subaerially. Additional sequence boundaries, not included in the study, are thought to occur within the Turner Sandstone Member, the Wyoming equivalent of the Juana Lopez Member and Codell Sandstone Member (Larue, 1995; Merewether et al., 2007). The Turner Sandstone Member is described as upward-coarsening sands consisting of lower shoreface deposits and incised valley fill (Merewether et al., 1979; Larue, 1995). Weimer and Flexer (1985) interpreted the Turner Sandstone Member as brackish to marine and tidal flat to estuarine valley fill (Merewether et al., 2007).

Time-equivalent strata in southern Alberta and southwestern Saskatchewan, Canada, record the same sea level fall described for the Codell Sandstone Member. A bentonite marker bed occurs at the base of the Verger Member and in the lower Fort Hays Member. This bentonite has been dated (^{40}Ar-^{39}Ar) at 89.19 Ma± 0.51 and 89.40 Ma± 0.31 (Nielsen et al., 2003). The base of the Niobrara Formation in central Colorado is dated at 89.3 Ma and 88.9-88.1 Ma in northwestern Kansas (Merewether et al., 2007). The Carlile Formation in Alberta and Saskatchewan is informally subdivided into an upper, middle, and lower unit; the upper unit is time-equivalent to the Codell Sandstone Member (Nielson et al., 2008). An erosional surface between the Carlile Formation and the Verger Member is interpreted as a subaerial exposure surface (Plint and Kreitner, 2007; Nielsen et al., 2008; Schröder-Adams et al., 2012). This erosional surface is coeval with the unconformable surface between the Juana Lopez Member and the Niobrara Formations (Merewether et al., 2007; Nielsen et al., 2008). The erosion surface in Alberta and Saskatchewan was defined as a subaerial exposure surface using a combined chemostratigraphic and biostratigraphic approach. This approach includes the use of total organic carbon, evidence of benthic and planktonic foraminifera, carbon isotopes from multiple studies, sea level curves, and lithology. This method was applied to Middle Albian to Late Santonian age strata. Over the studied time frame, there were six separate events that were interpreted to represent subaerial exposure, and surfaces of sea level fall. One of the described events, sequence boundary 5, represents missing section from the Middle Turonian to the Middle Coniacian and encompasses the sequence boundaries described in this study. In all six events, sea level fall was sufficient enough to expose the forebulge of the associated foreland basin.

Shoreline Migration

At the highstand of the Greenhorn hemicyclothem (Lower Turonian), the eastern shoreline of the KWIS was located between central Missouri and the Kansas-Missouri border (Williams and Stelck, 1975). During the Greenhorn regressive hemicyclothem, the eastern shoreline began to migrate to the west. Following peak highstand conditions of the Greenhorn hemicyclothem, deep water conditions prevailed in the study area, as indicated by the Fairport Chalky Shale Member. The gradational upward-shoaling observed in the overlying Blue Hill Shale Member reflects a slight shallowing in water depth and westward progradation of the eastern shoreline of the KWIS. The exact position of the shoreline at this time, however, has not been established. Lower to Middle Turonian strata in Kansas are consistently deeper water facies indicating the shoreline is still east of central Kansas. Cretaceous strata are not preserved east of central Kansas. The easternmost exposures are described as very fine-grained sandstone to thin clayey sandstone (Krutak, 1970; McLane, 1982). The easternmost sections are thought to represent an offshore to offshore transition depositional environment. The presence of marginal marine deposits with brackish- and freshwater strontium isotope values in the study area indicates a rapid westward shift in the eastern shoreline to the Pueblo area. Based on this study, this rapid shift in shoreline is interpreted to result from the sea level fall documented within the Codell Sandstone Member (sequence boundary 1 on figure 7). The full extent of this sea level fall during this event is still undetermined, however, it is significant enough to have caused this westward shift in the eastern shoreline. The distance from the interpreted position of the Greenhorn highstand shoreline to the outcrops (lowstand shoreline shown on figure 9) measured during this study is between 700 and 1100 kilometers. A sea level fall and shoreline shift of this nature would suggest that a substantial portion of the regressive hemicyclothem is missing.

Falling sea level and westward migrating shorelines are recorded in the facies and lithology associations exhibited through the Carlile Shale vertical succession. Glenister and Kauffman (1985) describe both the Fairport Chalky Shale Member and the Blue Hill Shale Member as roughly thirty meters thick in the Pueblo area. Measured sections from this study show that the Codell Sandstone Member deposits are on average less than thirty meters thick in the study area. Depositional environments interpreted for outcrop exposures of the Codell Sandstone Member in Kansas are similar to those proposed for exposures for the lower Codell Sandstone Member in the Pueblo area (Hattin, 1975; Kauffman et al., 1977; Krutak, 1970;

Glenister and Kauffman, 1985). Both reflect progradation across a low gradient surface, which would have resulted in laterally widespread facies seen in the Carlile Shale.

Paleowater depths for the KWIS are difficult to determine. Kauffman and others (1977) interpreted the deposits of both the Fort Hays Member and the Bridge Creek Member of the Greenhorn Formation to be indicative of maximum transgression. Hattin (1981) postulated that the Fort Hays Member of the Niobrara Formation was deposited in water that was no less than 15 meters and no more than 50 meters deep. Kauffman (1967) interpreted the Bridge Creek Member was deposited in water that was no deeper than approximately 150 meters and as little as 30-60 meters based on faunal assemblages and benthic communities. Other interpretations assume a deeper seaway and range widely from 30 meters to greater than 600 meters (Eicher, 1969; Asquith, 1970; Kauffman, 1967; Kauffman, 1984; Winn et al., 1987). Sageman and Arthur (1994) proposed a range of 150 to 300 meters for the Greenhorn highstand water depth in the Early Turonian (i.e. the Bridge Creek Member). This range was calculated from a literature review of lithofacies which were assigned approximate depths based on modern shelf equivalents. To determine the magnitude of sea level fall associated with the sequence boundary in the Codell Sandstone Member, the conservative sea level interpretation (30-60 meters) of Kauffman (1967) will be used.

If the Bridge Creek Member were deposited in 30-60 meter deep water, this would suggest that overlying members of the Carlile Shale were deposited in water shallower than 30-60 meters. This is inferred from the introduction of clastics and increasingly shoaling facies between the Bridge Creek Member and the Codell Sandstone Member. The amount of sea level fall from the deposition of the highstand strata of the Bridge Creek Member to the lowstand strata of the Codell Sandstone Member could have been as little as 30-60 meters. Van Wagoner and others (1991) showed that sea level falls of 30 meters were probably common in the KWIS, based on strata from the western margin of the seaway. This sea level fall is followed by a more substantial sea level fall at the base of the Juana Lopez Member (sequence boundary 2 on figure 7), and may be a precursor to this larger sea level fall.

CONCLUSIONS

The Codell Sandstone Member of the Carlile Shale near Pueblo, Colorado is separated into two distinct facies: a distal lower shoreface facies at the base of the member and an estuarine facies association at the top of the member. The estuarine facies association is composed of complex relationships of bioturbated, heterolithic, channelized, and deltaic facies. Estuarine strata are classified based on their position within the estuary, which is determined by the degree to which each facies is influenced by marine, tidal, and fluvial processes. These facies overlie a sequence boundary and comprise an incised valley fill that is up to 10 meters thick in the study area. $^{87}Sr/^{86}Sr$ ratios collected from the study interval show the presence of fluvial to brackish-water input within the incised valley fill. The incised valley fill is overlain by a well-known sequence boundary that serves as the contact between the Codell Sandstone Member and the overlying Juana Lopez Member. The Carlile Shale records a westward migration of the eastern shoreline of the KWIS through the upward-shoaling sediments of the Fairport Chalky Shale Member, Blue Hill Shale Member, and the Codell Sandstone Member. The eastern shoreline of the KWIS is interpreted to have shifted 700 to 1100 kilometers from early Middle Turonian to the end of the Middle Turnonian. The majority of this shoreline translation occurred during the sea level fall recorded within the Codell Sandstone Member. This shift occurred during a sea level fall that could have been as little as 30-60 meters. A sea level fall of this magnitude, associated with a significant shift in shoreline, suggests that the sea floor was of low gradient over large distances. It also indicates that a significant portion of the Greenhorn regressive hemicyclothem is missing.

FIGURES AND TABLES

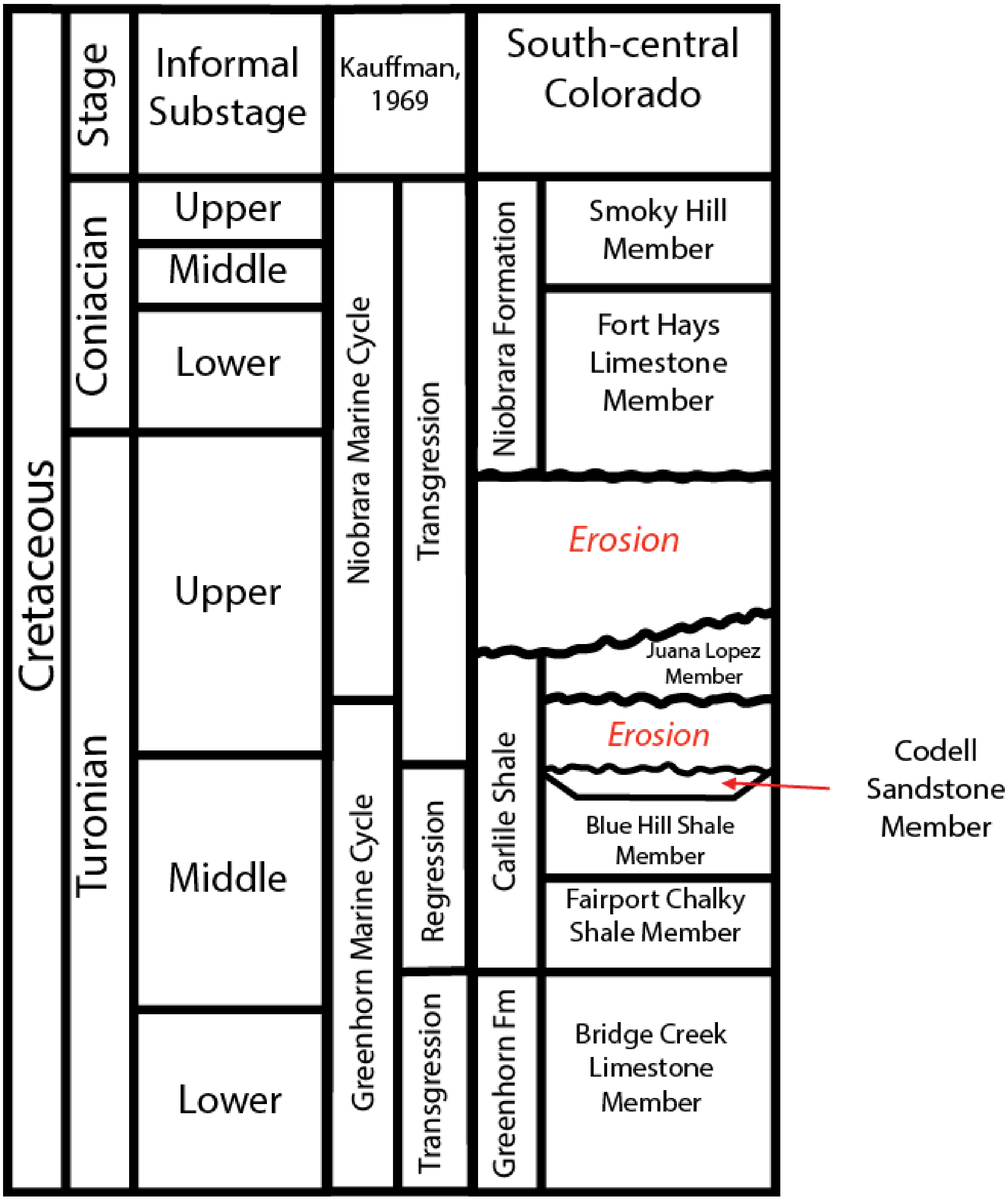

Figure 1. Stratigraphic column for the Turonian and Coniacian stata of south-central Colorado [modified from Merewether et al. (1983) and Kauffman (1969)].

