SEQUENCE STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE HARDING SANDSTONE, CENTRAL COLORADO: IMPLICATIONS FOR THE HABITAT OF EARLY FISH

by

JESSICA LYNN ALLEN

(Under the Direction of Steven M. Holland)

ABSTRACT

Sixteen outcrops throughout the Cañon City Embayment and surrounding areas in Colorado were stratigraphically described to conclude that two ancient genera of fish, Astraspis desiderata and Eriptychius americanus, inhabited a low wave energy microtidal shallow marine environment. Debated for over a century, the habitat of these fish has been previously interpreted as fluvial, estuarine and marine. The facies interpretation and sequence stratigraphic analysis presented here provide new understanding to the ongoing debate. The Harding is interpreted here as mostly shoreface facies interrupted with an interval of lagoonal associated facies in the Cañon City area. Low wave energy conditions near the shore allowed extensive burrowing by organisms in the sediment that resulted in the pervasive bioturbation and lack of sedimentary structures. Fish remains are most commonly preserved on flooding surfaces either overlying or underlying shoreface facies and are associated with minor condensed intervals.

INDEX WORDS: Harding Sandstone, Middle Ordovician, sequence stratigraphy, Astraspis desiderata, low wave energy microtidal shoreline

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CHAPTER 1

INTRODUCTION

This thesis is written as a manuscript intended for submission to the *Journal of Sedimentary Research*. Because of this, it is best read as a single chapter. The second chapter discusses in more detail the previous literature, geological background, methods, results, discussion and conclusion.

The purpose of this study was to assess the depositional environment and habitat of some of the earliest vertebrates found in the Harding Sandstone. There have been three modern studies that have attempted to determine the habitat of these fish, but they do not share similar methods or conclusions. This paper examines the Harding on a local and regional scale and uses sequence stratigraphic insights to provide a new interpretation of the depositional environment of the Harding and to assess previous interpretations.

The fieldwork for this study was undertaken during the summer of 2001. During this time, 16 outcrops were stratigraphically described and measured. These descriptions are the backbone to the facies interpretations. Once the facies were interpreted, they were correlated across all the outcrops. A sequence stratigraphic interpretation was conducted to understand the changes in facies over time and across the region. Fish were counted at every horizon where they occurred. Using facies interpretations and fish occurrence data, the habitat of the fish found in the Harding is interpreted to be shoreface.

CHAPTER 2[1]

SEQUENCE STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE HARDING SANDSTONE, CENTRAL COLORADO: IMPLICATIONS FOR THE HABITAT OF EARLY FISH

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INTRODUCTION

The Middle Ordovician Harding Sandstone of central Colorado is well known for its fish deposits (Walcott 1892). Dermal plates of two genera, Astraspis desiderata and Eriptychius americanus, are found abundantly in the Harding. The presence of these fish has spawned a long debate on their depositional environment that has not been resolved by three modern studies. Fischer (1978), Spjeldnaes (1979) and Graffin (1992) each studied a different Harding outcrop in detail and each came to a different interpretation: estuarine, open marine and fluvial, respectively. The depositional environment of the Harding remains unresolved today.

Here, I present an interpretation of the depositional environment and sequence stratigraphy of the Harding Sandstone. This paper uses a sequence stratigraphic framework, based on 16 outcrops across central Colorado, to assess the depositional environment of the Harding. The misunderstanding of chronostratigraphically important surfaces, such as flooding surfaces and sequence boundaries, may have hampered previous facies interpretations (Miall 1997; Van Wagoner et al. 1990). These surfaces are used here to divide the Harding into genetically related packages of strata for which depositional environments may be interpreted. This new interpretation is used to evaluate previous studies of the Harding and then to establish the depositional environment in which some of the oldest known fish lived.

GEOLOGICAL BACKGROUND

The Harding Sandstone, a quartz arenite with lesser amounts of mudshale and siltstone, overlies the Lower Ordovician Manitou Limestone and underlies the Upper

Ordovician Fremont Dolomite. The Harding crops out along Colorado's Front Range and other Proterozoic-cored ranges uplifted during the Laramide orogeny (Fig. 1). During the Ordovician, Colorado was located on the northwestern margin of Laurentia at a latitude of 10-20° South (Scotese and McKerrow 1990). This latitude would have placed it within an equatorial humid zone (Witzke 1980).

This warm coastal environment of the Harding was well suited for the extensive array of invertebrates living there. Its rich diversity is well documented and includes an array of conodonts, bivalves, linguloid brachiopods, sponges, trilobites, cephalopods and gastropods (Sweet 1954). The most notable fossils of the Harding are dermal plates of two early vertebrate taxa, Astraspis desiderata and Eriptychius americanus. While most of the fish fossils consist of disarticulated plates, three articulated specimens have also been found within the Harding (Walcott 1892; Lehtola 1983; Sansom et al. 1997). These represent some of the oldest articulated vertebrates known in the world (Sansom et al. 1997).

The debate over the depositional environment of the Harding was initiated by Walcott (1892). When Walcott discovered the first articulated specimen over a century ago, he interpreted the remains as having been preserved along a shoreline with deposits of the advancing sea overlying it. Romer and Grove (1935) later claimed that the fish lived in a freshwater environment; but were disarticulated during their transport into a marine setting. Denison (1956, 1967) dismissed their interpretation and argued that the plates were found over too large an area to have come from a single freshwater source. Robertson (1957) supported this claim by concluding that the plates were disarticulated by marine tides and longshore drift.

More recently, three modern studies have examined the facies and depositional environment of the Harding. Fischer (1978), Spjeldnaes (1979) and Graffin (1992) have each contributed, yet not resolved, the debate. What is striking about their studies is that each concentrated on different single outcrops and their methods and observations were not consistent. As a result, they all came to different conclusions: Fischer argued for an estuarine environment, Spjeldnaes suggested an intertidal open marine setting and Graffin concluded that the fish's habitat was fluvial. While they each added data to the debate, there remains little agreement on the depositional environment of the Harding and thus the habitat of some of the oldest fish in North America.

METHODS

During the summer of 2002, twelve outcrops in the Cañon City, Colorado area (eastern outcrops) and four in the west (western outcrops) were stratigraphically measured and described. The eastern outcrops include Beulah, Phantom Canyon, Gnat Hollow, Indian Springs, Mixing Bowl, Priest Canyon, Route 50, Sheep Mountain, Shelf Road, South Twin Mountain, The Bank, Type Quarry; the western outcrops include Bushnell Lakes, Chubb Park, Cotopaxi and Wellsville (Fig. 1). At each outcrop, beds thicker than a decimeter were described for grain size and shape, sorting, bedding thickness, continuity and evenness, bioturbation, trace and body fossils, physical sedimentary structures, color and diagenetic minerals. Fish fossils were characterized by the surface on which they were found and their relative size. Counts of fish plates in 2 to 10 centimeter squares were made depending on the thickness of the occurrence, size and concentration of plates. Concentrations of plates were measured wherever fish occurred.

Terminology for classification of “shales” follows Potter et al. (1980), bedding thickness follows Ingram (1954), cross stratification follows Ashley (1990) and ichnofabric index (ii) follows Droser and Bottjer (1989). Outcrops were correlated on the basis of stacking patterns, sequence boundaries and flooding surfaces. From these correlated sections, systems tracts were interpreted.

FACIES

Transition Zone Facies

Description.---This facies is represented by interbeds of very fine grained sandstone and mudshale, except for the lowest meter which contains very coarse to pebble quartz grains (Fig. 2, A, B). At the base of the facies, sandstone comprises between 20-30% of the total rock and increases upwards in each section to nearly 100%. This percentage of sandstone is lower in the more westward outcrops. Sandstone beds thicken upwards from 3-7 cm at the base of this facies to 10-30 cm at the top. The uppermost beds of sandstone are separated by thin partings (1-5 mm) of mudshale. Surfaces of beds are variably planar to wavy (Fig. 3). Most beds are highly bioturbated with an ichnofabric index of 4 to 5 and less commonly 2 to 3. Unbranching horizontal burrows are prevalent (Fig. 4, C, D). Identifiable trace fossils are rare and include <u>Chondrites</u>, <u>Diplocraterion</u> or <u>Arenicolites</u> and less commonly <u>Lockeia</u> (Fig. 4, F). Where bioturbation is limited, remnants of planar lamination are present. Other types of lamination, including wave-ripple lamination, hummocky-cross stratification and current-ripple lamination, are absent. This facies also contains fragmented lingulid brachiopods, rare crinoid columnals, and rare orthoconic nautiloids. Pyrite nodules are present and can be as large as 1 cm. White to light red burrow mottling is common with the remaining portions of the facies a beige to off-white color. This facies averages 4-5 meters thick with a maximum thickness of 7 meters at Cotopaxi.

Interpretation.--- This facies is interpreted as having been deposited in a transition zone environment. The interbedding of mudstone and sandstone, the most diagonostic feature, indicates temporally fluctuating deposition. While the trace fossil assemblage is limited, it mostly represents a mixed <u>Skolithos</u> and <u>Cruziana</u> ichnofacies. These ichnofacies are common in marine sandy shore environments characterized by frequent deposition and erosion (Howard 1972; Pemberton et al. 1992). Owing to the lack of significant number of articulate brachiopods, the assemblage of body fossils does not fit well into most described Ordovician paleocommunities. The presence of crinoids and nautiloids suggests an environment where water was relatively shallow and salinity was normal (Cocks and McKerrow 1978a; Bretsky 1969). Pyrite is indicative of a reducing marine environment (Maynard 1982). Most of the pyrite has been diagenetically oxidized into hematite and goethite stains that give this facies its color.

