The sedimentology and sequence stratigraphy of the Curtis Formation along the eastern San Rafael Swell, Utah

Arve Rein Nes Sleveland

Thesis submitted for the degree of
Master of Science in Geology
60 credits

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Abstract

Investigation of the marginal marine Curtis Formation of the Middle to Upper Jurassic succession, composed of the Entrada Sandstone, the Curtis Formation and the Summerville Formation, in ascending order. As a whole, the succession represents an alternation between continental and marine strata. The sedimentary succession is well exposed in east-central Utah, USA. Descriptive sedimentological data have been collected, from outcrops along the eastern flank of the San Rafael Swell, to link the Curtis Formation vertical and lateral variability to temporal and spatial distribution of depositional environments, and its relation to stratigraphically neighbouring units.

The Curtis Formation was deposited during tectonically induced marine transgression onto a low angle retroarc foreland basin, consistently dominated by tidal mechanisms. At the end of the transgression the Summerville Formation was deposited contemporaneously with the Curtis Formation as proximal and distal equals, respectively, as they record an unconformably bounded, full transgressive-regressive sequence (Peterson, 1994).

Utilization of sequence stratigraphic concepts reveal complex interfingering depositional architecture that directly related to the autogenically controlled spatial distribution of tidal sub-environments in a basin of dynamically shifting depositional environments. Accordingly, it is suggested that the Curtis Formation may be used as analogue for other tidally influenced environments in future sequence stratigraphic analyses.

Keywords: sedimentology, sequence stratigraphy, depositional environments, distribution of tidal sub-environments, North American Cordillera, retroarc foreland basin, paleoenvironment, Jurassic, Curtis Formation, San Rafael Group, Colorado Plateau, Utah

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Personal thanks go to may loving wife, for her unwavering support and faith in me, during long stays overseas conducting field work and especially during the last couple of months, when I spent most of my time at school, completing this thesis. Thanks are also due to my family and friends in supporting me through the work of this project.

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June 2016

Contents

Chapter 1: Introduction

The Jurassic sedimentary succession of Utah, USA, comprise a collection of sequentially alternating continental- and marine strata, that were deposited in a retroarc foreland basin related to the North American Cordillera (Hintze and Kowallis, 2009). These successive shifts in depositional environments have provoked geologists to resolve both local- and regional- to continental scale problems regarding the designated depositional development. The number of cross-disciplinary studies on these strata are consequently numerous. However, the understanding of the Middle to Upper Jurassic Curtis Formation of the San Rafael Group is limited to locally confined studies of intra-formational features (Eschner and Kocurek, 1986; Kreisa and Moiola, 1986) and regional- to continental scale studies covering tectonic regimes (Lawton, 1994; Peterson, 1994) and the successive development of depositional environments (Caputo and Pryor, 1991; Wilcox and Currie, 2008).

Through utilization of descriptive sedimentology and sequence stratigraphic concepts, this thesis revolves around the late Callovian-Oxfordian (Wilcox and Currie, 2008) Curtis Formation; a marginal marine unit that is situated between two continental deposits, the Entrada Sandstone below and the Summerville Formation above. The main scope of this study is to link the Curtis Formation vertical and lateral variability to a temporal and spatial distribution of depositional environments, and to discuss the relation to stratigraphically neighbouring units. Ultimately, the depositional architecture and its tie to basinal forcing mechanisms and a relative sea level curve is discussed.

Sedimentological data collected from 9 measuered sections in east-central Utah (see Figure 1.1 for map) along the eastern flank of the San Rafael Swell; a nearly continuous outcrop that extends ~100 km north-south. The recorded sedimentary succession covers the full Curtis Formation interval including its lower and upper transitions to the Entrada Sandstone and Summerville Formation, respectively, except at places where the Summerville Formation is eroded.