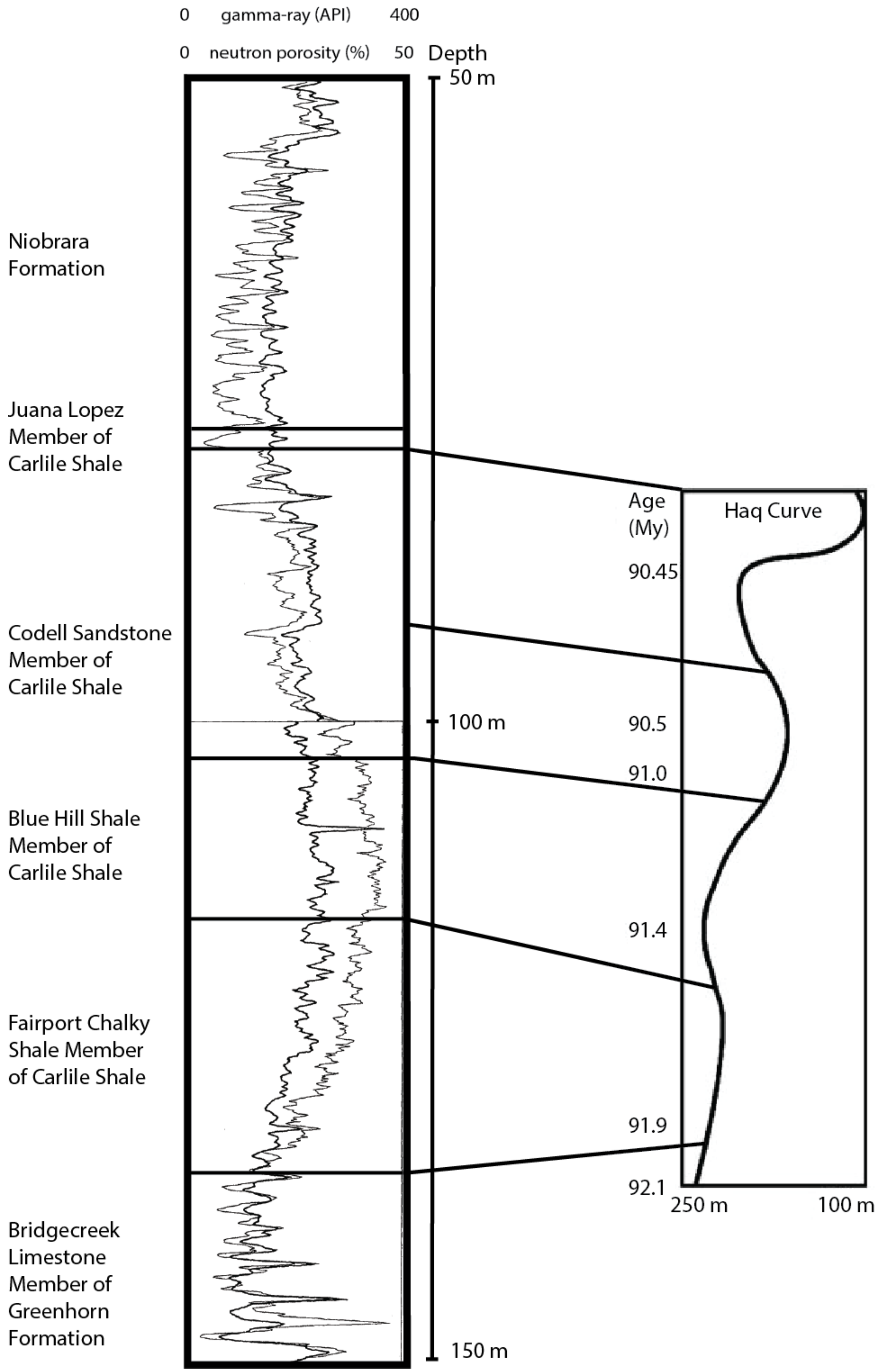
0 gamma-ray (API) 400
0 neutron porosity (%) 50
Depth
50 m
100 m
150 m
Niobrara Formation
Juana Lopez Member of Carlile Shale
Codell Sandstone Member of Carlile Shale
Blue Hill Shale Member of Carlile Shale
Fairport Chalky Shale Member of Carlile Shale
Bridgecreek Limestone Member of Greenhorn Formation
Age (My)
Haq Curve
90.45
90.5
91.0
91.4
91.9
92.1
250 m
100 m

Figure 2. Gamma Ray (bold line) and Neutron Porosity (fine line) well log from the upper part of the Greenhorn Formation to the lower part of the Niobrara Formation, taken from the USGS Portland #1 core. This figure records the Greenhorn regressive cycle, showing that the change in sea level is generally falling. Correlation of strata to the Haq and others (1987) sea level curve was modified from a similar correlation interpreted by White and Arthur (2005).

Figure 3. Paleogeographic map showing the potential position of the eastern shoreline for the Early Turonian KWIS. The blue line represents the position of the Greenhorn highstand shoreline (Williams and Stelck, 1975). The red line represents the inferred position of the eastern shoreline for the *Watinoceras coloradoense* biozone and the purple line shows the eastern limit of preserved Turonian strata (Sageman and Arthur, 1994).

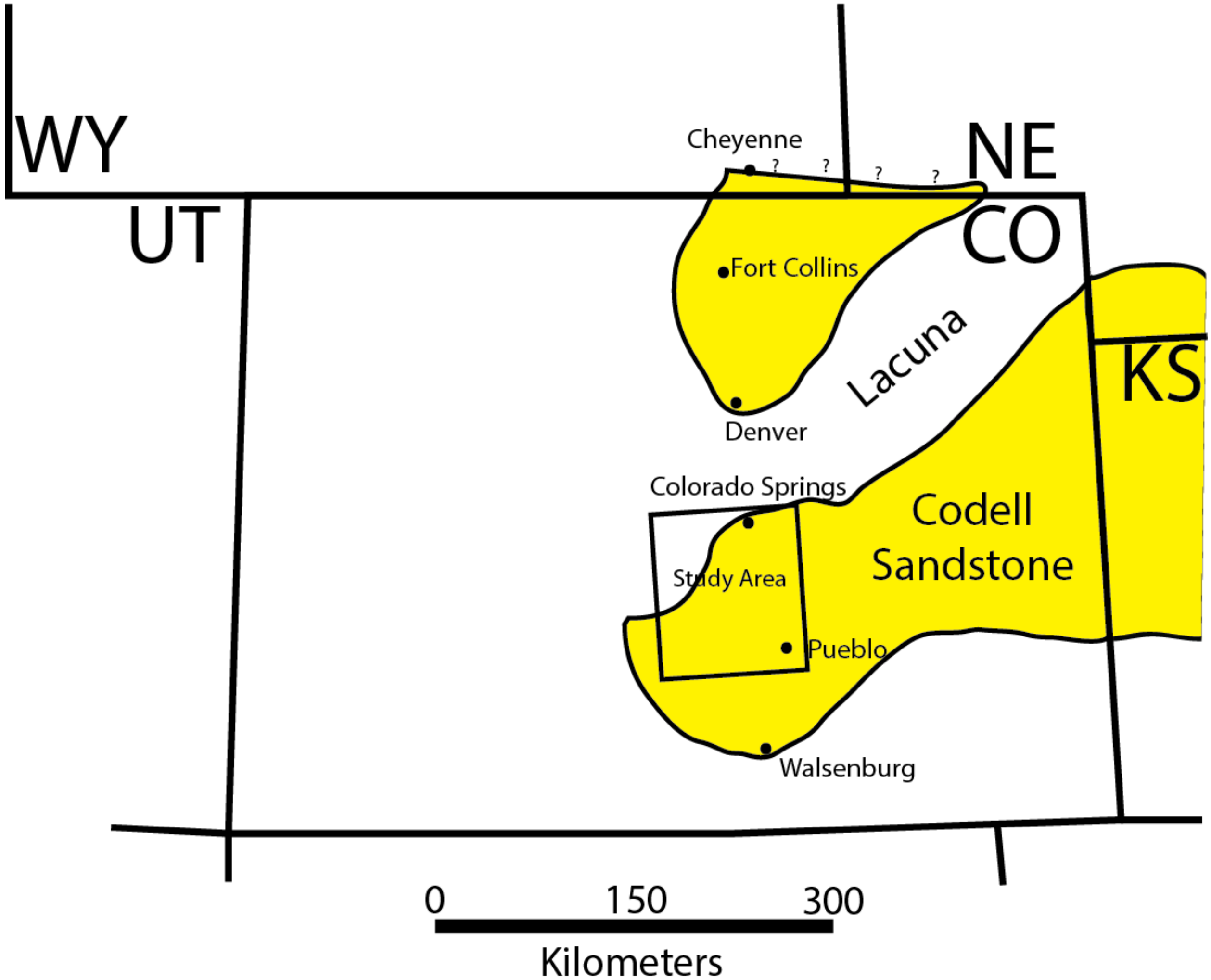

Figure 4. Map showing the areal extent of the Codell Sandstone Member with the location of the study area [modified from Merewether et al. (1983)].

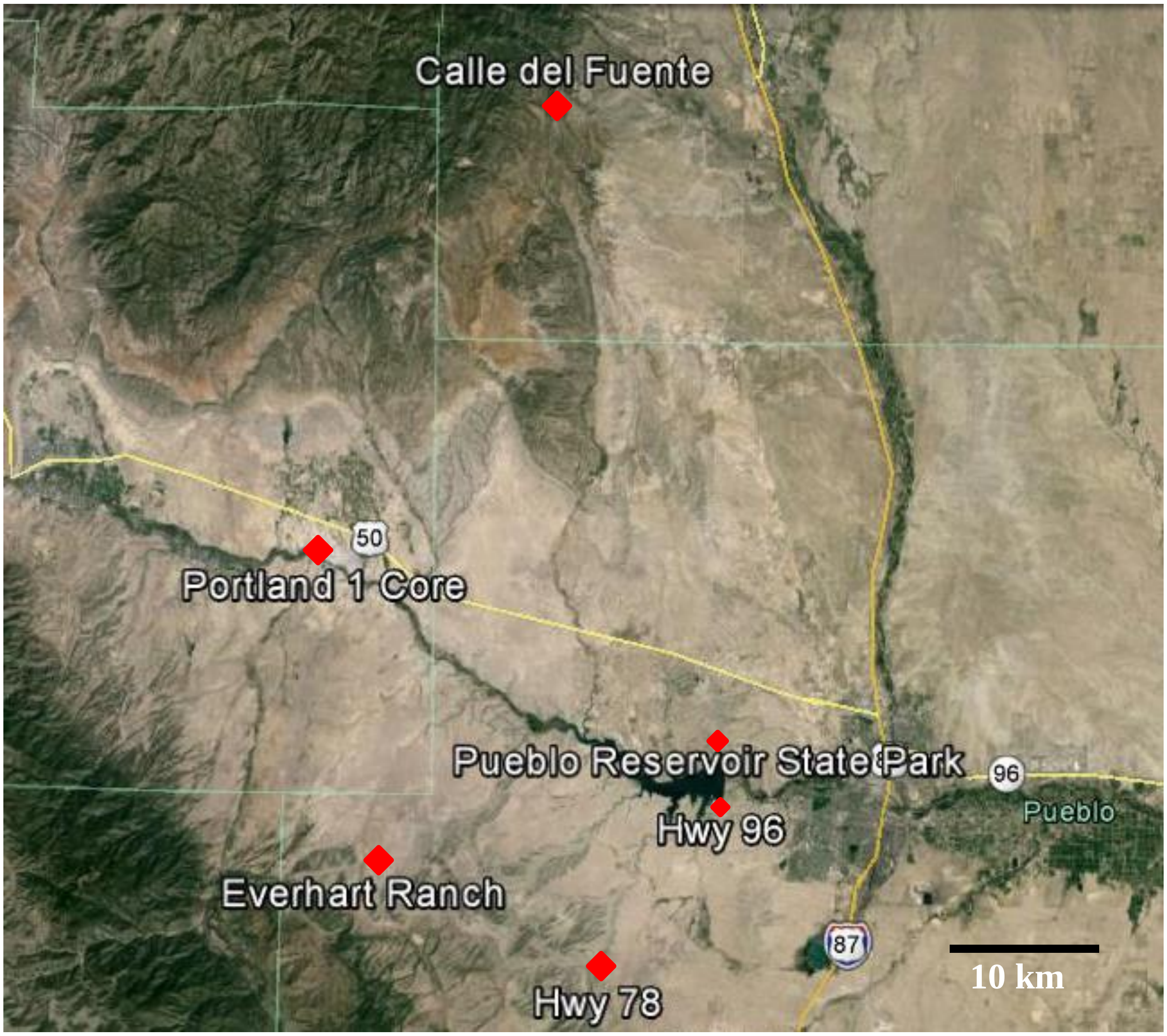

Figure 5. Google Earth image showing the location of the measured sections described in this study.