Bioturbation has presumably destroyed many of the sedimentary structures that were originally present, as suggested by the presence of planar laminae where bioturbation is less intense. The intensity of bioturbation and lack of significant hummocky-cross stratification or wave-ripple lamination suggests minimal disturbance by waves or currents, which allowed burrowing infauna sufficient time to rework sediments between storms (Frey and Howard 1986; Pemberton et al. 1992).

The proportion of mudshale in this facies increases westward, indicating a westward dip of the Harding seafloor. This would suggest that the shoreline was aligned approximately north-south (Fig. 5), an interpretation that agrees well with previous paleogeographic maps of the mid-Ordovician (Scotese and McKerrow 1990).

Shoreface Facies

Description.---This facies is composed of very fine to fine-grained quartz arenite, except for the lowest meter of the Harding, where it contains very coarse to pebble size quartz grains. The sandstone is well sorted and tends to be argillaceous in the east and tightly cemented in the west. Beds are 0.3-2 meters thick (Fig. 2, B). Surfaces of beds are wavy or planar. Bioturbation is pervasive (ii 5) and, as a result, beds are dominantly internally structureless (Fig. 2, D). Indistinguishable unbranching vertical and horizontal burrows are common. Identifiable trace fossils include <u>Chondrites</u>, <u>Skolithos</u>, <u>Diplocraterion</u> and <u>Thalassinoides</u> (Fig. 4, E, F). Intervals 2-5 cm thick of planar lamination may be dispersed within otherwise structureless strata. Such laminated intervals can be found roughly every meter or as a single occurrence in the whole facies. Locally, small-scale foresets and trough cross-lamination may be present but are rare. Fragmented lingulids, molds of poorly preserved bivalves, and fish plates are found mostly on top of bedding surfaces and less commonly within beds. Pyrite nodules are common and range in diameter from 1 to 3 cm. This facies has a beige to pale red color with white to light red burrow mottling. The total thickness of the facies varies among outcrops with a maximum of 8 meters at Shelf Road.

Interpretation.---These characteristics collectively indicate a low wave energy shoreface environment. Sandstone beds thicken upwards and comprise more of the section, reflecting an overall increase in shear stress as a result of shallowing (Reinson

1984). Identifiable traces are uncommon, yet are most represented by a mixed Skolithos and Cruziana ichnofauna. These ichnofacies are found most commonly in conditions characteristic of sandy shallow marine settings and could have formed during periods of high energy, such as a storm (Pemberton et al. 1992). A similar body faunal assemblage has been described from Upper Ordovician of the central Appalachians and has been interpreted to reflect a nearshore environment (Bretsky 1969). Bretsky's Appalachian lingulid fauna of the Orthorhynchula-Ambonychia Community is composed mostly of bivalves, gastropods and lingulids and resembles the Harding body faunal assemblage. A Silurian lingulid community also shares similar faunal compositions, mostly lingulids and bivalves, to that of the Harding (Cocks and McKerrow 1978a). Both of these communities were interpreted to inhabit barrier islands, beaches and lagoons where salinity fluctuates (Cocks and McKerrow 1978b; Bretsky 1969). The body fossils assemblage in this facies in the Harding supports a shoreface interpretation. The presence of large pyrite nodules is also evidence for a marine setting (Maynard 1982).

The scarcity of physical sedimentary structures may be attributable to the very well sorted texture of the rock or to intense bioturbation. The presence of planar laminae suggests that sedimentary structures were generated but subsequently destroyed by bioturbation. The relatively slow tempo of deposition of a low wave energy shoreline would have allowed extended inhabitation and the opportunity for extensive biological reworking of sediment between sediment transporting events. As a result, the fauna of this facies has destroyed most of the physical structures as well as identifiable biogenic structures, resulting in structureless beds (cf. Frey and Pemberton 1985). The dominance of bioturbation over physical sedimentary structures in this facies supports the interpretation of low wave energy.

Tidal Inlet Facies

Description.---This facies is similar to the Shoreface facies and is distinguished from it primarily by the presence of large-scale trough cross-bedding and lateral accretion surfaces. Foresets within troughs of large-scale cross beds dip towards the west. Sets of lateral accretion surfaces are 1.5 meters high and 3-5 meters wide (Fig. 6). Individual lateral accretion beds are thick (10-30 cm) and structureless within. Lateral accretion surfaces dip at angles of 14-24° to the northeast. The rock is a well-sorted fine-grained sandstone. Bioturbation is intense within beds and an ichnofabric index of 4 is typical. With the exception of a few Diplocraterion, there is a lack of discrete burrows. Fragmented bivalves and fish plates are rarely preserved along bedding surfaces. This facies has a beige to pale red color.

Interpretation.---This facies is interpreted as a migrating tidal inlet. Lateral accretion surfaces are typical of channel migration (Kumar & Sanders 1976). The similarity and association of this facies with the shoreface facies indicates that the channel was migrating through shoreface facies. The relatively shallow depths of the channels demonstrated by the thickness of the lateral accretion sets suggest a microtidal barrier island system (Hayes 1975). Similarly shallow channel are seen in the modern microtidal Rhode Island coast (Boothroyd et al. 1985).

Both paleocurrent indicators, lateral accretion surfaces and trough cross-stratification, support a north-south shoreline (Fig. 5). The dips of the lateral accretion surfaces suggest that channels were migrating from the southwest to the northeast, parallel to the shoreline. Trough cross-beds indicate that paleocurrents in the tidal inlets preferentially flowed towards the west, perpendicular to the shoreline.

Central Basin Facies

Description.---This facies is represented by mudshale in beds 0.1-3 cm thick. Planar bedding is traceable but disrupted by bioturbation with ichofabric indices of 2 to 3. There are no recognizable trace fossils. Thin fragmented bivalves and fish plates are uncommon. The majority of this facies is a dark maroon, but light green, red and light purple mottling is present locally. The maximum thickness of an exposed section of this facies is 4.5 meters (Fig. 2, E) at Shelf Road. Load casts can be seen in the sandstone beds overlying this facies at the Type Quarry.

This facies is generally poorly exposed and can be observed only along road cuts or in quarries. Covered intervals in the Cañon City area in the same stratigraphic position as known exposures of this facies are inferred to be lagoonal facies.

Interpretation.---This facies is interpreted to have been deposited in the central basin of a lagoon or a bay (sensu Zaitlin et al. 1994). In such a protected environment, clay can settle out readily from suspension. Muddy substrate and possibly low salinity from a freshwater influence of a lagoon made it uninhabitable for many organisms with the exception of bivalves (Cocks and McKerrow 1978b). Burrowing organisms were present, however, not populated enough to destroy all the sedimentary structures and thus remnant planar lamination can be seen throughout this facies.

Washover Fan Facies

Description.---This facies is represented by sandstone beds consisting of well-sorted very fine-grained sand. Beds are 0.1-0.8 meters thick. Bedding surfaces are planar and sharply underlain and overlain by mudshale of the central basin facies (Fig. 2, G). Bioturbation varies between an ichnofabric index of 3 to 5. There are no recognizable burrows or trace fossils. Planar lamination occurs sparingly within otherwise bioturbated strata and there is an absence of current ripple lamination and landward dipping foresets. Rare fragmented lingulids and fish plates are found dispersed throughout the beds. This facies is an off white to light red color, but light purple to dark purple mottling is common. The maximum thickness of 0.8 meters can be seen at the Type Quarry.

Interpretation.--- These sandstone beds are interpreted as washover fans. The stratigraphic position of this facies indicates that these sandstone bodies were deposited within a lagoon or bay. There are only two forms of isolated sandstone beds in a lagoonal basin: flood tidal deltas and washover fans (Hayes 1975). Flood tidal deltas form by deposition of sediment through a tidal inlet. This provides a continuous supply of sediment resulting in the deposition of a relatively thick succession of sandy beds. On the other hand, washover deposits are generated during storm events and result in thin, isolated beds of sandstone (McGowen and Scott 1975). Bioturbation following deposition presumably obliterated any evidence of physical sedimentary structures, such as steeply dipping foresets.

Bayhead Delta Facies

Description.---This facies consists of interbedded very fine sandstone and mudshale. At the base of this facies, 1-3 cm beds of sandstone comprising 20% of the total thickness of the facies are separated by 1-5 cm beds of mudshale. The proportion of sandstone increases upward over 0.5-2 meters (Fig. 2, C). Both sandstone and mudshale have planar and locally wavy bedding surfaces. Bioturbation is moderate (ii 3), but not pervasive enough to destroy all lamination, with planar and wavy lamination found in areas of less bioturbation. Diplocraterion and horizontal burrows are preserved within the sandstone beds. Molds of fragmented bivalves and lingulids are present within mudshale beds. This facies alternates between dark maroon and light red at the base and becomes dominantly dark maroon up section. This facies ranges from 2-3 meters thick.

Interpretation.---This facies is interpreted as bayhead deltas deposited within a lagoon or bay. A prograding bayhead delta is the only method of depositing very thin layers of sandstone that systematically coarsen upwards from central basin muds (Hayes 1975; Bhattacharya and Walker 1992). Fine wavy lamination of alternating sands and muds indicates a tidal influence on the delta deposits. Bioturbation fluctuates in such an environment because of variations in sedimentation rates and salinity (Frey and Pemberton 1985). Because of these conditions, most physical structures are disrupted, but some are preserved.