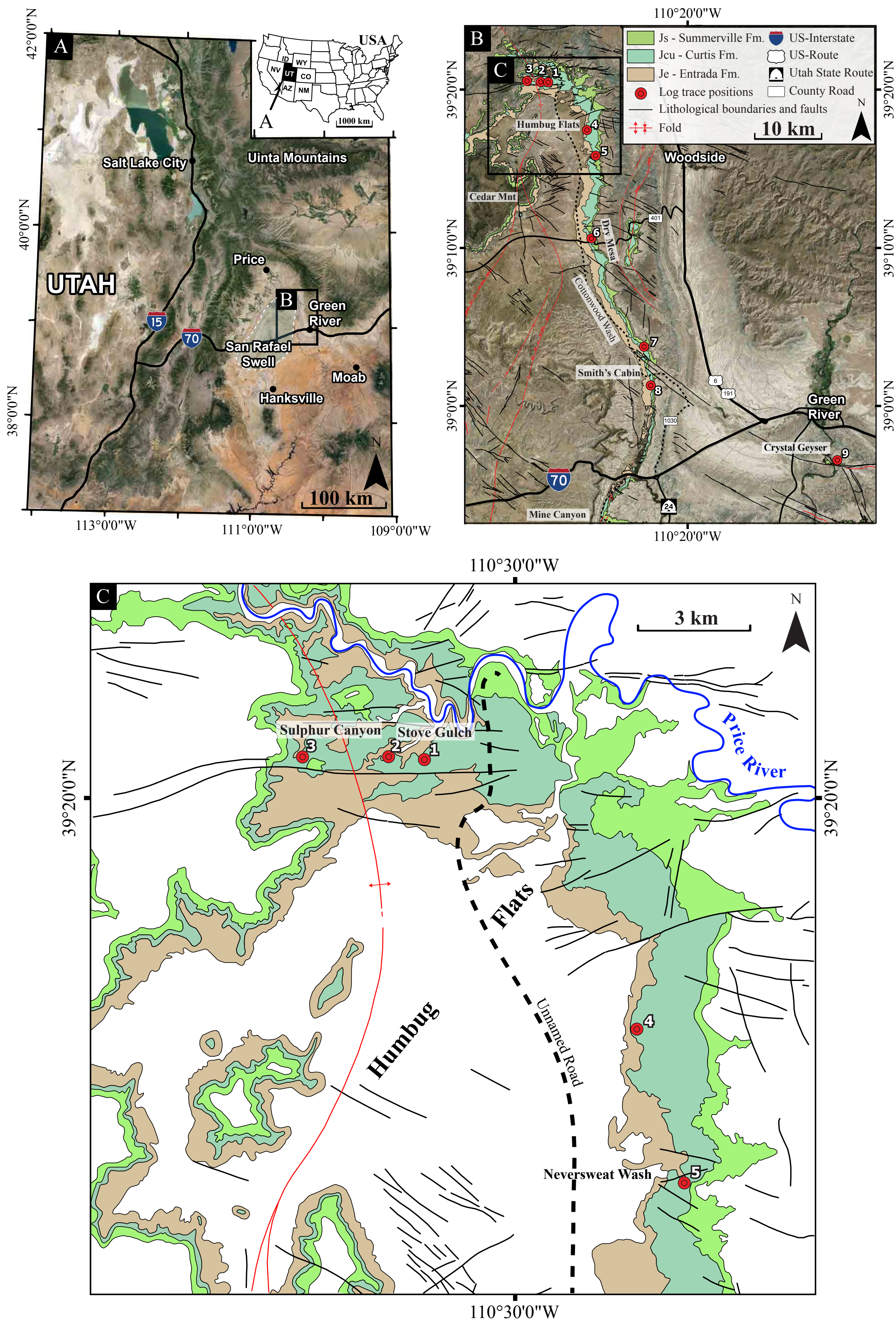


Figure 1.1: USA mini map: Overview of the contiguous USA showing location of Utah (**UT**) and bordering states; Idaho (**ID**), Wyoming (**WY**), Colorado (**CO**), New Mexico (**NM**), Arizona (**AZ**) and Nevada (**NV**) **A**: Map of Utah with key cities, towns and roads. See legend for symbology. **B**: Map of the designated study area with locality names, roads and log trace positions (see corresponding legend) as well as outcrops of the designated stratigraphic units. Note the geographically isolated locality of Crystal Geyser. **C**: Closer overview of northern part of the study area.