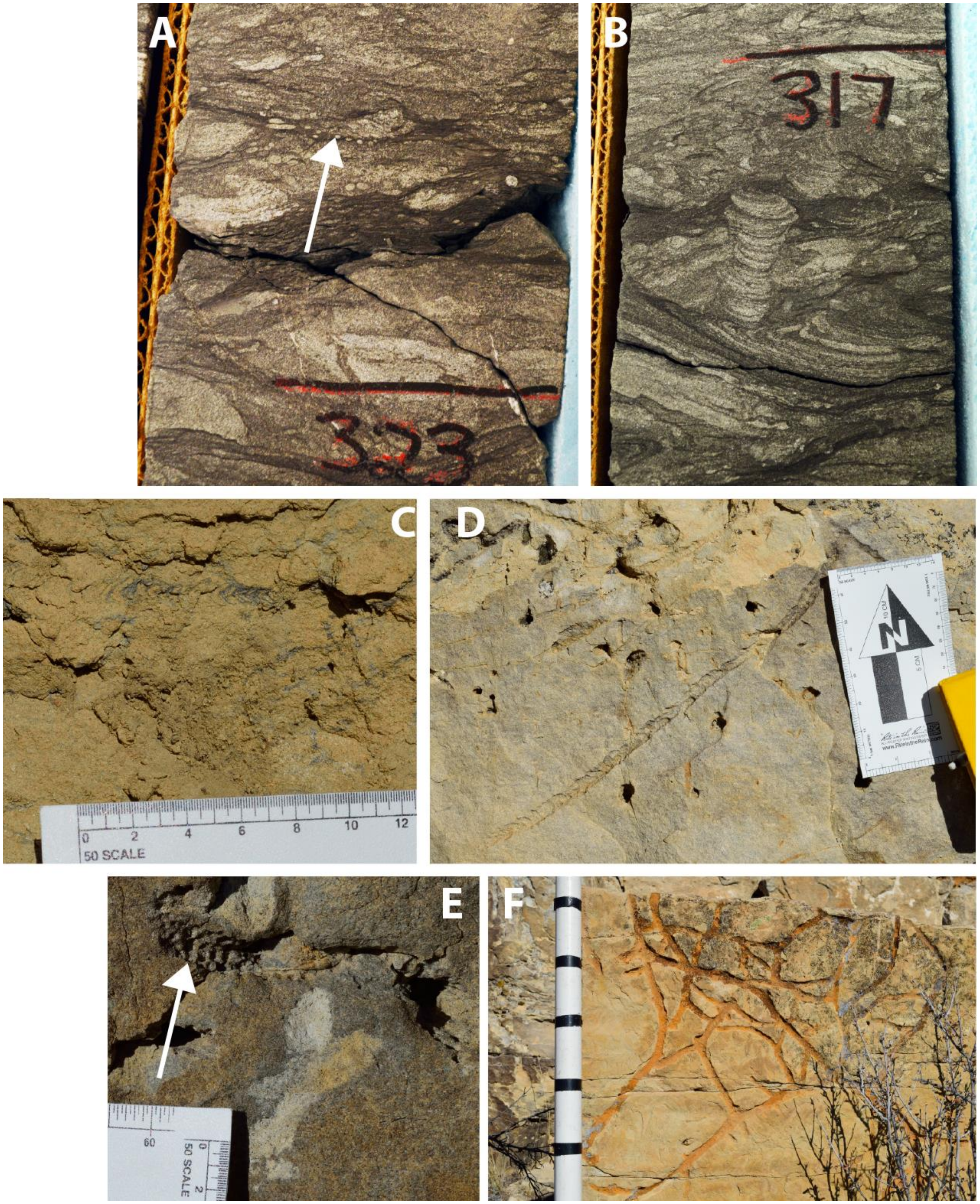

Figure 6. Trace fossils in the Codell Sandstone Member. **A)** *Chondrities* from the USGS Portland #1 core. **B)** *Teichicnus* from the USGS Portland #1 core. **C)** Horizontal backfilled *Rhizocorallium* near the top of the frame taken at the Pueblo Reservoir State

Park measured section. **D)** *Ophiomorpha* near the top of the Codell Sandstone Member at the Everhart Ranch measured section. **E)** *Ophiomorpha* with large pellets lining the walls taken at the Pueblo Reservoir State Park measured section. **F)** *Thallasinoides* network on a float block near the top of the Codell Sandstone Member taken near the Colorado Highway 78 measured section. Jacob staff is marked with 10 centimeter increments.

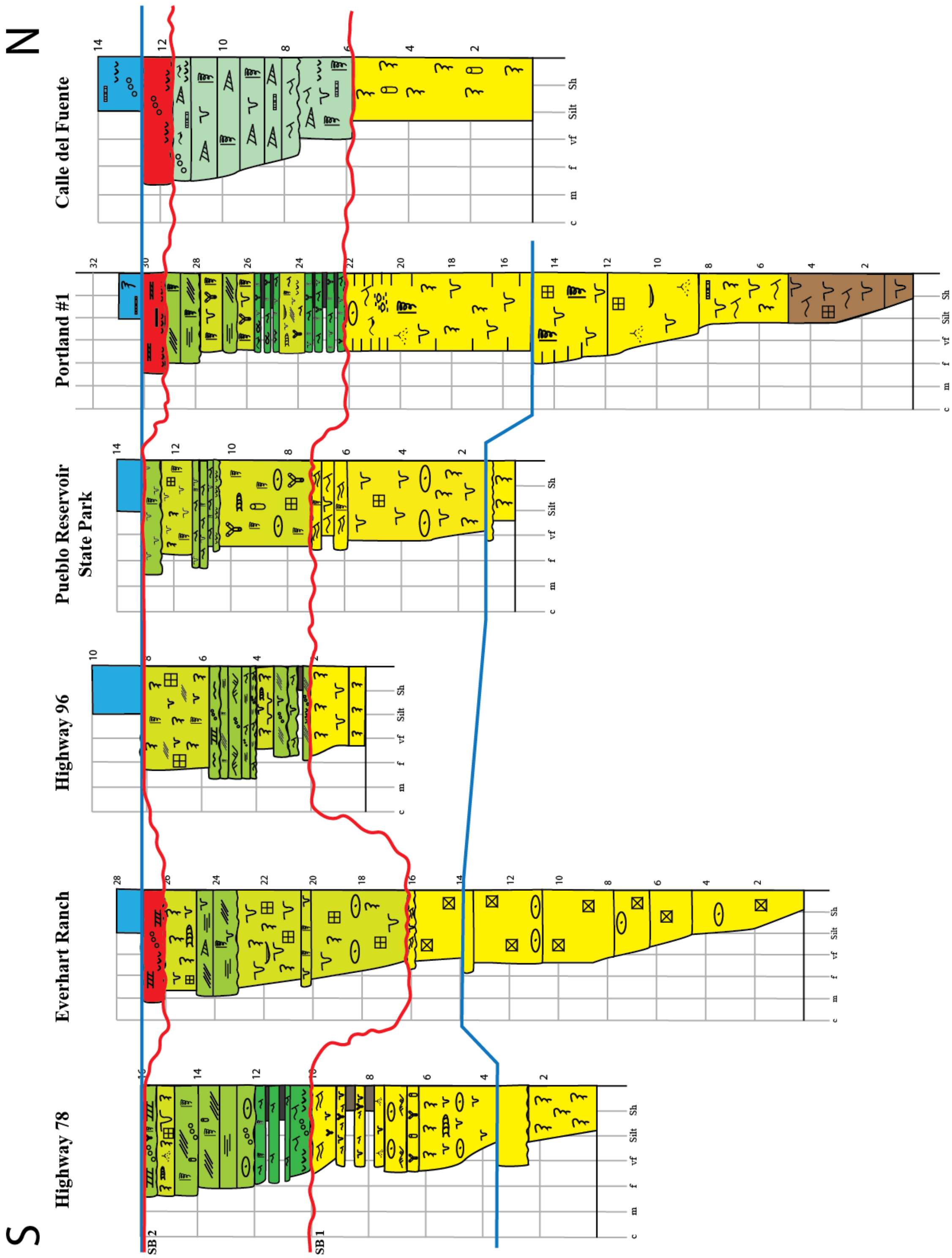

Figure 7. A. North-south cross section of measured sections showing facies and sequence stratigraphic interpretation.

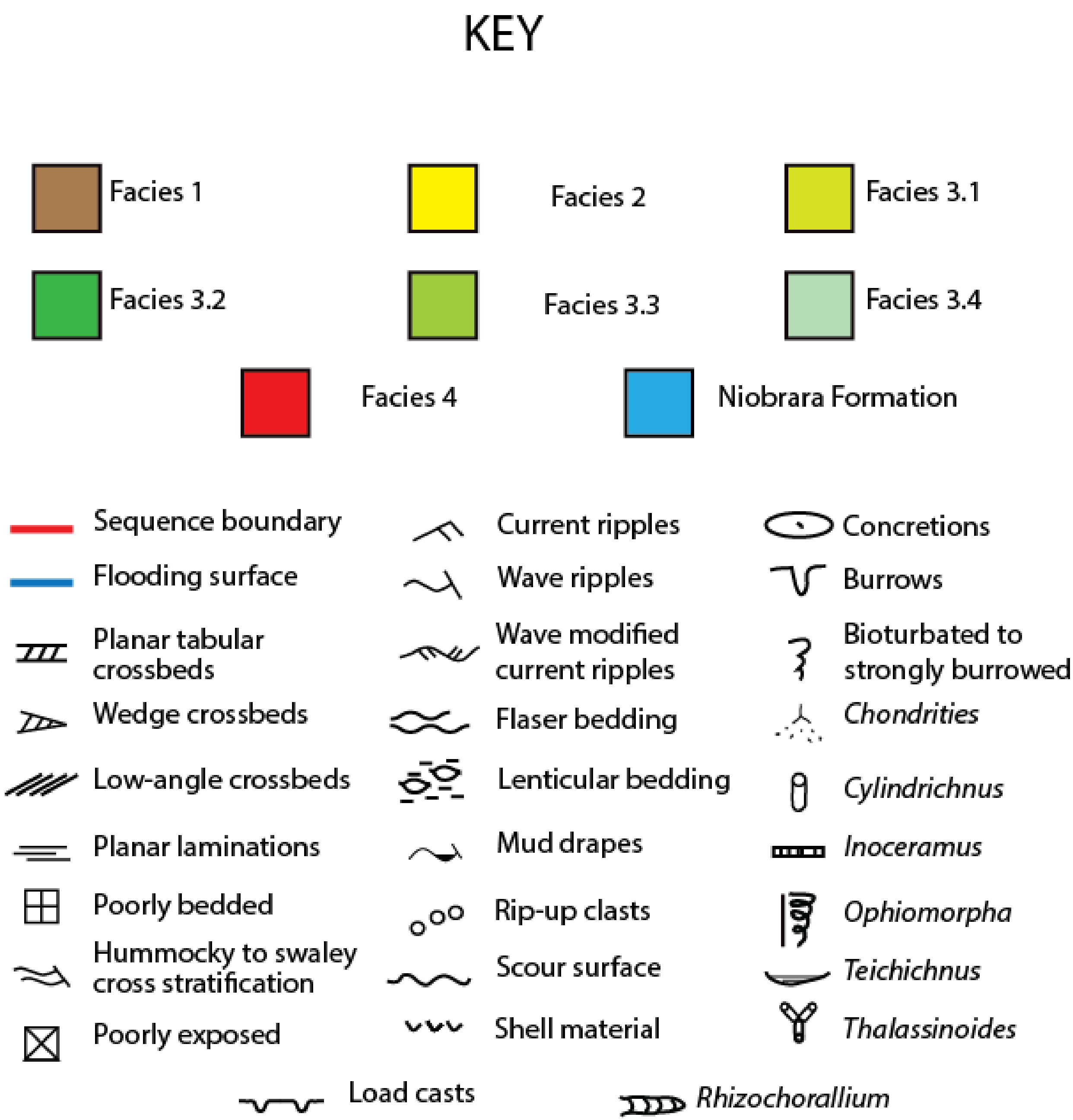

Figure 7 B. Key for the measured sections shown in figure 7 A.