Flood Tidal Delta Facies

Description.---This facies is found at a single outcrop, Indian Springs, and most diagnostic feature is a 1.5-meter thick very fine sandstone (Fig. 1; Fig. 2, E). Near its base, a series of sandstone beds (5-10 cm thick) are separated by 1-5 cm beds of mudshale, all of which grades upward into a single thick bed of sandstone (Fig. 2, F). Bedding surfaces are wavy and planar. Bioturbation is minimal (ii 1-2), and there are no identifiable trace and body fossils. Planar lamination is present throughout this facies. The uppermost bed is characterized by inclined planar laminae that dip <5° to the northeast (60° NE). This facies is a dark maroon with some light red and purple mottling. The maximum thickness of the facies is 2.2 meters.

Interpretation.---This facies is interpreted to record deposition on a flood tidal delta. Gently inclined planar laminae in a coastal setting can be found in the foreshore, in washover fans and in flood tidal deltas. Foreshore facies would be expected to overlie shoreface, whereas this facies grades upward from lagoonal muds (Campbell 1971). Washover deposits are expected to be thin isolated beds, but these beds are not present in this facies (Hobday and Jackson 1979; Wright and Sonu 1975). Deposits of a flood tidal delta are dominated by gently landward dipping laminae (Boothroyd et al. 1985; Hayes 1980). This suggests that land lay to the east with open ocean to the west, consistent with westward fining in the transition zone facies and paleocurrent indicators in the tidal inlet facies.

Paleosol Facies

Description.---This facies is comprised of an argillaceous siltstone with lesser amounts of very fine-grained sandstone. The maximum thickness of this facies is 1 meter, but is typically 10-30 cm thick. This facies lacks distinct beds or bedding surfaces, as well as burrows, trace fossils and body fossils. It is dark maroon in color and is exposed in man-made outcrops, but is covered in all natural outcrops studied. This facies is found only beneath the sequence boundary that caps the Harding Sandstone.

Interpretation.---This siltstone just below a sequence boundary is interpreted as a weathering profile (Fig. 7, D). During the creation of the sequence boundary, the previously deposited sediment was exposed subaerially long enough to form a paleosol (cf. Miall 1997).

Facies Associations and Parasequences

Shoreface Facies Association: Description.---The Shoreface Facies Association consists of shoreface, transition zone and tidal inlet facies. In this facies association, each parasequence consists of a transition zone facies that coarsens upward into shoreface facies (Fig. 2, A, B). This succession averages approximately 3 to 5 meters in thickness. This association is dominant in the western outcrops, where it comprises most of the sections. In the east, this facies association is found only at the base and top of the Harding.

In some cases, the transition zone facies is composed of a single bed overlain by shoreface facies (Fig. 8). In the case, parasequences are repeated to create stacked shoreface beds separated by very thin mudshale beds. This expression of the Shoreface Facies Association is seen only in the upper section of the Harding. Such stacked shorefaces are more common in the east, where they encompass most of the upper half of the section. Tidal inlets are associated with occurrences of stacked shoreface deposits.

The Shoreface Facies Association comprises the majority of the Harding in most outcrops. The shoreface facies is the most prevalent of its component facies and comprises approximately 40% of the total exposure of the Harding. Although the transition zone facies is thinner than the shoreface facies, it occurs regularly throughout the section.

Interpretation.---The most striking feature of the Shoreface Facies Association is its pervasive bioturbation, which has destroyed the majority of physical sedimentary structures. This features suggests that the Harding is a low wave energy coast.

Several modern settings may be partial analogs to the Harding, such as the low wave energy mesotidal coast of Georgia (Frey and Howard 1986; Frey and Howard 1988; Howard et al. 1972; Wunderlich 1972). The Georgia coast has an average wave amplitude of 0.25 meters during fair-weather and a mean tidal range of 2.4 meters (Frey and Howard 1988). Surficial sediments on the Georgia coast contain ripple lamination and planar cross bedded sands that have not undergone any biological reworking. These features are not seen in the Harding because the Harding coast had even lower wave energy. Below 5 meters water depth along the Georgia coast, bioturbation begins and continues to intensify as the water deepens. Thirty percent of the 500 box cores from Georgia contained at least one bed 10 centimeters or thicker completely bioturbated. Because the Harding is even more bioturbated than these Georgia coast sediments, it is interpreted as having lower wave and tidal energy.

A similar pattern of physical and biogenic structures is seen in the sediments deposited in the Gulf of Gaeta in the Mediterranean (Reineck and Singh 1971). Ripple bedding is predominant there in water depths less than 2 meters. In water depths from 2-6 meters, sands are planar laminated and bioturbation increases with depth. Below 6 meters, biogenic structures have destroyed all physical sedimentary structures. Low wave conditions on the Gulf of Gaeta and Georgia coast enable extensive bioturbation and removal of sedimentary structures in shelfal waters. In the Harding, wave and tides were presumably less intense and allowed the near complete removal of physical sedimentary structures in the shallowest water depths.

Lagoonal/Bay Facies Association: Description.---The lagoon or bay and its associated facies--flood tidal delta, bayhead deltas and washover fans--are located in the lower to middle portion of the eastern outcrops and make up the Lagoonal Facies Association. In this facies association, there is only one completely upward-coarsening parasequence, a flood tidal delta (Fig. 2, E). This parasequence grades upwards from central basin muds into a thick laminated sandstone bed, completing a flood tidal delta parasequence. The only exposure of such a flood tidal delta in the Harding, at Indian Springs, is located directly above the basal contact with the Manitou.

Bayhead deltas are relatively common within the Lagoonal Facies Association; yet never culminate in mouth bar deposits (Fig. 2, C). These parasequences begin as sands mixed with central basin muds and coarsen upwards, but not to the thick sandstone bed expected of a mouthbar. All three bayhead deltas found in the Harding (Indian Springs, Priest Canyon and Type Quarry) are capped prematurely by a flooding surface. Two found at the base of the Lagoonal Facies Association overlie a sequence boundary and are overlain by central basin muds. The third is located at the top of the Lagoon Facies Association, overlies a covered interval interpreted as the central basin facies and is overlain by shoreface facies in a sharp contact.

Although limited to locations within the Lagoonal Facies Association, the stratigraphic and geographic location of washover fans is not predictable. These washover sands are isolated, with sharp contacts at their base and top with central basin muds (Fig. 2, G). Each washover fan varies in thickness and stratigraphic location. Washover fans are found in 5 outcrops: Mixing Bowl, Shelf Road, South Twin Mountain, Type Quarry and Route 50. Most of them, with two exceptions found at the top of Route 50 and Shelf Road, occur near the base of the Lagoon Facies Association. The middle of the Lagoonal Facies Association is always devoid of washover fan deposits.

Interpretation.---The presence of one flood tidal delta in the Harding suggests that it was deposited within a microtidal low wave estuarine/lagoonal environment because microtidal coasts possess few tidal inlets and flood tidal deltas (Hayes 1975; Boothroyd 1985). As tidal range increases, flood tidal deltas tend not to develop whereas ebb tidal deltas become prevalent (Hayes 1980). The rarity and thinness of flood tidal delta facies in the Harding also suggests that wave conditions were low because large waves tend to favor the deposition of flood tidal deltas (Hayes 1980; Hubbard et al. 1979).

Bayhead deltas deposit fluvially derived sand as they prograde into a lagoon or bay and resulted in interbedded sands and muds that coarsen upwards into sand-dominated mouthbar deposits (Bhattacharya and Walker 1992). In the Harding, this complete succession does not occur because these successions are interrupted by flooding surfaces.

Washover fans are common on modern microtidal coasts because storm surges, which create washover fans, can easily erode through the relatively narrow barrier islands and deposit sands derived from the barrier island into the lagoon (McGowen and Scott 1975). As the storm subsides, deposition on the washover fan stops and their subaqueous portions become subject to biotubation, which allows steeply dipping foresets to be obscured (Boothroyd 1985). This creates isolated, irregular and thin sandstone beds, like those seen in the Lagoonal Facies Association. Over time, widening of the barrier island by deposition on the seaward side can lead to a decrease in development and deposition of washover fans (Davies et al. 1971; Hobday and Jackson 1979). This pattern is seen in the Harding, in which most occurrences of washover fan deposits occur near the base of the Lagoonal Facies Association.

Microtidal barrier island or estuarine systems have four characteristic types of sandstone bodies. The barrier islands themselves are characteristically thin and elongate with few tidal inlets (Hayes 1975). The rarity of tidal inlets reduces the frequency of a second type of sandstone body, flood tidal deltas. When flood tidal deltas do form, the low tidal amplitude and shallowness of the lagoons causes the flood tidal delta deposits to be relatively thin (Hayes 1975; Hubbard et al. 1979). Rivers form bayhead deltas on the landward side of the lagoon. Lastly, a thin barrier island is susceptible to storm surges and thus washover fans are abundant (McGowen and Scott 1975). Each of these sandstone bodies is seen in the Harding and they collectively argue for a microtidal interpretation.

It is difficult to determine whether these facies were deposited within a lagoon or within a bay of a partially enclosed estuary (Reinson 1984). Based on the facies interpretation alone, these environments are too similar and cannot be differentiated. Distinguishing these environments would require additional outcrops that run regionally parallel to the shoreline. Oriented perpendicular to the shoreline, the central basin muds of a bay would be laterally restricted along the coastline. A lagoon, oriented parallel to the shoreline, would be laterally extensive parallel to the shore. In the Harding, the shoreline is interpreted as running from north to south. Unfortunately, the Cañon City area is well within the scale of modern partially enclosed estuaries and key outcrops outside its dimensions, located to the north or south such as Beulah, are poorly exposed. Without better exposure, it is not possible to determine whether these central basin mudshales reflect depositions in a lagoon or a partially enclosed estuary.