Chapter 2: Geologic framework

2.1 Mesozoic tectonic setting

Time periods of the Mesozoic Era includes the Triassic- (251 - 201 Ma), Jurassic- (201 - 145 Ma) and Cretaceous (145 - 66 Ma) periods (Cohen et al., 2013). Utah's geologic history has, since the Mesozoic Era, been profoundly influenced by the *North American Cordillera*; a series of partly overlapping orogenies initiated by a major tectonic event following the breakup of the supercontinent Pangaea (Hintze and Kowallis, 2009).

As the supercontinent Pangaea broke up during the Triassic Period, and formed the Atlantic Ocean, the North American continental plate drifted north-westward, parted from the South American continental plate, collided with a Pacific island arc system, ultimately resulted in the subsequent creation of a retroarc foreland basin towards the North American craton (Hintze and Kowallis, 2009). The collision towards the Pacific Ocean resulted in the development of a substantial subduction zone at the western margin of the North American plate, approximately at the present day location of Nevada, and inaugurated the North American Cordillera by several overlapping orogenies (Hintze and Kowallis, (2009). The Upper Jurassic - Early Cretaceous *Nevadan orogeny* is evidenced by Utah-Nevada border granitic intrusions as an orogenic belt grew west of Utah. The following Early Cretaceous *Sevier orogeny* resulted in crustal shortening and a thick sedimentary succession deposited in a foreland basin. Tectonic upwarps of the Early Cenozoic (66 Ma - present) *Laramide orogeny* rose the Uinta Mountains (see location in Figure 1.1) and folded the Mesozoic sedimentary succession of central Utah in resulting in the *San Rafael Swell* (see location in Figure 1.1). The San Rafael Swell is a dome-shaped fault-tip, anticline (Ogata et al. 2014), with eastward vergence, that later was eroded and formed the outcrops included in this thesis (see Chapter 1).

A less prominent (yet significant), Middle Jurassic orogeny, named the *Elko orogeny*, was proposed in 1990 by Thorman et al. (cited in Thorman and Peterson, 2004) from evidence suggesting an orogenic event in eastern Nevada - western Utah not connected to the following Sevier orogeny. Thorman et al. proposed that orogenically related deformational structures could be accurately dated to Middle Jurassic age, in contrast to the Sevier orogeny of (earliest) Upper Jurassic, and differs from the Sevier orogeny by its content of extentional- as well as contractional structures (Thorman and Peterson, 2004). The Elko orogeny was additionally proposed to have been responsible for the creation of a foreland basin in central Utah during the Middle-Upper Jurassic Period based on the significant westward thickening of the low gradient sedimentary succession within the San Rafael Group (see sub-chapter 2.3 below).

2.2 Paleogeography and -climate

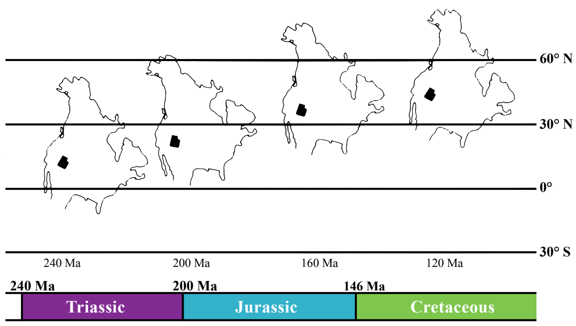


Figure 2.1: Paleogeographic reconstruction chart of Utah (black) during the Mesozoic Era, modified from Hintze and Kowallis (2009 fig. 1, p. 2-3).