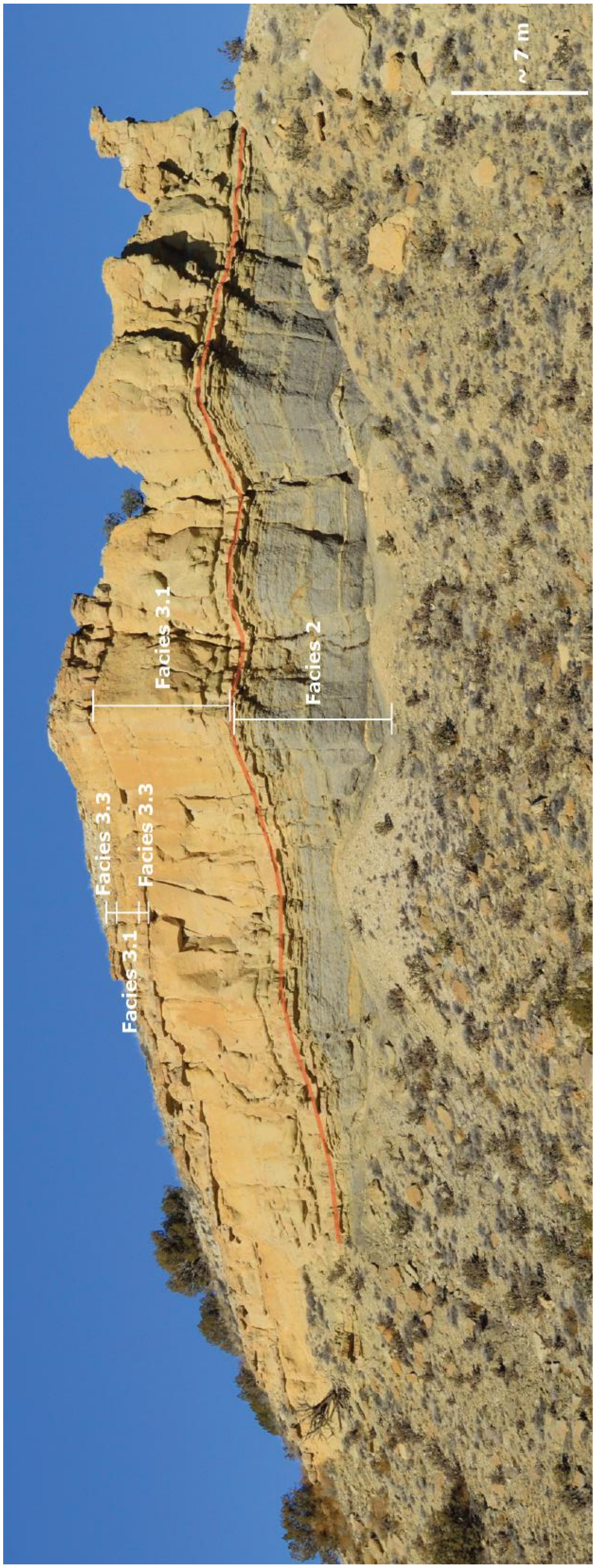
~ 7 m
Facies 3.1
Facies 2
Facies 3.3
Facies 3.3
Facies 3.1

Figure 8. The red line marks the location of the interpreted sequence boundary that separates the Codell Sandstone Member into distal lower shoreface deposits (below the sequence boundary), and estuarine deposits (above the sequence boundary). Facies are marked in white text. Photograph was taken at the Pueblo Reservoir State Park measured section near Liberty Point.

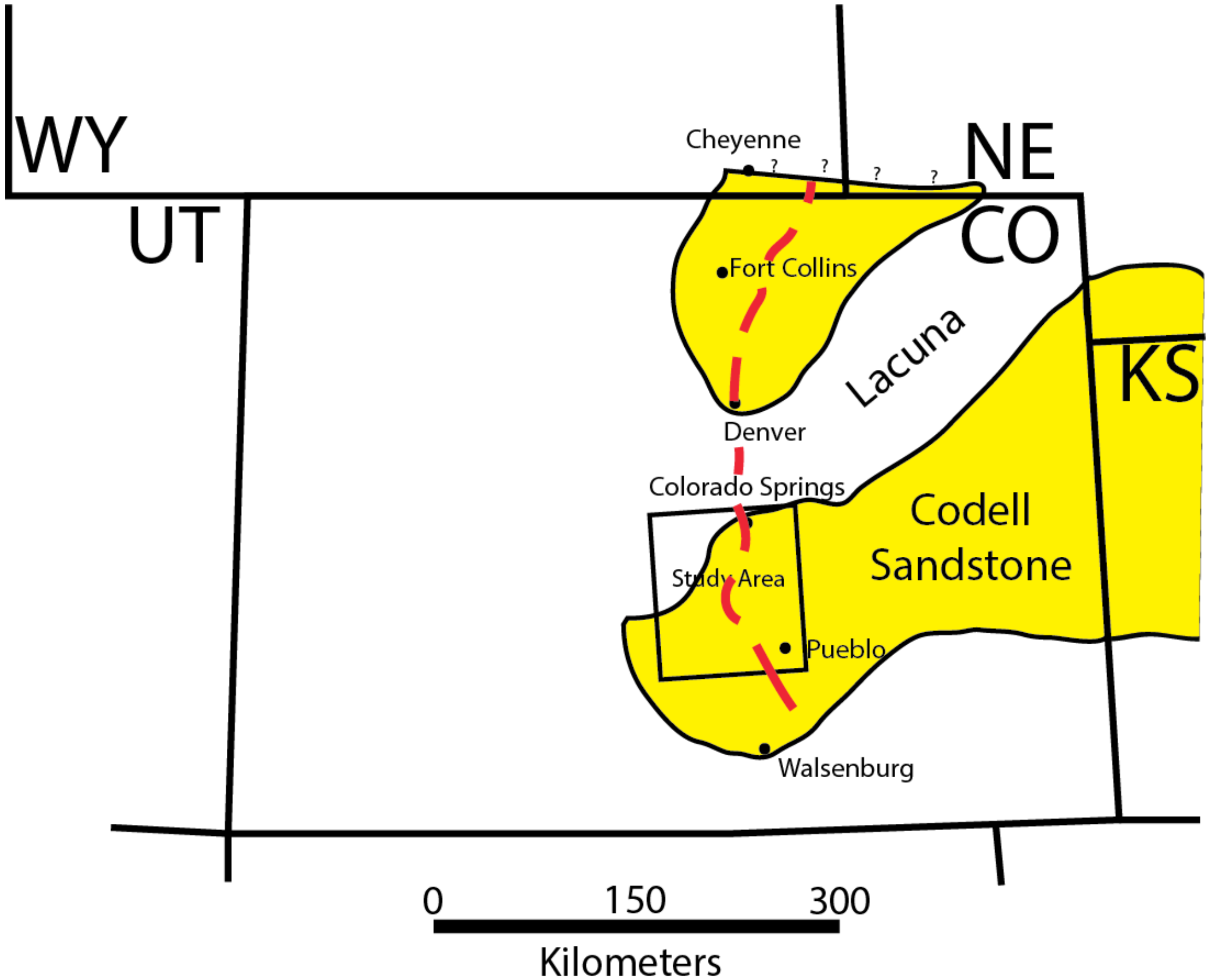

Figure 9. Map showing the areal extent of the Codell Sandstone Member in relation to the inferred lowstand shoreline, as proposed by this study, shown by the dashed red line [modified from Merewether et al. (1983)].

Tables

Sample Name	Facies	Material	Diagenetically Altered?	EXP AVG	Corrected
E099 279.7	3.2	*Inoceramus*	No	0.707427	0.707428
E099 276.8	3.1	Bivalve	Yes	0.708936**	0.708936**
E099 228.3 "A"	Niobrara	*Inoceramus*	No	0.707353	0.707354
E099 228.3 "B"	Niobrara	*Inoceramus*	No	0.707366	0.707367
E099 260.6	4	*Inoceramus*	Yes	0.707330	0.707331
K_{JL} 1	4	*Inoceramus*	No	0.707361	0.707362
K_{JL} 2	4	*Inoceramus*	No	0.707377	0.707377
K_C 1	3.4	Ino / Foram	No	0.707898*	0.707899*

Table 1. Strontium isotope analyses from samples collected from the Codell Sandstone and the Juana Lopez members. Samples "E099 279.7", "E099 276.8", "E099 228.3", and "E099 260.6" are from the USGS Portland #1 core. Samples "K_{JL} 1", "K_{JL} 2", and "K_C 1" are from the measured section at the Calle del Fuente outcrop along Colorado Highway 115. "E099 279.7" was collected from facies 3.2. "E099 276.8" was collected from facies 3.1. "E099 228.3" "A" and "B" were collected from the Fort Hays Member of the Niobrara Formation. "E099 260.6" was collected from facies 4. Sample "K_{JL} 1" was collected from facies 4. Sample "K_{JL} 2: was collected from facies 4. Sample "K_C 1" was collected from facies 3.4. Asterisk (*) indicates a brackish-water ratio while two asterisks (**) indicate a freshwater ratio.

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APPENDIX

Figures

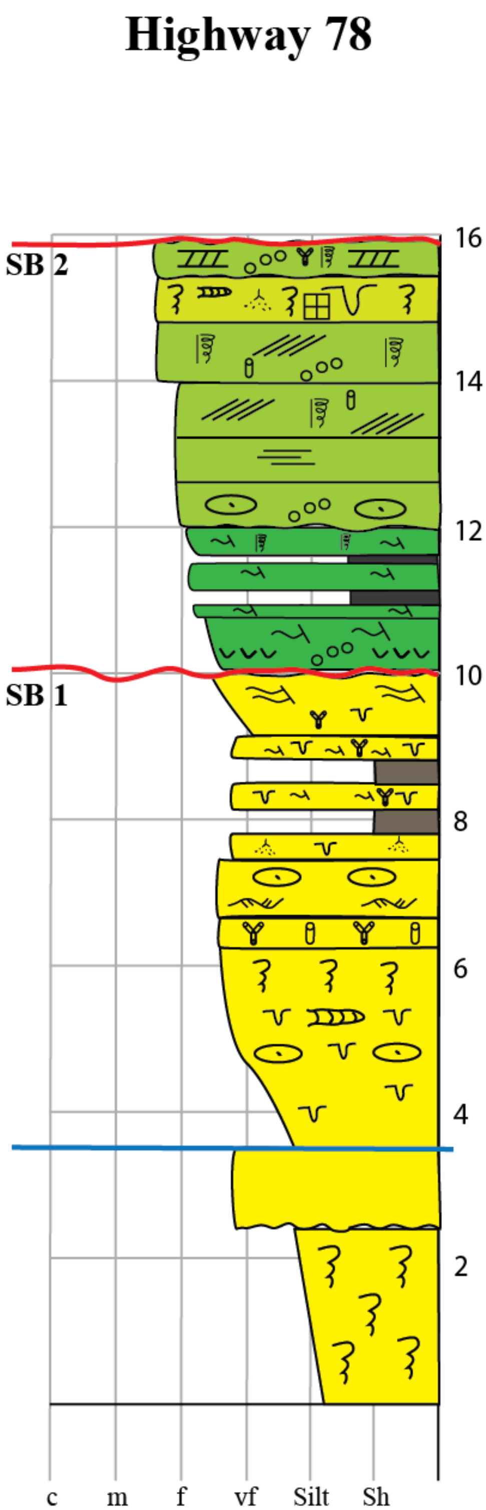


Figure. Colorado Highway 78 measured section showing facies and sequence stratigraphic interpretation.

Everhart Ranch

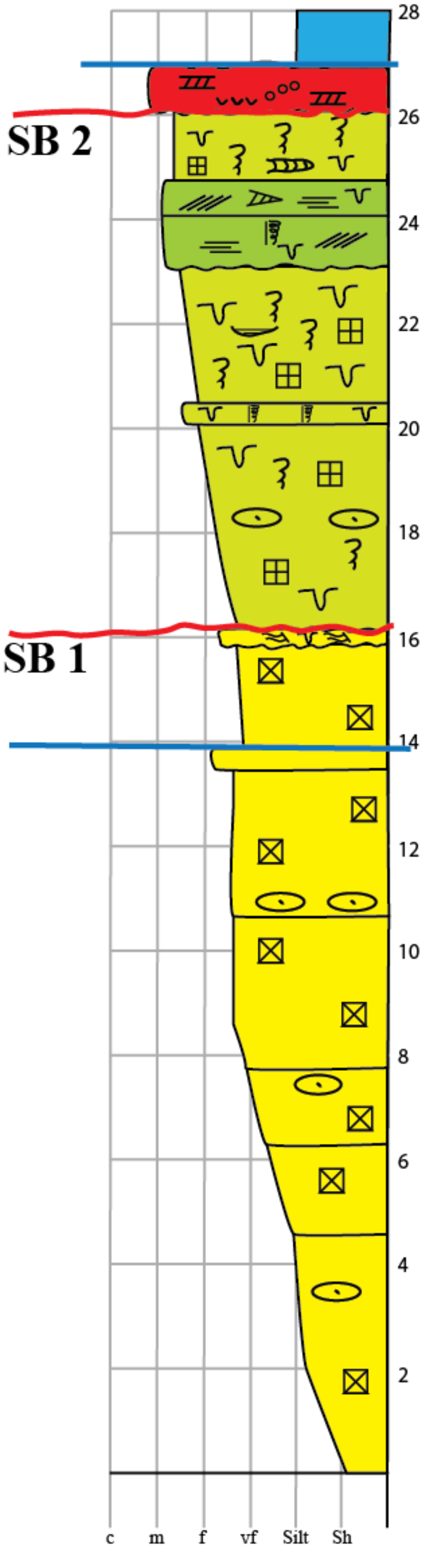


Figure. Everhart Ranch measured section showing facies and sequence stratigraphic interpretation.