Based on the relationship between the Lagoonal Facies Association and Shoreface Facies Association throughout the Harding, the north-south shoreline laid both east and west of the Cañon City area. A north-south shoreline interpretation is supported by facies distributions as well as limited paleocurrent evidence including gently landward inclined laminae, trough cross-beds, and lateral accretion surfaces. During the first series of Shoreface Facies Association parasequences, the shoreline lay to the east of Cañon City, with open ocean to the west (Fig 5.). During the deposition of the Lagoonal Facies Association, in the middle of the Harding, the shoreline must have been to the west of Cañon City. The shoreline returned to the east of Cañon City as the Shoreface Facies Association become dominant at the top of the section.

SEQUENCE STRATIGRAPHY

Flooding Surfaces

Flooding surfaces in the Harding are characterized by abrupt facies changes and features of stratigraphic condensation. These two features can occur together or in isolation. Abrupt facies changes are expressed as a sharp contact of deeper facies overlying shallower facies. Abrupt changes in facies are the typical expression of a flooding surface and such sharp contacts are indicative of a non-Waltherian facies succession (Van Wagoner et al. 1990).

Condensation features found on flooding surfaces are easily recognizable. These layers are identified by their distinctive maroon to brown color (Fig. 7, B, C). These iron-stained surfaces have been widely recorded on flooding surfaces in carbonate facies (e.g., Nicolaides and Wallace 1997; Holland and Patzkowsky 1998; Mutti and Bernoulli 2003). Holland and Patzkowsky (1998) attributed similar iron-stained hardgrounds to prolonged bacterially-mediated sulfate reduction during a slow in sedimentation during a relative rise in sea level.

Concentrations of fragmented lingulids, bivalves, gastropods, crinoid columnals and fish plates are preserved on flooding surfaces and layers range from 2 to 10 centimeters thick. These accumulations of bioclasts represent a period of slow deposition or sediment starvation (Kidwell 1991). Slow rates of deposition commonly occur during the time of initial flooding (Brett 1995). These shell beds are expected above flooding surfaces at the base of a parasequence (Banerjee and Kidwell 1991).

Burrowing mottling is also present at these surfaces as is <u>Thalassinoides</u>, which is preserved just above the condensation layer. <u>Thalassinoides</u> indicates firmground conditions during a deepening event. It has previously been recorded at condensed disconformities in the Miocene in Maryland (Kidwell 1989). All of these condensation features are evidence of flooding surfaces.

Sequence A

The contact between the Manitou Limestone and the overlying Harding Sandstone is a sequence boundary. Subaerial exposure on this surface is evidenced by a paleokarst. The paleokarst is represented by relief up to 20 cm over 1 m in the underlying limestone (Fig. 7, A). The Harding was deposited on the irregular topography of the Manitou Limestone. The contact is directly overlain by a regolith. It is only seen at one outcrop, Priest Canyon and is a weathered purple to yellow mottled siltstone. This regolith is directly overlain by a quartz coarse-grained sand to pebble lag. This lag lies in the Transition Zone and Shoreface Facies. It is usually structureless but large-scale trough cross-bedding is rarely found in it. Where the regolith does not occur, the lag directly overlies the contact.

In the western outcrops, the basal sequence boundary is overlain by two parasequences, both composed of Shoreface Facies Association. Based on the decrease in thickness of the shoreface in the upper portion of these parasequences, they are considered to be retrogradationally stacked and placed within the transgressive systems tract. The presence of the transgressive systems tract immediately overlying the sequence boundary suggests that the sequence boundary is also the transgressive surface implying that the lowstand system is farther to the west. These transgressive systems tract parasequences cannot be correlated to the east and are inferred to onlap eastward onto the basal sequence boundary.

Overlying the transgressive systems tract is the maximum flooding surface and the highstand systems tract (Fig. 9). In the highstand systems tract, there are two parasequences of the Shoreface Facies Association that correlate across all of the outcrops. The increased thickness of shoreface facies in the upper parasequence indicates progradational stacking. The location in the sequence, above the transgressive systems tract, suggests that this is the highstand systems tract. In the eastern outcrops, the lowstand and transgressive systems tracts are not present. Here, the basal contact of the sequence is a combined sequence boundary, transgressive surface and maximum flooding surface.

Sequence B

The mid-Harding sequence boundary represents a basinward shift in facies that is expressed differently in western and eastern outcrops. In the west, transition zone facies are overlain in a sharp contact by shoreface facies (Fig. 7, E).   In the east, the Lagoonal Facies Association directly overlies the Shoreface Facies Association. At the Type Quarry, a layer (0.5 m) of fragmented bivalve shells dispersed within central basin muds lies just above this sequence boundary. This sequence boundary is best exposed in the east where washover fan or bayhead delta facies directly overlie shoreface facies. Because the central basin facies is poorly exposed, this sequence boundary is usually covered in the east except at the Type Quarry.

In the west, a possible lowstand systems tract and the transgressive systems tract composed of the Shoreface Facies Association overlie the mid-Harding sequence boundary (Fig. 9). There are three parasequences of Shoreface Facies Associations in this section. The basal two parasequences only correlate across only three outcrops (Fig. 9). In these parasequences, there is little facies change, suggesting an aggradational stacking pattern. Because of this, they could be within the lowstand systems tract or the transgressive systems tract. The third parasequence shows a significant deepening compared to the underlying parasequence. Because of this, it is interpreted as lying within the transgressive systems tract.

In the Cañon City area, the Lagoonal Facies Association overlies the mid-Harding sequence boundary (Fig. 9). The first parasequence consists of Lagoonal Facies Association that correlates to the Shoreface Facies Association down dip. The individual facies of the Lagoonal Facies Association discussed previously each record a local shallowing event on a small scale and are not correlatable between outcrops. The Lagoonal Facies Association is overlain by a flooding surface with a Shoreface Facies Association parasequence above it. Lagoonal or estuarine systems and their associated facies tend to occur during transgressions (Zaitlin et al. 1994). Because of this, these parasequences are interpreted as the transgressive systems tract.

The highstand systems tract contains three parasequences that can be correlated across all outcrops (Fig. 9). These parasequences are composed of stacked shoreface facies. Based on the minimal change of facies across flooding surfaces and the overall dominance of shoreface facies, these parasequences are interpreted to display aggradational to progradational stacking and are interpreted as the highstand systems tract.

In the highstand systems tract, there are two occurrences of high-frequency sequence boundaries (cf. Mitchum and Van Wagoner 1991). These surfaces can be characterized by a coarse grained lag with little to no facies change. It is composed of subrounded quartz grains and can be up to 10 cm thick. This high-frequency sequence boundary is seen at Chubb Park, Wellsville and Bushnell Lakes. The second lies in the east and is represented by an abrupt facies change. At Route 50, Shelf Road, Type Quarry and possibly South Twin Mountain a thin occurrence of central basin facies overlie shoreface facies. In a highstand systems tract on a low accommodation shelf such as the Harding, high-frequency sequences are expected to occur (Mitchum and Van Wagoner 1991).

The upper sequence boundary is represented by the contact between the Harding Sandstone and the overlying Fremont Dolomite or Fountain Formation. In the west, the strata beneath this contact are tightly cemented and stained to dark maroon to purple indicatative subaerial exposure. In the east, this weathering profile is expressed as a paleosol, which records subaerial exposure.

THE OCCURRENCE OF FISH IN THE HARDING

Previous workers (Walcott 1892; Denison 1956; Sansom et al. 1997; Spjeldnaes 1979) have commented on the abundance of disarticulated fish remains. Only three articulated fish have ever been reported from the Harding (Walcott 1892; Lehtola 1983; Sansom et al. 1997). Fish fossils in the Harding are generally preserved as disarticulated fragments of mineralized skeletal plates. The plates can be elongate, circular or square. They average approximately 5 mm in size, but can be as small as 2 mm or as large as 1 cm in length.

Fish plates occur most abundantly on flooding surfaces, particularly where there is evidence of condensation, such as iron staining (Fig. 4, B, Fig. 7, B, C). Of the 62 horizons at which fish plates were found, 53 occurred at flooding surfaces (Table 1). Depending on the size of the plates, these fish can be found in concentrations up to 5 plates per square centimeter. Higher concentrations correspond with horizons at which fish plates are smaller in size. Less commonly, fish plates are preserved within a burrowed bed or an individual burrow fill, with a total of 9 occurrences in either of these settings. The location of fish plates suggests that disarticulation occurred during the time in which the flooding surface was formed. The concentrations of fossils on these beds suggest that they have been highly time averaged (Behrensmeyer et al. 2000). For occurrences within beds, bioturbation may have also been a means of disarticulation, particularly where a lack of lamination suggests intense levels of burrowing.

Fish plates are also commonly associated with shoreface facies (54 of 62 horizons; Table 2). This total includes all fossil occurrences within beds as well as those that lie at flooding surfaces that border the shoreface facies. Shoreface facies accounts for 62% of the total exposed outcrop, while 87% of the fish occur within this facies. Two occurrences of fish plates lie within tidal inlet facies. Four lie within washover fan facies, and the remaining two are within central basin facies.

Reconciling Previous Studies on the Depositional Environment of the Harding

Because most previous studies agreed that the Harding contains marine facies, the first critical issue surrounds the location of fish plate occurrences in the Harding. Originally, there was no debate between Walcott (1892), Romer and Grove (1935), Robertson (1957) and Denison (1956, 1967), as they all agreed that the fish were deposited in a marine environment. The disparity arose from Romer and Grove's claim that the fish fossils were transported to a marine setting in from a fluvial environment.

Romer and Grove's (1935) conclusion was based on the littoral nature of the deposit and fragmented nature of the fish fossils. Denison (1956, 1967) and Robertson (1957) later concluded that this extensive disarticulation was caused by marine activity such as waves and longshore drift, rather than fluvial transport. Given the location of fish plates in the Harding, it is likely that much of the disarticulation was caused during the creation of flooding surfaces.

Three modern studies have examined the depositional environment of the Harding and each came to a different conclusion regarding the habitat of fish in the Harding. At the Indian Spring outcrop, Fischer (1978) attributed an array of trace fossils in the Harding to a diverse set of aglaspidids, limuloids, and scorpions. This unique trace fossil assemblage was interpreted to be at the top of an estuarine point bar deposit and overlain by tidal mudflat deposits. Facies below the trace fossil horizon were interpreted as coarse grained alluvial channel sands overlain by current laminated sands and then rippled sands. Fischer (1978) stated that an articulated fish fossil was found in association with the trace fossil bed, implying that the fish shared the same environment as the trace makers.

There are both similarities and differences between Fischer's (1978) interpretation of Indian Springs and mine. Instead of an estuarine channel lag, I interpret the lag as a transgressive lag lying above the transgressive surface, maximum flooding surface and sequence boundary. I interpret the facies underneath the trace fossil bed as a flood tidal delta rather than channel sands. Fischer interpreted the overall environment as estuarine, which is similar to my interpretation. While the overall environmental interpretations are similar, the interpretation of the fish's habitat differs. The fish fossil at Indian Springs has not been documented since Fischer. Even if fish were found within central basin facies, the rarity of fish found in this facies and the abundance found in the shoreface lead me to believe that the fish Fischer found was transported in from an open marine habitat.

Spjeldnaes (1979) examined the widest range of criteria in his study of the Harding at the Type Quarry. Some of these, such as mineral composition and the petrography of quartz grains, are not diagnostic for interpreting depositional environment and will not be discussed further. His diagnostic criteria include sedimentary structures, boron, and fossils. Spjeldnaes (1979) concluded that the lack of sedimentary structures in the Harding was a result of bioturbation.   He conducted a boron analysis to infer paleosalinity, even though he states the Harding lacks the abundant illite needed to contain the boron. He found that the Harding contained extremely high values of boron, suggesting hypersaline conditions at the high end of an environment characterized by fluctuating salinity. His trace and body fossil assemblage consists of straight unbranching burrows, vertical borings, Chondrites, Lockeia, Diplocraterion, conodonts, inarticulate brachiopods, bivalves, gastropods and cephalopods, all of which were encountered in this study. Based on the diversity of genera, he concluded that the area was highly biologically active. These lines of evidence were used to support the interpretation that the environment was shallow marine in an intertidal to shallow subtidal setting.

Spjeldnaes's conclusions are similar to those in this study. I agree that the lack of sedimentary structures is due to bioturbation. Because he states that the Harding is illite poor, it is difficult to have confidence in the boron analysis. On a low wave energy microtidal coast dilution of inflowing waters by marine processes is greatly slowed and with a freshwater influence coastal water should be somewhat brackish. I concur that the fauna suggests an open marine system. One disparity between my arguments is that Spjeldnaes interprets the habitat as including the intertidal zone, but I found no evidence of intertidal conditions. Furthermore, on a microtidal coast, the intertidal zone would be expected to be narrow. Generally, I agree with Spjeldnaes that the fish habitat was an open marine shallow subtidal/shoreface environment.

Graffin (1992) described the sedimentary structures and lithology in a facies analysis of the Manitou Limestone, Harding Sandstone and Fremont Dolomite at the Bushnell Lakes exposure. He interpreted most of the Manitou, Harding and Fremont as shoreface, foreshore and offshore, except for the uppermost Harding, which he interpreted as fluvial. This conclusion was based on the presence of a basal coarse-grained lag that graded upward into epsilon bedding, or lateral accretion surfaces, with trough cross-bedding. Because the fish were found in this uppermost facies of the Harding, he concluded that the fish lived in a freshwater fluvial environment.

Graffin (1992) was first to interpret the fish as having lived and been buried within a fluvial environment. While most of his facies are interpreted as marine, the discrepancy lies in the beds containing fish fossils. I interpret the lag to be the result of a high-frequency sequence boundary. This is based on the lack of normal grading from coarse to fine that would be expected in fluvial deposits. The lag is overlain and underlain by a sharp contact with fine-grained sandstone. The lateral accretion surfaces reported by Graffin were not found. If they are present, they may well occur within a tidal inlet facies, which can occur with the shoreface facies as seen in the Harding at Shelf Road. The tidal inlet facies contains trough cross-stratification and is similar lithologically to the Shoreface Facies, supporting a tidal inlet interpretation for Graffin's fluvial deposits.

Even if Graffin's interpretation was correct, fluvial facies are not seen throughout the rest of the Harding. None of the facies in the Harding fine upwards, as would be expected in a fluvial channel facies. The main diagnostic sedimentary structures, large-scale trough cross-stratification that grade upwards into small-scale trough cross-stratification, are missing. Erosional beds with lateral accretion surfaces only exist in tidal inlet facies. The structureless beds within the tidal inlet facies would not be expected since, bioturbation in a fluvial channel is kept to a minimum. Laterally adjacent environments are also missing, including floodplain deposits with numerous paleosols. Without these features, the Harding is interpreted as it originally was by Walcott as open marine.

While many previous works share similar interpretations to mine, there are differences within the specific details of each depositional environment. The marine processes that result in disarticulation described by Robertson (1957) and Denison (1956, 1967) are thought to play a secondary role relative to bioturbation. In the modern studies, differences lie in the occurrence of fish within the Harding, as in Fischer (1978) and Graffin (1992), and the type of open marine environments the fish inhabited, as in Spjeldnaes (1979).

CONCLUSIONS

1. The Harding Sandstone was deposited on a low wave energy microtidal coast. The majority of the outcrops are composed of shoreface and transition zone facies and

have all been partially or completely bioturbated. The low wave energy condition of the coast has allowed extended burrowing by infauna and resulted in the destruction of most of the physical sedimentary structures. The remaining facies of the Harding-- lagoonal muds, flood tidal deltas, bayhead deltas and washover fans-- are characteristic of a barrier island or estuarine system. They suggest the development of a microtidal lagoon or bay during the major transgression recorded in the Harding.

2. Flooding surfaces in the Harding Sandstone are characterized by condensation layers and sharp contacts between facies. Some flooding surfaces are characterized by both features, some by only one. Most fish plates found in the Harding occur at these condensed layers at flooding surfaces.

3. The Harding consists of two depositional sequences. The first is completely composed of Shoreface Facies Association. It contains a transgressive and highstand systems tract in the west and only a highstand systems tract in the east. The second sequence consists of transgressive and highstand systems tracts that can be correlated throughout the entire study area. The transgressive systems tract of the second sequence consists of transition zone and shoreface facies in the west and lagoonal and shoreface facies in the east. The highstand of the second sequence locally contains high-frequency sequences.

4. The Harding fish are interpreted to have lived within the shoreface environment. The disarticulated nature of the fish is interpreted to be the result of reworking and time-averaging during the creation of flooding surfaces, possibly aided by bioturbation. Fish plates are found most abundantly on flooding surfaces of Shoreface Facies.

CHAPTER 3

CONCLUSIONS

The Harding Sandstone was deposited on a low wave energy microtidal coast. Shoreface and transition zone facies are the most dominant in the Harding. The most striking feature of these facies is their lack of physical sedimentary structures. This is interpreted to be the result of extensive bioturbation. Low wave energy conditions allowed burrowing infauna to completely rework the sediment. A lesser amount of the Harding is composed of central basin muds, flood tidal delta, bayhead delta and washover fan facies. These facies are interpreted to be deposited within a microtidal lagoonal or bay setting.

Flooding surfaces are characterized by sharp contacts and condensation layers. Fish plates are found abundantly on these layers.

The Harding has two sequences. The first is composed of all Shoreface Facies Association in the transgressive and highstand systems tract in the west and highstand systems tract in the east. The second sequence contains a transgressive systems tract of Shoreface Facies Association in the west and Lagoonal Facies Association and Shoreface Facies Association in the east. The highstand systems tract is composed of mostly stacked shoreface facies.

Fish are mostly found disarticulated on flooding surfaces in association with the shoreface facies. Less commonly fish plates occur within bed. The disarticulation of the fish is attributed to time averaging on a flooding surface. Because fish plates are most commonly found in shoreface facies associated deposits and less commonly in a lagoonal or bay setting, the habitat of the fish in interpreted to be open shallow marine.

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Figure 1: Locations of Harding outcrop belts (light grey) and measured sections in central Colorado. Line connecting localities shows path of cross-section in Figure 9. B: Beulah, BL: Bushnell Lakes, CB: Chubb Park, C: Cotopaxi, FC: Phantom Canyon, GH: Gnat Hollow, IS: Indian Springs, MB: Mixing Bowl, PC: Priest Canyon, R5: Route 50, SM: Sheep Mountain, SR: Shelf Road, STM: South Twin Mountain, TB: The Bank, TQ: Type Quarry, W: Wellsville.