Highway 96

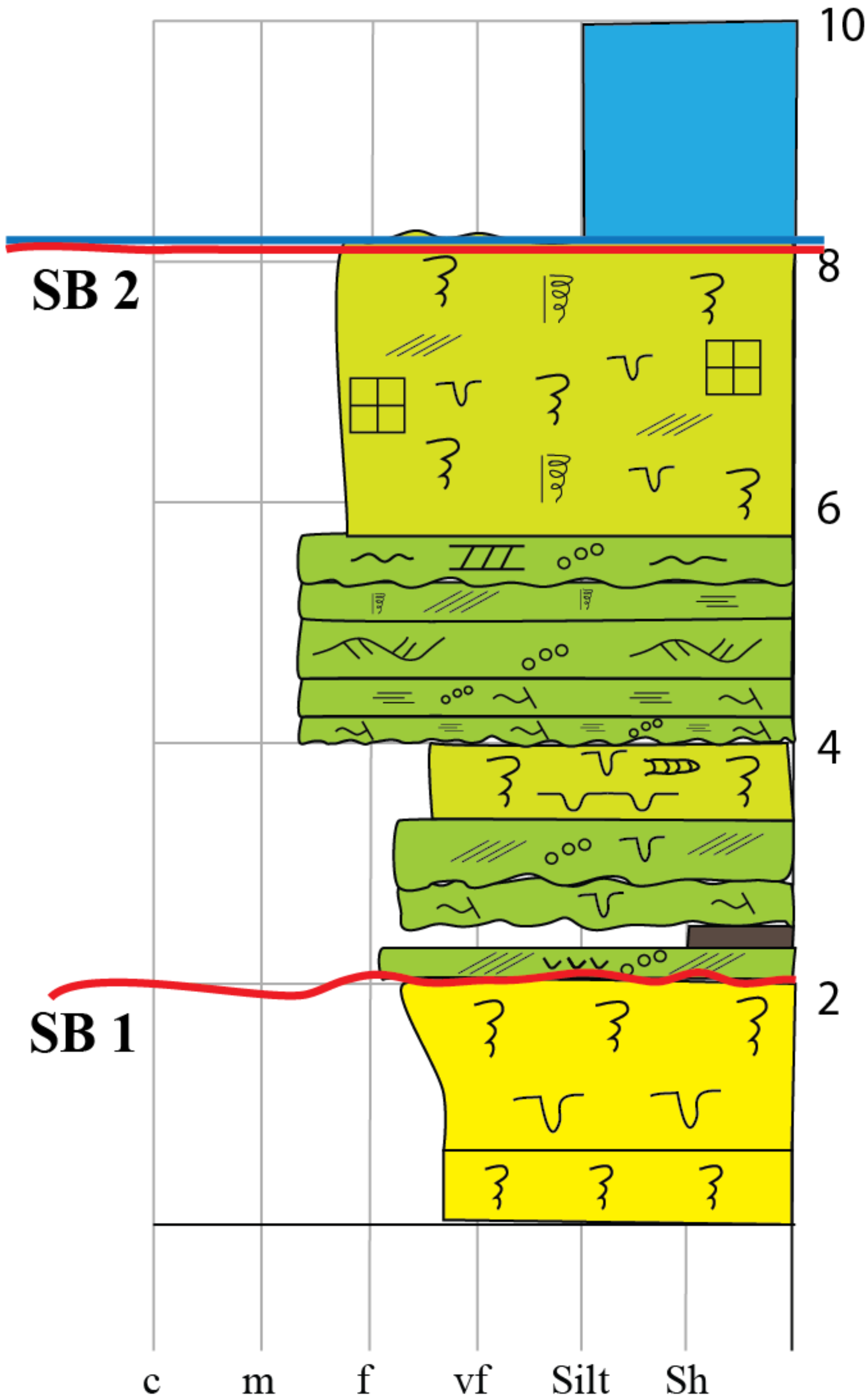


Figure. Colorado Highway 96 measured section showing facies and sequence stratigraphic interpretation.

Pueblo Reservoir State Park

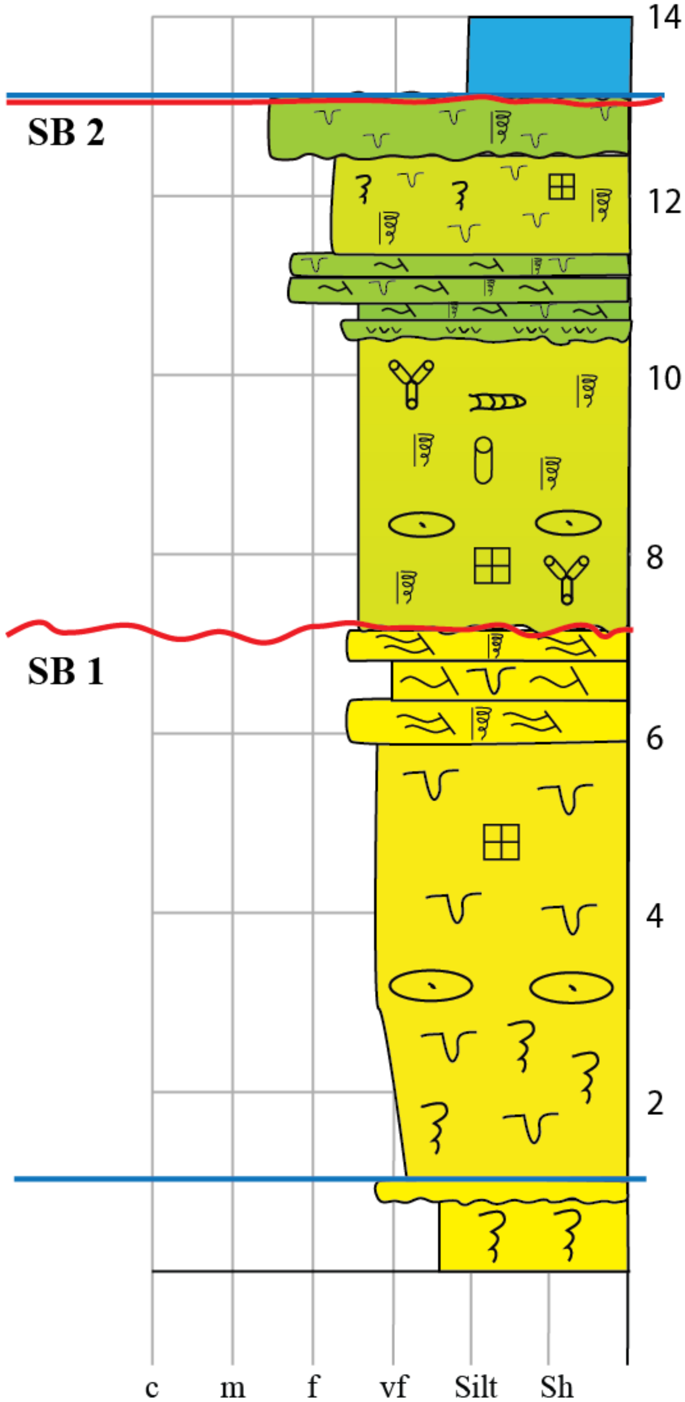


Figure. Pueblo Reservoir State Park measured section showing facies and sequence stratigraphic interpretation.

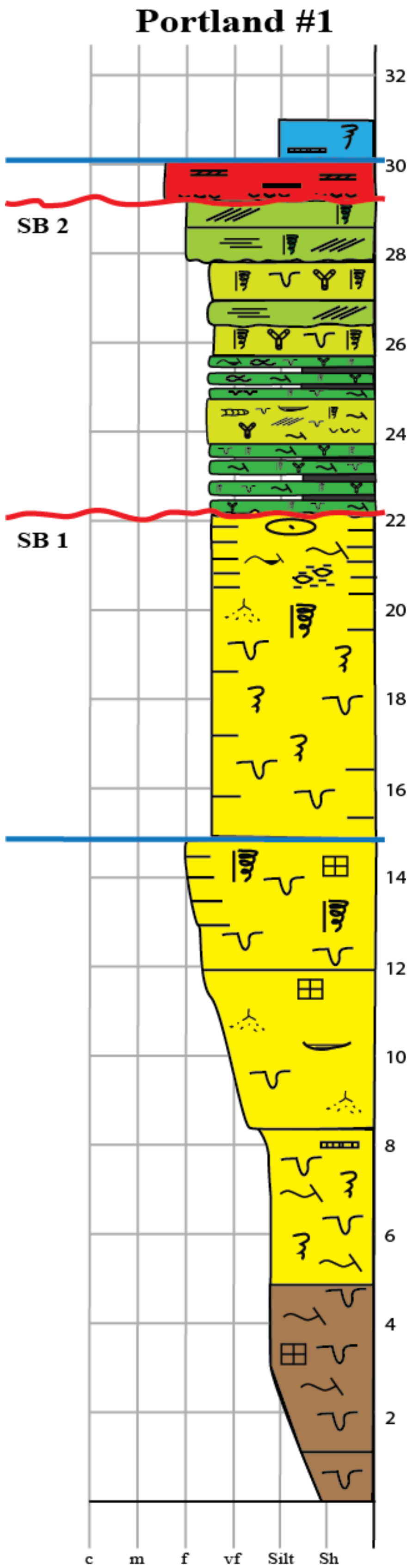

Portland #1
SB 2
SB 1
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
c
m
f
vf
Silt
Sh

Figure. USGS Portland # 1 Core measured section showing facies and sequence stratigraphic interpretation.

Calle del Fuente

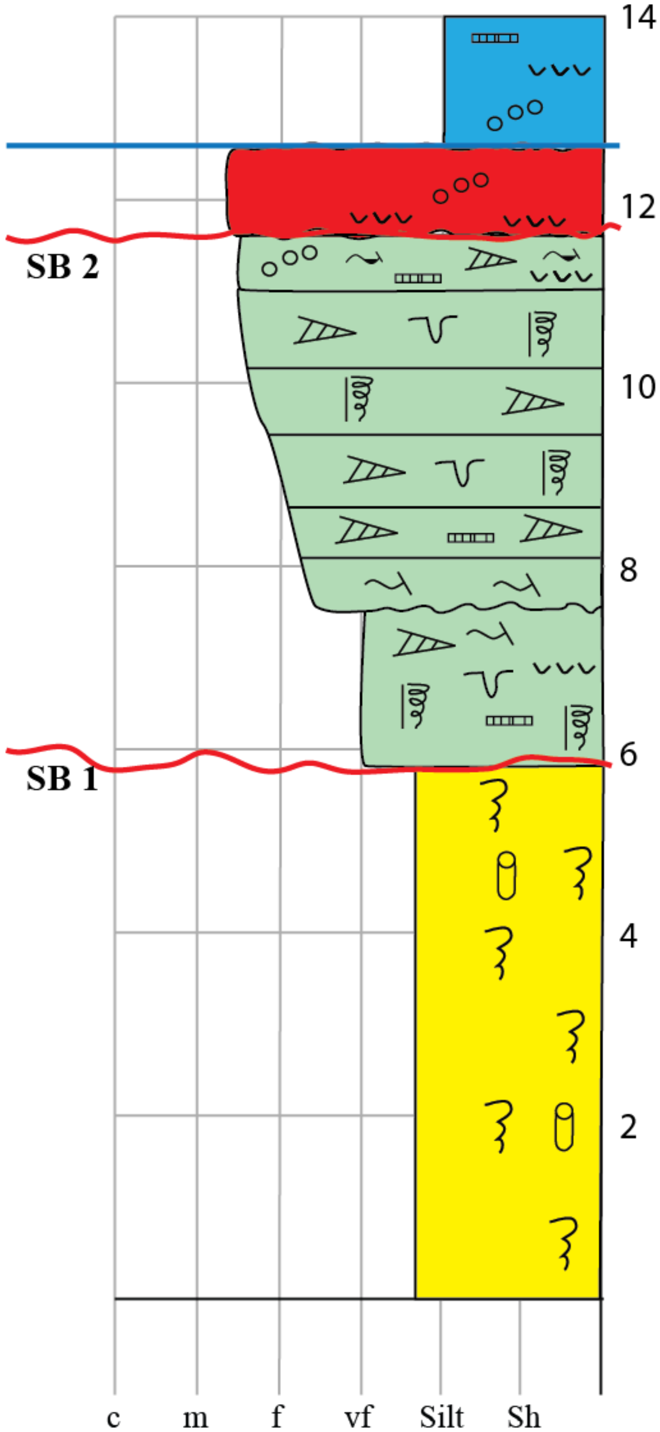


Figure. Calle del Fuente measured section showing facies and sequence stratigraphic interpretation.

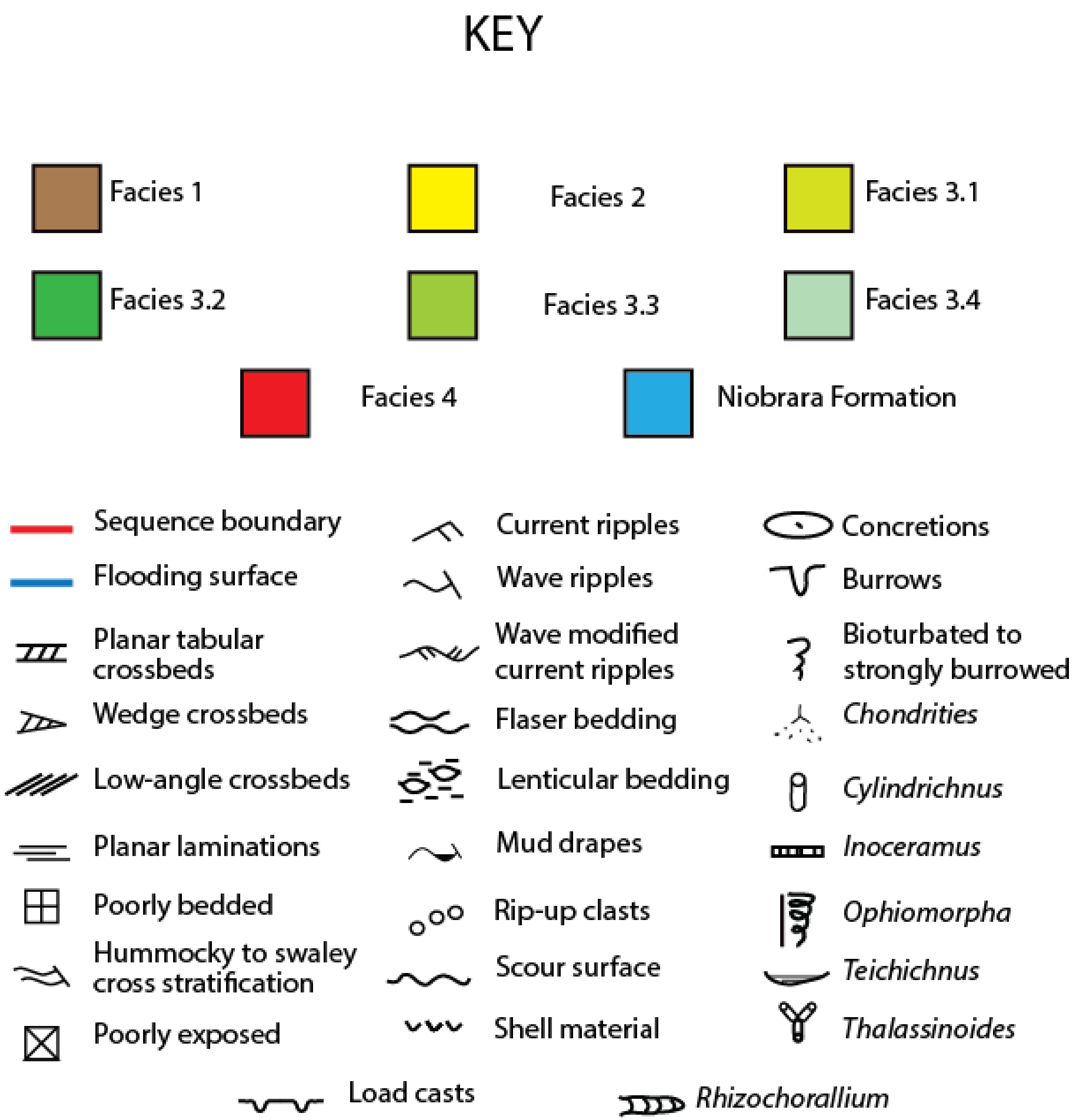


Figure. Measured section legend for the detailed measured sections.

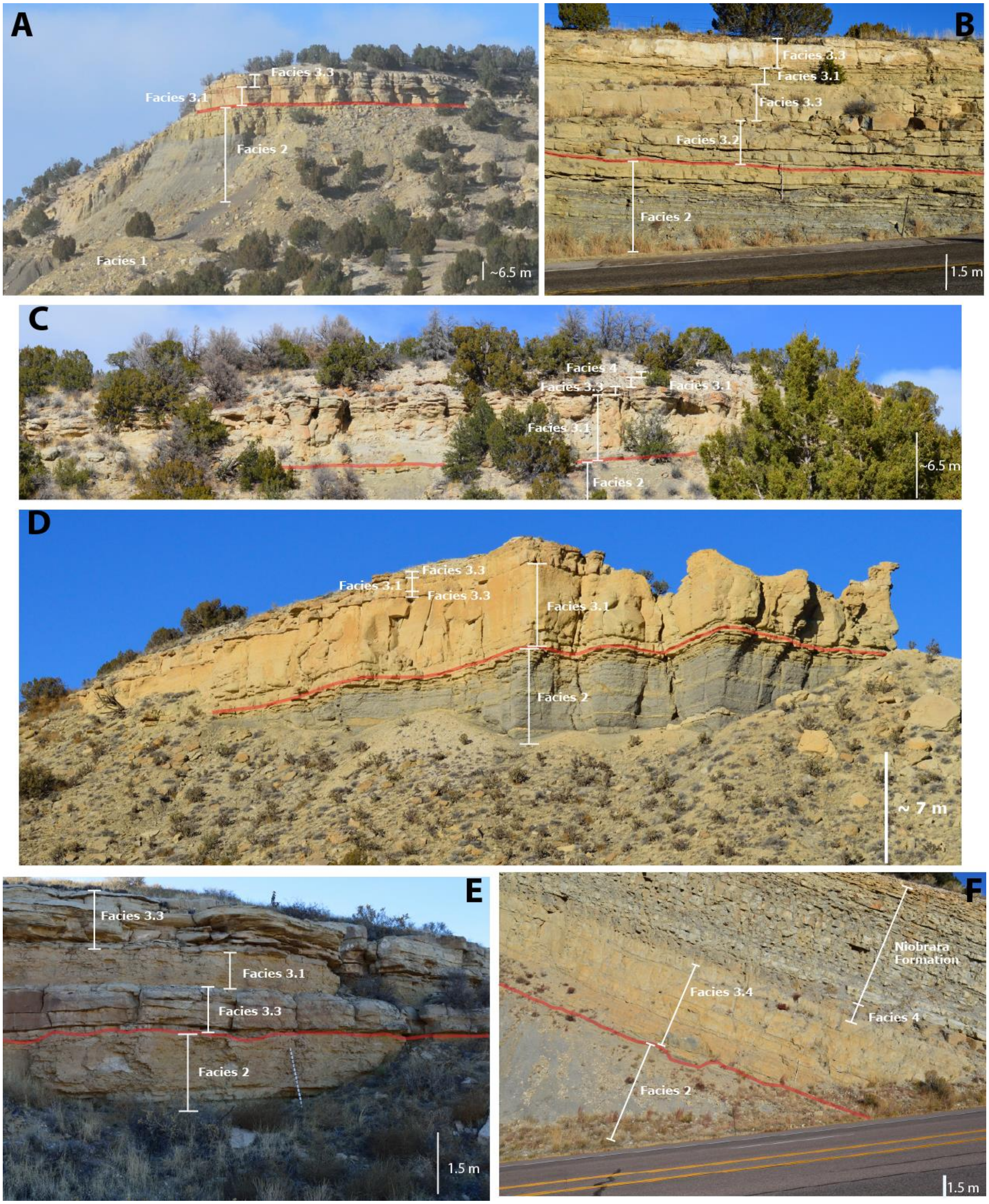


Figure. A collage of outcrop photos. The red line superimposed on the photos marks the location of the interpreted sequence boundary that separates the Codell Sandstone Member into distal lower shoreface deposits below the boundary, and estuarine deposits above the boundary. **A)** Frame A is an exposure along Colorado Highway 78. **B)** The Colorado Highway 78 measured section with a Jacob Staff for scale. **C)** The Everhart Ranch section as seen from the road. **D)** Pueblo Reservoir State Park measured section. **E)** The Colorado Highway 96 measured section with Jacob Staff for scale. **F)** Calle del Fuente measured section along Colorado Highway 115.

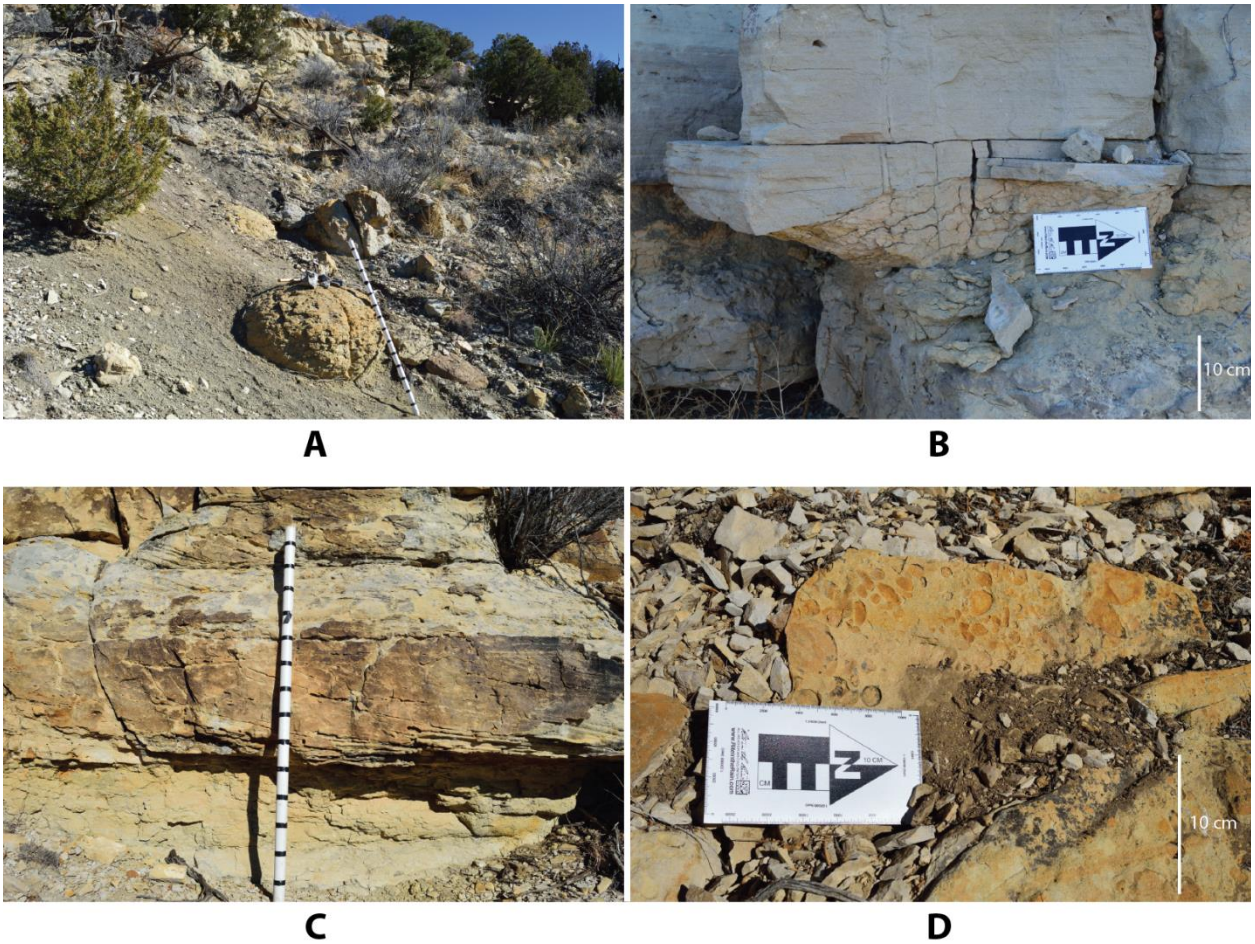


Figure. **A)** Shows a concretion horizon near the upper contact of the Blue Hill Shale Member at the Everhart Ranch section. Jacob staff is marked with 10 centimeter increments. **B)** A gutter cast along an erosional surface within facies 3.3 from the Colorado Highway 96 measured section. **C)** 30-40 centimeter crossbedding from facies 3.3 of the Codell Sandstone Member. Foresets dip at a high-angle to the right. Jacob staff is marked with 10 centimeter increments. **D)** Rip-up clasts surface in a piece of float from the Juana Lopez Member.