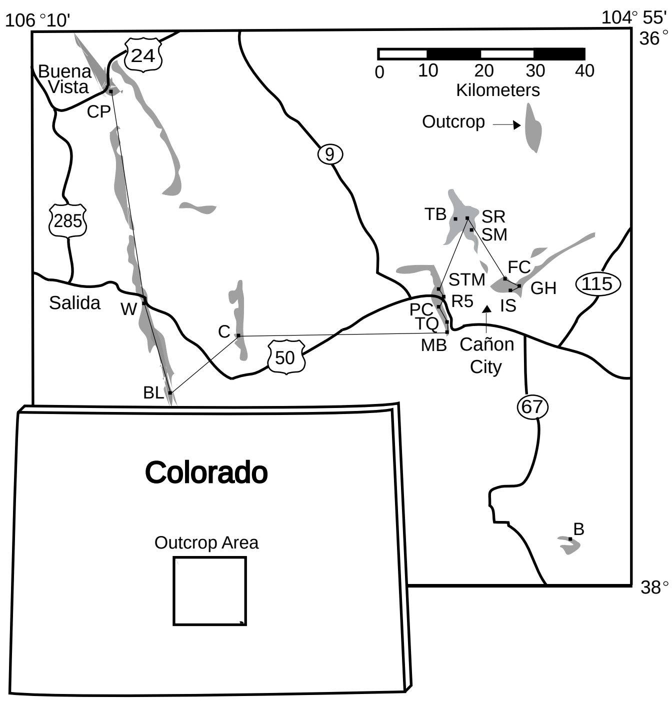

106 °10'
104° 55'
36°
38°
Buena
Vista
CP
24
285
Salida
W
BL
C
50
9
0
10
20
30
40
Kilometers
Outcrop
TB
SR
SM
STM
FC
GH
115
R5
PC
TQ
MB
IS
Cañon
City
67
B
Colorado
Outcrop Area

Figure 2: Outcrop photographs of the Harding Sandstone facies. **A**.) Coarsening upward section of transition zone facies at Gnat Hollow, meters 4-8. (Jacob staff marked in decimeter increments.) **B**.) Upward bed thickening from transition zone facies to shoreface facies at Bushnell Lakes, meters 9-16. **C**.) Thin, slightly upward coarsening beds of bayhead delta facies at Type Quarry, meters 19-20. **D**.) Highly bioturbated shoreface facies at Shelf Road, meters 21-24. **E**.) Section of thinly bedded mudshale interpreted as lagoonal facies at Shelf Road, meters 10.5-18.6. A 20 cm washover sand bed is present near the base, meter 10.8-11. White arrow points to a flooding surface. **F**.) Contact with Manitou Formation covered by lag and a coarsening upward section of flood tidal delta facies at Indian Springs, meters 0-3. The flood tidal delta facies is overlain sharply by bay head delta facies. **G**.) Lagoonal shales with washover fan sands at Route 50, meter 13.5-14.5.

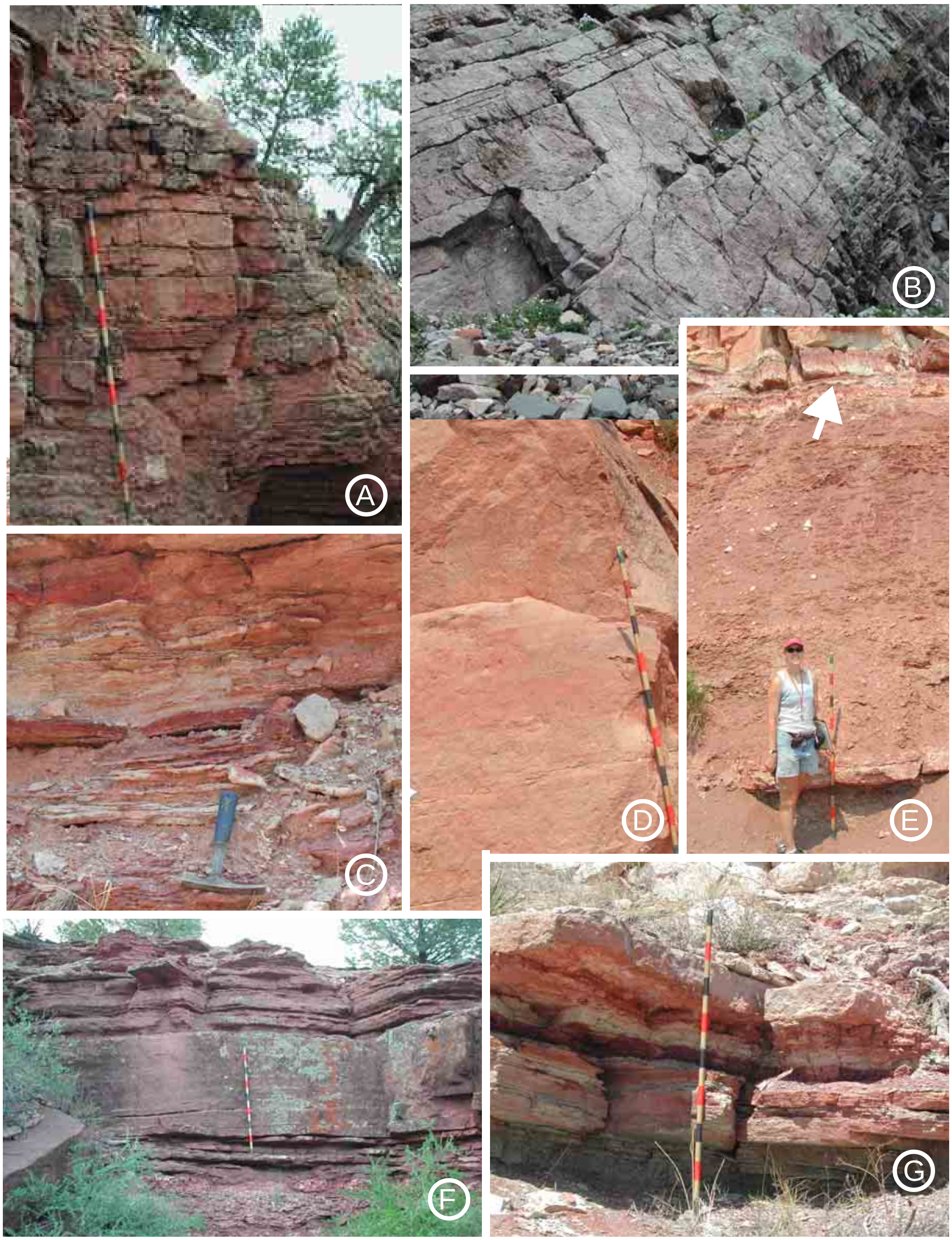

A
B
C
D
E
F
G

Figure 3: Wavy and planar bedding surfaces in transition zone facies at Sheep Mountain, meter 3 (card=9 cm).

Figure 4: Body and trace fossils of the Harding Sandstone. **A**.) Fish plates found in a concentration at Cotapaxi, meter 40.3. White arrow points to a single plate. (Scale ticks=1 mm) **B**.) Fish plate concentrated on a flooding surface at Type Quarry, meter 20.9. White arrow points to highly concentrated cluster of plates. **C**: Burrow cast on the base of a bed at Type Quarry, meter 5.4. **D**.) Burrowed fabric on the side of a very thick bed of shoreface facies at Mixing Bowl, meter 6.5. **E**.) <u>Thalassinoides</u> preserved above a flooding surface capping the shoreface facies at Type Quarry with pencil for scale, meter 21.1. **F**.) <u>Arenicolites</u> preserved in a very thick bioturbated shoreface bed at Shelf Road, meter 8.3.

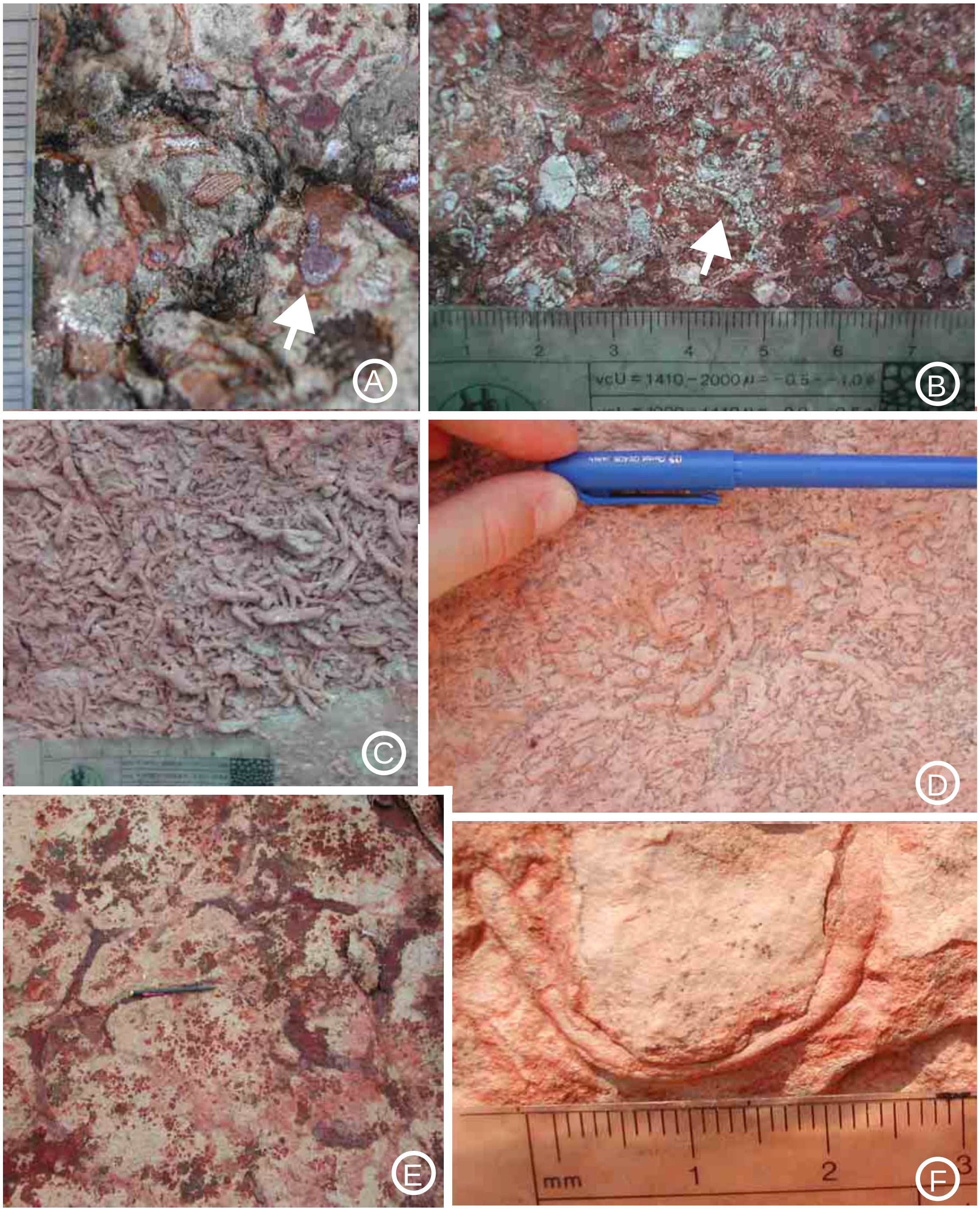

A
B
C
D
E
F
mm

Figure 5: Paleogeographic map of central Colorado at the top of Sequence A. The shoreline is aligned approximately north-northeast and the transition zone shoreface contact follows this same alignment. Cañon City lies near the shoreline with open marine environment to the west.