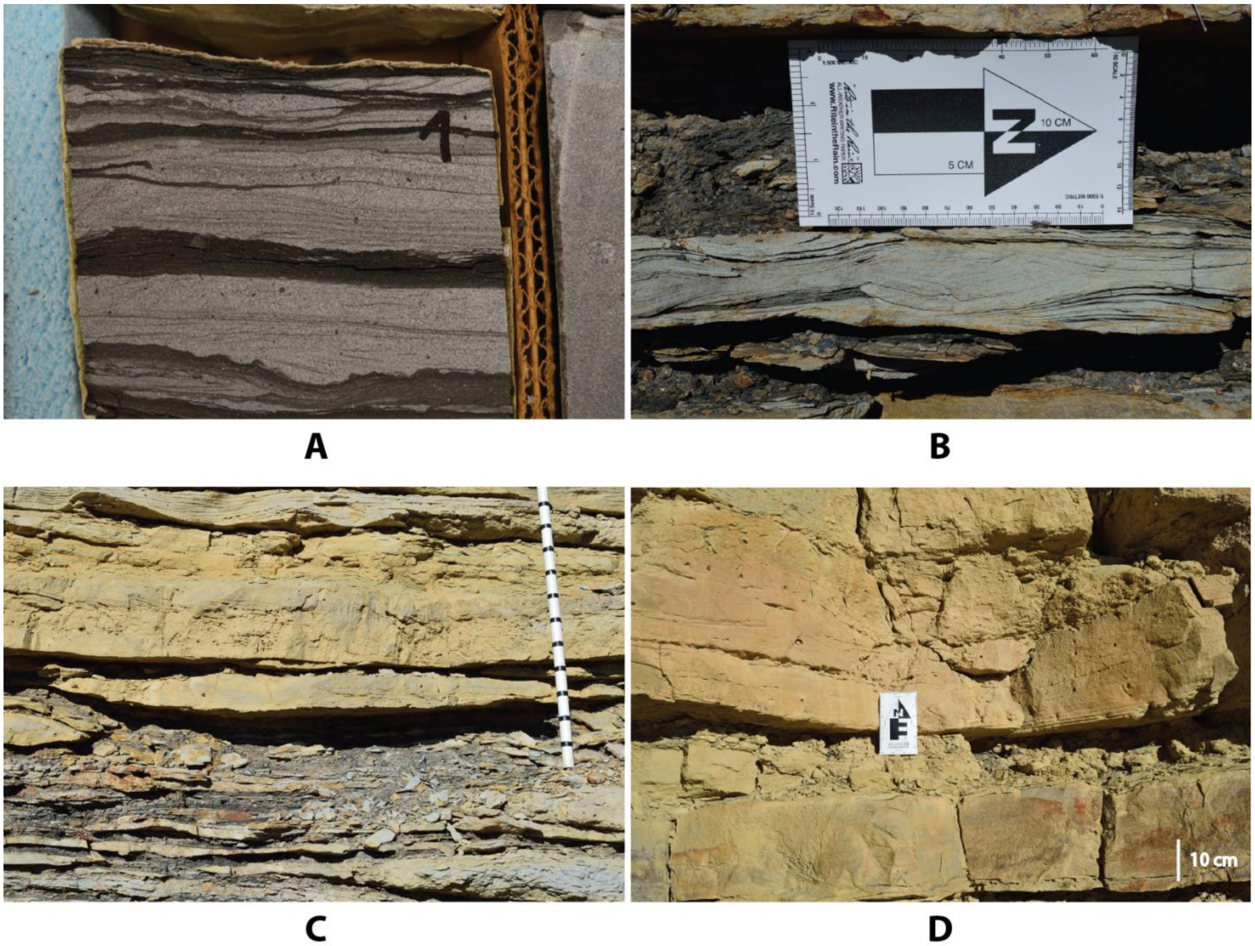


Figure. A collage of physical sedimentary structures observed during the course of the study. **A)** Centimeter-scale flaser-bedded sands and soft sediment deformation from the USGS Portland #1 core near the 273.5’ mark (facies 3.2). **B)** Wave-rippled bed from facies 3.2 of the lower Codell Sandstone Member at the Colorado Highway 78 measured section. **C)** Scour and fill structure from facies 3.2 in the Colorado Highway 78 measured section. Jacob staff is marked with 10 centimeter increments. **D)** HCS bedding below the sequence boundary in facies 2 located in the Pueblo Reservoir State Park measured section.

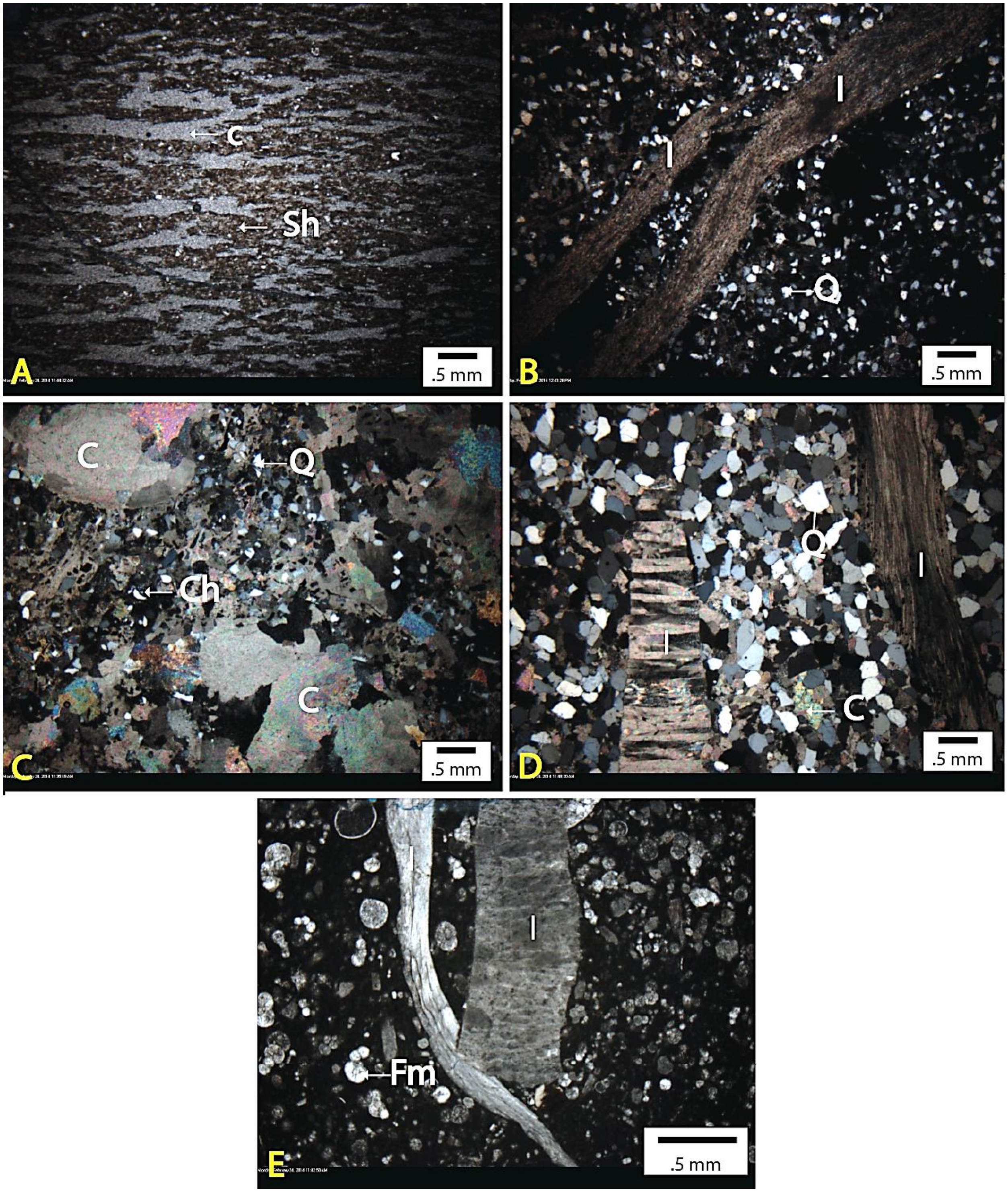


Figure. Photomicrographs of thin sections in cross polarized light from the USGS Portland # 1 core. **A)** Section "E099 358.9" from the Blue Hill Shale Member shows silty-shale with veins of calcite cement. **B)** *Inoceremus* fragments from "E099 279.7" in facies 3.2. **C)**

"E099 276.8" section showing chert and quartz grains in calcite cement. **D) "**E099 260.6" section showing *Inoceremus* fragments in the Juana Lopez Member. **E)** Section "E099 228.3" from the Fort Hays Member of the Niobrara Formation showing *Inoceremus* and foraminifera.