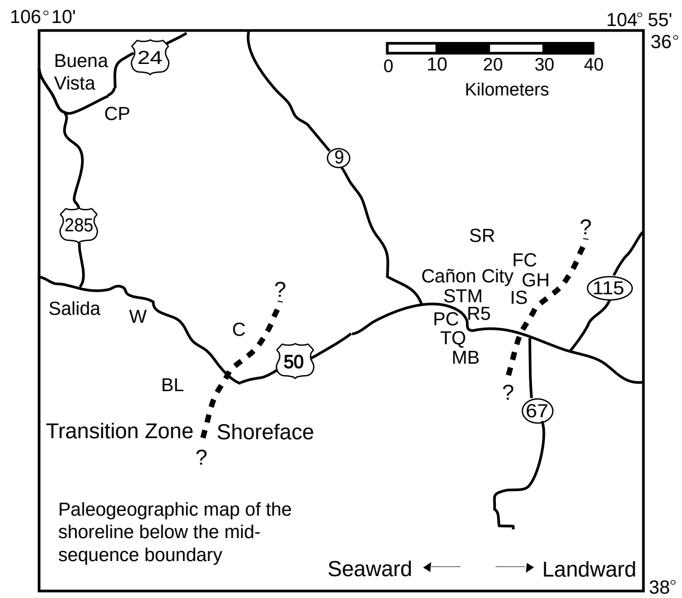

106° 10'
104° 55'
36°
38°
0 10 20 30 40
Kilometers
Buena Vista
24
CP
285
9
Salida
W
C
BL
50
SR
FC
GH
Cañon City
STM
IS
PC
R5
TQ
MB
115
67
?
Transition Zone
Shoreface
Paleogeographic map of the shoreline below the mid-sequence boundary
Seaward
Landward

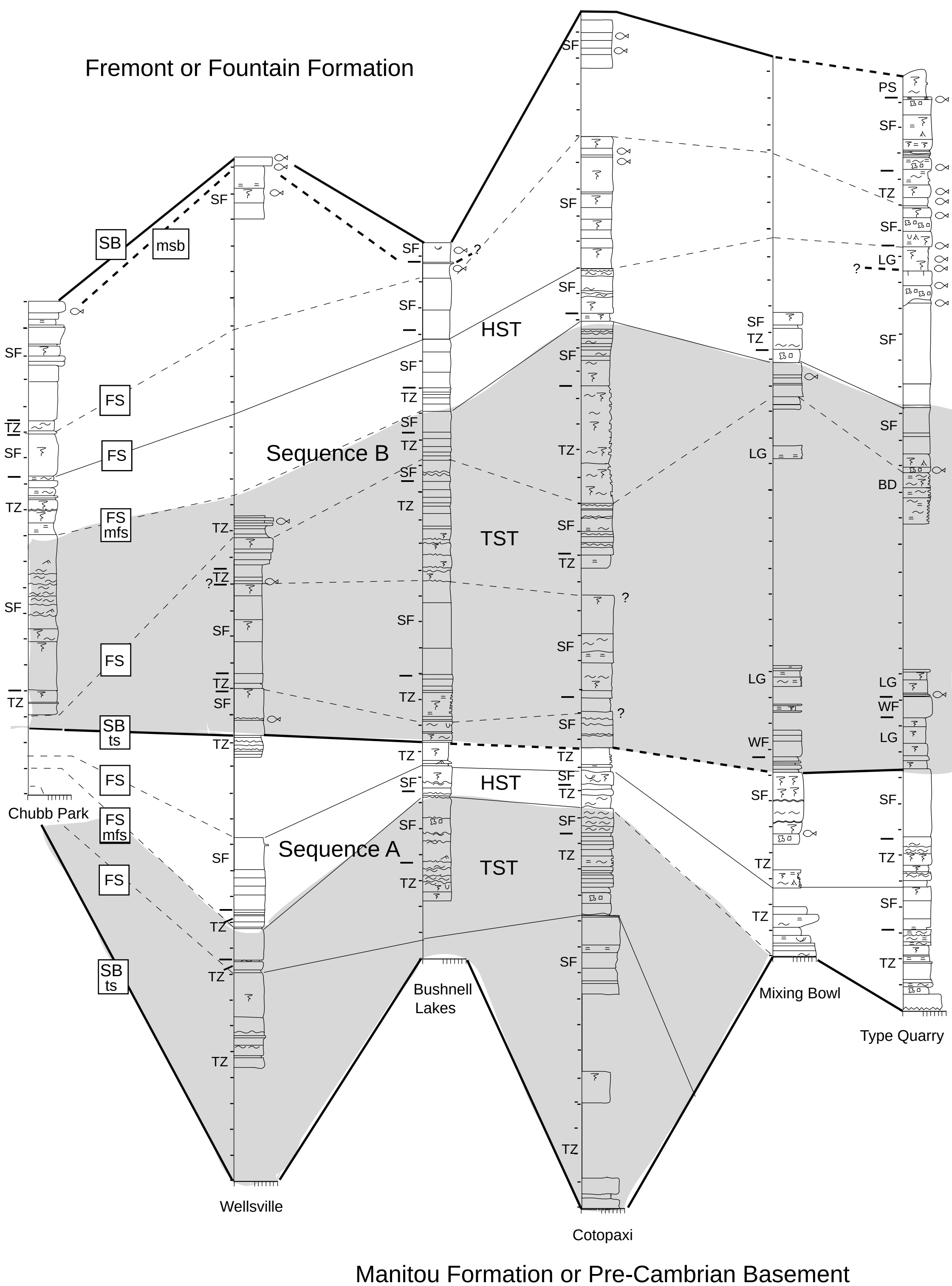
Figure 6: Tidal inlet facies at the meter position, 32-34 of Shelf Road. Note lateral accretion surfaces dipping to the right (arrow).

Figure 7: Outcrop photographs of flooding surfaces and sequence boundaries within the Harding Sandstone. **A**.) Basal sequence boundary and contact between the Manitou Formation and the Harding Sandstone at Shelf Road. Vertical relief of 20 cm over 1 meter laterally is seen at this contact. **B**.) Flooding surface, at the finger, recognized by shoreface facies overlying bayhead delta facies at Type Quarry, meter 20.9. This surface is stained reddish brown and contains a concentration of fish fragments. <u>Thalassinoides</u> is preserved just above this surface (Figure 4, E). **C**.) Flooding surface marked by a dark red color and fish concentrations at Priest Canyon, meter 17.7. White arrow points to fish scales concentrated at the base of the photograph. Black arrow points to burrow mottling that occurs throughout the Harding. **D**.) The upper sequence boundary and contact between the Harding Sandstone and Fremont Formation at Type Quarry. The paleosol can be seen in the bottom half of the picture. **E**.) The mid-sequence boundary at Wellsville with shoreface facies overlying transition zone facies, meter 17.


A
B
C
D
E

Figure 8: A thin layer of transition zone facies between two thick beds of shoreface facies representing the Shoreface Facies Association found at meter 24, Shelf Road.

Figure 9: Correlated cross-section of measured outcrops of Harding Sandstone as shown in Figure 1. East-west direction between most sections is less than 10 km; east-west direction between Mixing Bowl and Cotopaxi is roughly 40 km. Harding consists of two sequences. Both sequences lack lowstand systems tracts. Sequence A's trangressive systems tract is only preserved in the west. In Sequence B, the transgressive and high-stand system tracts are preserved. Note lack of systematical regional variation in thickness, suggesting a continental shelf with a low slope.