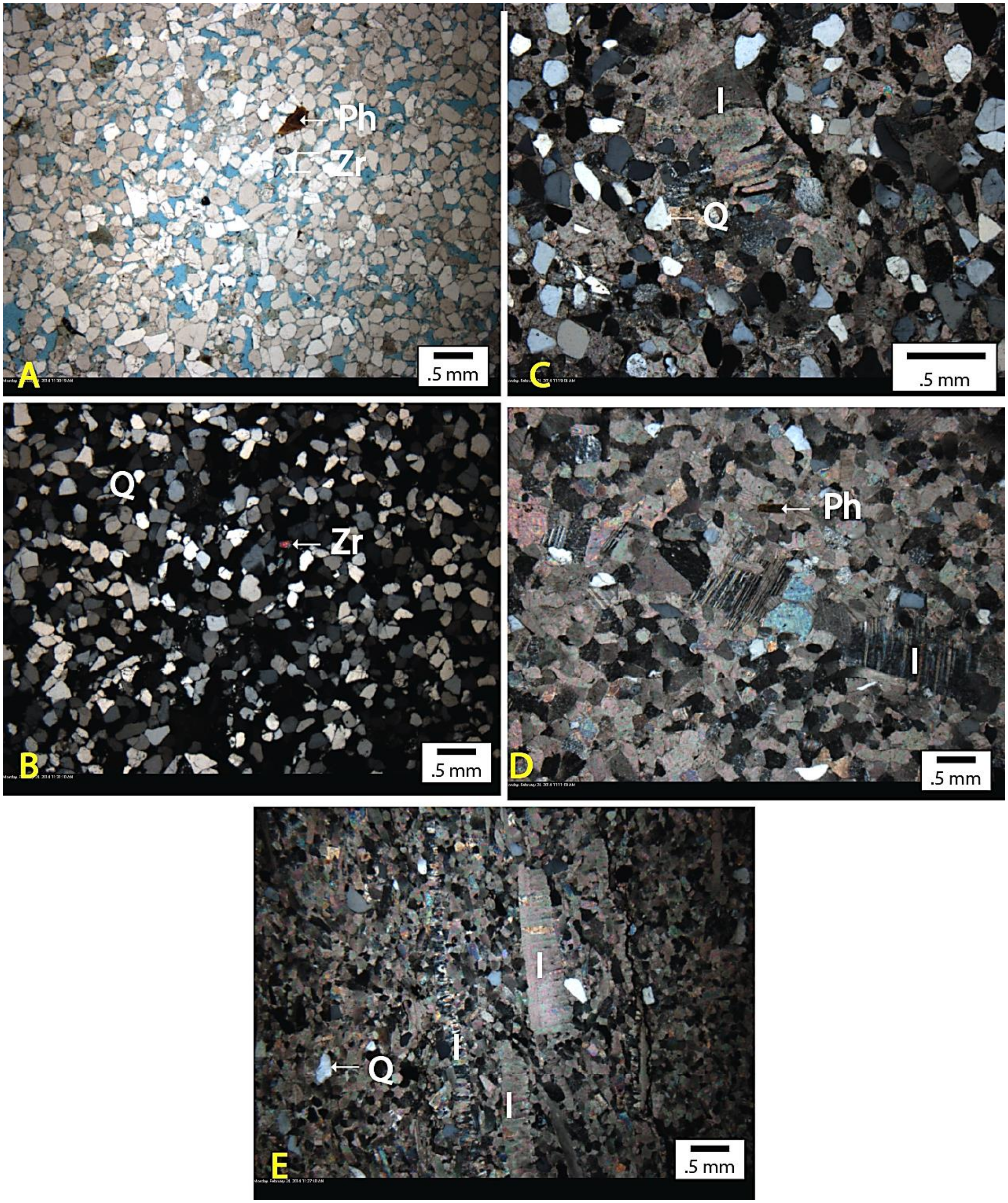
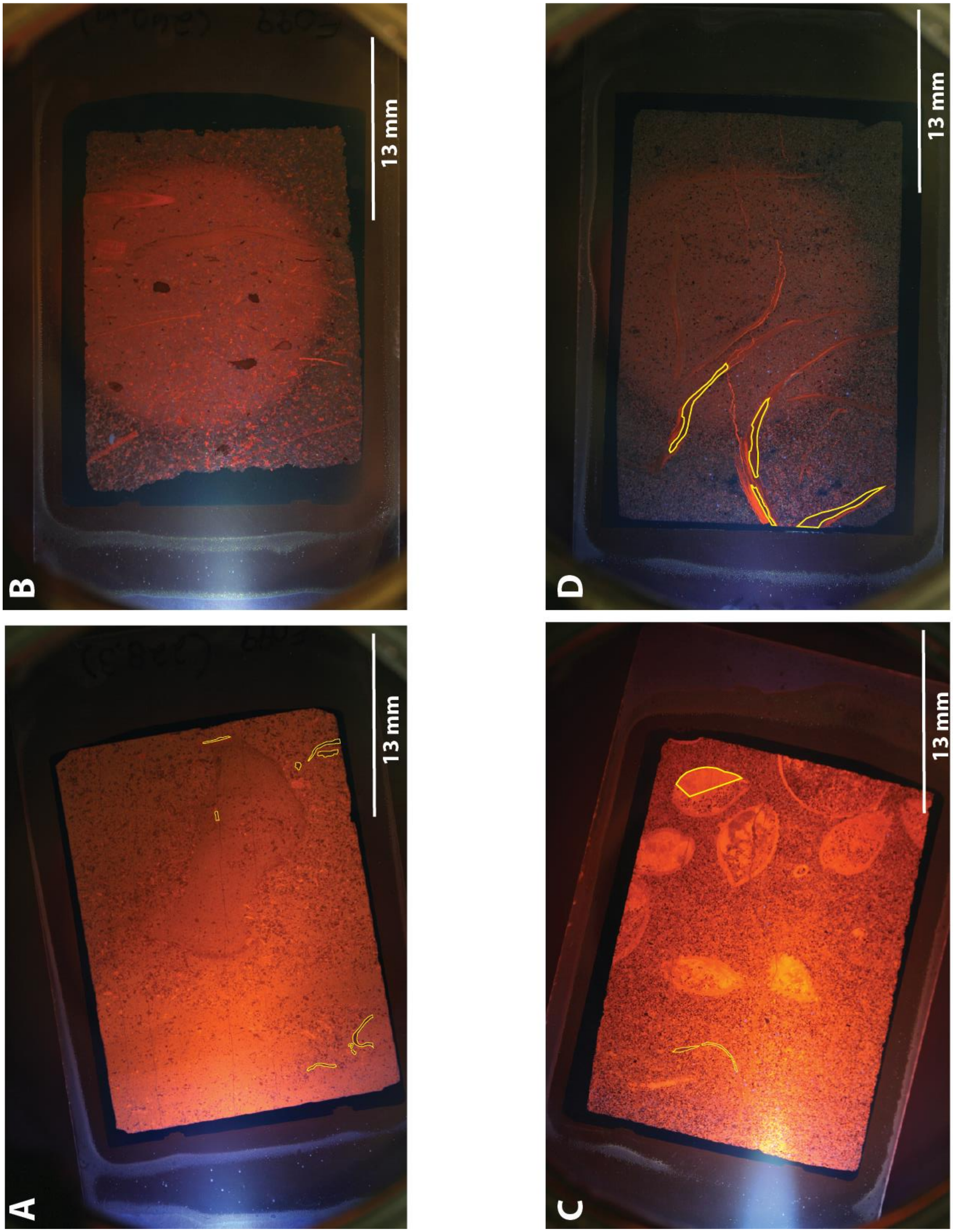


Figure. Photomicrographs of thin sections from the Calle del Fuente measured section. **A)** Section "K_C 2" from facies 3.4 seen in plain polarized light. Grains are dominantly quartz with a few zircons and phosphate-rich fragments. The blue space represents porosity. **B)** Cross polarized view of frame A. **C) "**K_C 1" section showing *Inoceremus* fragments and quartz in calcite cement. **D)** Sample "K_{JL} 1" showing *Inoceremus* fragments, phosphate-rich fragments, and quartz grains in calcite cement. **E)** Sample "K_{JL} 2" showing *Inoceremus* fragments.


A
13 mm
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13 mm
C
13 mm
D
13 mm

Figure. Cathodoluminescence photographs from the USGS Portland #1 core. Luminescent material indicates that there has been diagenetic alteration. The yellow lines outline the areas that were targeted for strontium sampling. **A)** Sample “E099 228.3” is from the Fort Hays Member of the Niobrara Formation. The chalky matrix has been alterated, but some inoceremus fragments were unaltered and were able to be sampled. Photo was taken at 5.1 Kv, 1.5 mamp, and 59.5 mTorr. **B)** Sample “E099 260.6” is from the Juana Lopez Member. This sample was too altered to sample for strontium isotope analysis. Photo taken at 5.1 Kv, 1.6 mamp, and 57 mTorr. **C)** Sample “E099 276.8” shows abundant bivalve shells that are dominantly diagenetically altered. This sample was milled for both altered material as well as unaltered material. Photo taken at 9.0 Kv, 1.5 mamp, and 41.5 mTorr. **D)** Sample “E099 279.7” shows several large *Inoceremus* fragments that record partial alteration. Photo taken at 4.6 Kv, 1.6 mamp, and 57 mTorr.

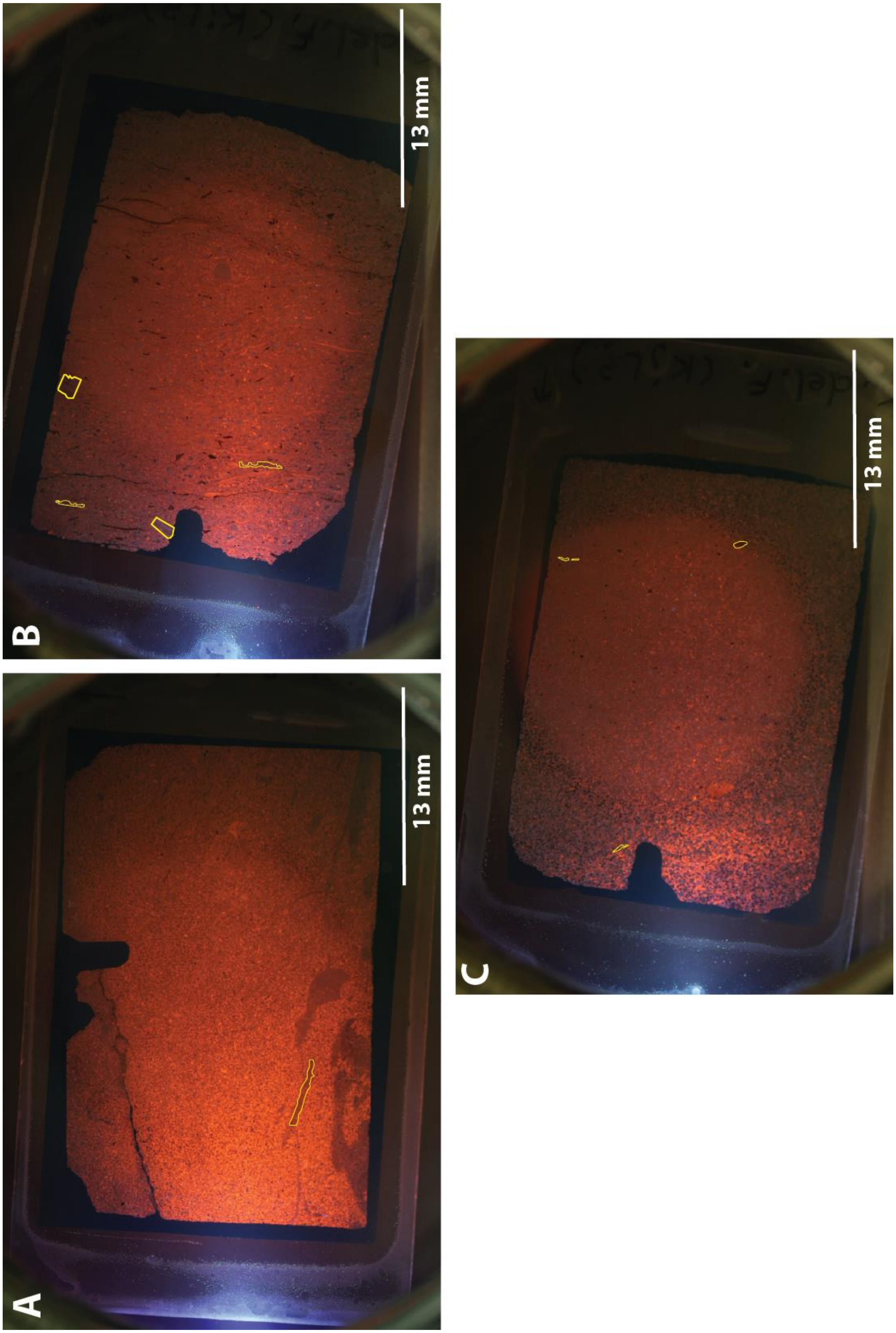
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Figure. Cathodoluminescence photographs from the Calle del Fuente measure section. Luminescent material indicates that there has been diagenetic alteration in this thin section. The yellow lines outline the areas that were targeted for strontium sampling. **A)** Sample "K_{JL} 1" contained few small shell fragments that showed no alteration. Photo taken at 4.5 Kv, 1.6 mamp, and 59 mTorr. **B)** Sample "K_{JL} 2" contained several small shell fragments that showed only partial alteration. Unaltered portions of the shell were mapped and milled. Photo taken at 4.5 Kv, 1.6 mamp, and 58 mTorr. **C)** Sample "K_{C} 1" shows shell fragments that are both altered and unaltered. Non-luminescent material was sampled for strontium. Photo taken at 4.8 Kv, 1.6 mamp, and 59 mTorr.

Methods

Samples for strontium isotope analysis were collected from the USGS Portland #1 core and the Calle del Fuente measured section at various horizons of interest. The horizons typically were located within the incised valley fill and near the Codell Sandstone Member-Juana Lopez Member contact. Samples were also taken from the Fort Hays Member of the Niobrara Formation and the Blue Hill Shale Member. Thin sections were made from those samples with the most fossil content, and then sealed with a blue epoxy and polished. The sections were then analyzed under cathodoluminescence to find diagenetically unaltered shell material, based on the luminescence characteristic, to mill for the strontium isotope analysis. The shell material showed partial alteration. A microscope–mounted drill assembly with a tungsten carbide bit was used to sample directly from the thin sections. The powdered microsamples, were collected from unaltered shell material, altered material, and cement, and were then sent to the University of Kansas Isotope Geochemistry Laboratory for processing of the ^{87}Sr / ^{86}Sr ratio. Samples were dissolved in 3.5 N HNO_3. Strontium was separated using ion-exchange columns filled with strontium-spec resin at the University of Kansas Isotope Geochemistry Laboratories. Samples were analyzed on the Sector 54 Thermal Ionization Mass Spectrometer (TIMS) in the same laboratory. Isotopic fractionation was corrected using $^{86}Sr/^{88}Sr = 0.1194$ and an exponential correction. Isotope ratios were adjusted to correspond to a value of 0.71248 on NBS987 for $^{87}Sr/^{86}Sr$ (external precision was 3ppm on ratio on standards during the duration of analyses) to be consistent with the McArthur et al. (2001) normalization.