Fremont or Fountain Formation
SB
msb
FS
FS
FS
mfs
FS
SB
ts
FS
FS
mfs
FS
SB
ts
Sequence B
Sequence A
HST
TST
HST
TST
Chubb Park
Wellsville
Bushnell
Lakes
Cotopaxi
Mixing Bowl
Type Quarry
Manitou Formation or Pre-Cambrian Basement

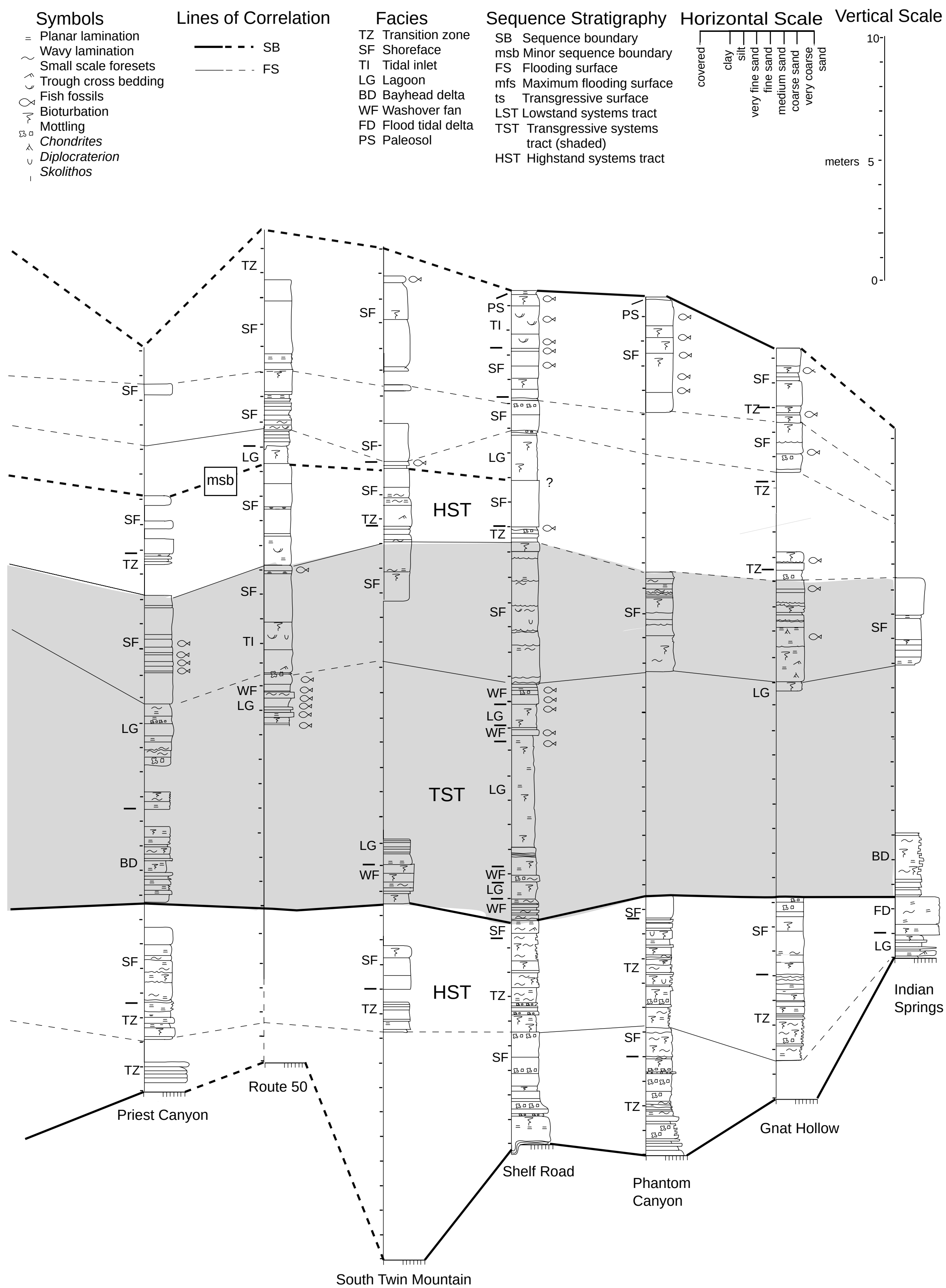

Symbols
Planar lamination
Wavy lamination
Small scale foresets
Trough cross bedding
Fish fossils
Bioturbation
Mottling
Chondrites
Diplocraterion
Skolithos
Lines of Correlation
SB
FS
Facies
TZ Transition zone
SF Shoreface
TI Tidal inlet
LG Lagoon
BD Bayhead delta
WF Washover fan
FD Flood tidal delta
PS Paleosol
Sequence Stratigraphy
SB Sequence boundary
msb Minor sequence boundary
FS Flooding surface
mfs Maximum flooding surface
ts Transgressive surface
LST Lowstand systems tract
TST Transgressive systems tract (shaded)
HST Highstand systems tract
Horizontal Scale
covered
clay
silt
very fine sand
fine sand
medium sand
coarse sand
very coarse sand
Vertical Scale
10
meters 5
0
msb
HST
TST
HST
Priest Canyon
Route 50
South Twin Mountain
Shelf Road
Phantom Canyon
Gnat Hollow
Indian Springs

Table 1.---Concentrations of fish plates on flooding surfaces and beds in the Harding.

Location	Number of Occurrences	Average Concentration (plates per cm^2)	Standard Deviation
Flooding Surface	52	1.25	1.46
Bed	9	0.40	0.45

Table 2.---Concentration of fish fossils for each facies that contains fish in the Harding.

Facies	Percentage of Exposed Facies	Percentage of Fish Occurrences (n=62)	Average Concentration (plates per cm^2)	Standard Deviation
Shoreface	62	87	1.10	1.31
Tidal Inlet	>1	3	0.03	0.04
Washover Fan	3	6	2.11	1.86
Lagoon	3	3	1.45	1.48
TOTAL	68	100	1.17	1.41

APPENDIX A

FISH OCCURRENCES THROUGHOUT THE HARDING

Outcrop	Facies	Meter	Size (L or S)	Surface(T or S)	Abundance	Side length	Area (cm^2)	Density (cm^2)
RF	LG	0.1	S	S	10	2	4	2.50
RF	LG	0.9		S	10	5	25	0.40
GH	SF	19.1	S	T	9	10	100	0.09
GH	SF	19.6	S	S	13	2	4	3.25
GH		19.6	S	T	16	2	4	4.00
GH	SF	22	S	T	18	10	100	0.18
GH	SF	26.4	S	S	5	2	4	1.25
GH	SF	26.9	L	T	20	5	25	0.80
GH		28.1	S	S	30	5	25	1.20
GH	SF	28.2-18.3	S	S	31	3	9	3.44
MB	SF	4.5	L	S	5	10	100	0.05
MB		22.4	S	S	30	5	25	1.20
MB	SF	22.4	S	T	20	2	4	5.00
PC		16.8	S	S	47	5	25	1.88
PC	SF	16.8	S	T	18	5	25	0.72
PC	SF	17.3	S	S	13	10	100	0.13
PC	SF	17.6	S	S	20	2	4	5.00
PC		17.9	S	S	25	5	25	1.00
PC	SF	17.9	S	T	20	2	4	5.00
RF	SF	1.7-1.9		S	22	5	25	0.88
RF		1.9		S	28	5	25	1.12
RF	SF	2.2		S	3	10	100	0.03
RF	SF	8.8		S	31	5	25	1.24
RF	SF	11.6		S	4	5	25	0.16
TQ	WF	12.1	S	T	43	3	9	4.78

TQ		27.3	S	T	7	2	4	1.75
TQ	SF	27.2-27.3	S	S	5	10	100	0.05
TQ	SF	27.3-27.4	S	S	6	10	100	0.06
TQ	SF	28	S	S	1	20	400	0.00
TQ	SF	28.4	L	T	8	3	9	0.89
TQ	SF	28.5	S	S	12	5	25	0.48
TQ	SF	29.4-29.6	S	S	1	20	400	0.00
TQ	SF	30.8	S	T	5	5	25	0.20
TQ	SF	31.2-31.7	S	S	1	20	400	0.00
TQ	SF	32.7	S	S	2	10	100	0.02
TQ		35	L	T	13	3	9	1.44
TQ	SF	35	S	S	7	3	9	0.78
FC	SF	31.2	S	S	21	5	25	0.84
FC		32.4	S	S	48	8	64	0.75
FC	SF	32.4	L	T	42	4	16	2.63
FC	SF	33.3	S	T	39	3	9	4.33
FC	SF	33.7-34.2	S	S	4	8	64	0.06
FC		34.2	T	S	42	10	100	0.42
FC	SF	34.2-34.8	S	S	21	10	100	0.21
SR	SF	18	S	S	18	6	36	0.50
SR	SF	18.3	S	S	43	8	64	0.67
SR	SF	18.4	S	S	18	5	25	0.72
SR		24.9	S	S	30	8	64	0.47
SR	SF	24.9	S	T	18	8	64	0.28
SR	SF	31.4	L	T	13	8	64	0.20
SR	SF	31.8	S	S	3	10	100	0.03
SR	SF	34.5	S	S	13	5	25	0.52
BL	SF	26.6	L	T	32	5	25	1.28

BL	SF	27.2	L	S	19	3	9	2.11
C	SF	40.4	S	S	11	8	64	0.17
C	SF	40.5	L	S	42	8	64	0.66
C		44.4	S	S	15	5	25	0.60
C	SF	44.4	S	T	54	5	25	2.16
C	SF	44.9	S	S	38	8	64	0.59
WV	SF	17.8	S	S	16	8	64	0.25
WV	SF	23	L	S	1	20	400	0.00
WV	SF	25.4	S	S	5	8	64	0.08
WV	SF	38	S	S	15	3	9	1.67
WV	SF	39	S	S	23	5	25	0.92
WV	SF	39.4	L	S	10	8	64	0.16
CP	SF	18.9	S	S	2	10	100	0.02
STM	SF	43.7			25	10	100	0.25
SR	TI	32.7	S	S	4	8	64	0.06
SR	TI	33.6	S	S	1	20	400	0.00
RF		1.1		S	7	2	4	1.75
RF	WF	1.2-1.3		S	1	10	100	0.01
RF		1.4		S	15	2	4	3.75
RF	WF	1.4		S	14	2	4	3.50
SR	WF	16.7	S	S	31	3	9	3.44
SR	WF	16.8	L	S	3	4	16	0.19
STM	SF	46.5						