Paleomagnetic polarity of rocks within the Mesozoic sedimentary succession of Utah was correlated (Steiner, 1978) to paleopole positions (Steiner, 1975) to suggest paleogeographic locations between 5 and 40 degrees north with a slight progressive clockwise rotation (see Figure 2.1) (Kocurek and Dott Jr., 1983; Hintze and Kowallis, 2009). Regional to global scale paleogeografic reconstructions, such as the one shown in Figure 2.1, signify that Utah was brought through the present day northern hemisphere trade wind belt, which led to interperative proposals regarding the Mesozoic climatic conditions (Kocurek and Dott Jr., 1983).

The Mesozoic sedimentary succession of Utah reflects deposition during alternating depositional environments, represented by widespread continental aeolianites, lacustrine- and fluvial accommodations, and restrictided- to marginal marine strata (Hintze and Kowallis, 2009). As present day equatorial climate is governed by the intertropical convergence zone, a zone where trade winds of the northern- and southern hemispheres merge, it was suggested that the Mesozoic climate of the Western United States bore resemblance to present day western Sahara (Kocurek and Dott Jr., 1983). A high-pressure cell, situated in the Pacific Ocean west of the North American plate, was suggested (Kocurek and Dott Jr., 1983) to explain the occurence of significant Jurassic arid aeolian desert deposits in Utah and neighbouring states. Kocurek and Dott Jr. (1983) described the Mesozoic climate as globally warm, with an avarage temperature as much as 10°C higher than present, with resultant potential of high absolute humidity, albeit not substantial to cause precipitation from the stable trade wind airflow. Wind-driven sediment transport directions were hence considered to reflect the suggested trade wind belt, and was found commensurate with average paleocurrent measurements within Mesozoic aeolian dune complexes (Hintze and Kowallis, 2009).

2.3 The Colorado Plateau and main Jurassic stratigraphic units

The Colorado Plateau (see Figure 2.2 for geographical extent) is a collection of exhumed sedimentary rocks representing the whole Phanerozoic Eon (541 - 0 Ma) (USGS, 2016). The exposed sedimentary succession of Utah represents the north-eastern portion of the Colorado Plateau (see Figure 2.2), and consists of units dated to Late Permian to Mid Paleogene (40-50 Ma) age (Hintze and Kowalliz, 2009). The Late Permian deposits are only exposed within the anticlinal San Rafael Swell, while the succession gradually grades into Paleogene age towards the Uinta Mountains (see Figure 1.1 for geographical reference). Main stratigraphic units of the Jurassic Colorado Plateau exposed in central Utah (Figure 2.3) are described below.

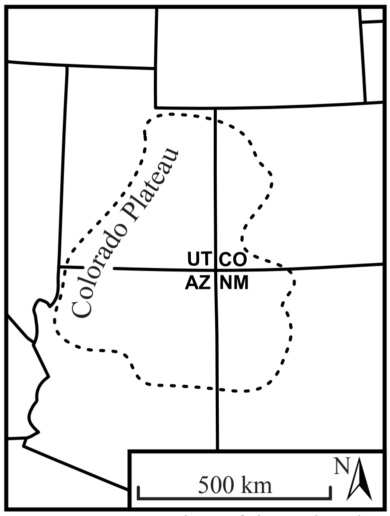


Figure 2.2: Overview of the Colorado Plateau geographic extent (based on information figure from USGS, 2016). See Figure 1.1 for full geographic reference.

2.3.1 Glen Canyon Group (Lower Jurassic)

Wingate Sandstone, Kayenta Formation and Navajo Sandstone (Lower Jurassic)

The *Glen Canyon Group* are represented in central Utah by primarily aeolian desert deposits of the Wingate Sandstone, the fluviatile Kayenta Formation and the aeolian sand sea (erg) Navajo Sandstone, that reach a combined recorded thickness in excess of 1400 m towards south-western Utah (Hintze and Kowallis, 2009). Outcrops that exhibit decameter scale, well defined cross-stratified, compound crescentic dune complexes, led to the description of the Navajo Sandstone as a deposit potentially representing the most significant and widespread aeolian desert ever recorded on Earth (Kocurek and Dott Jr., 1983).

Central Utah

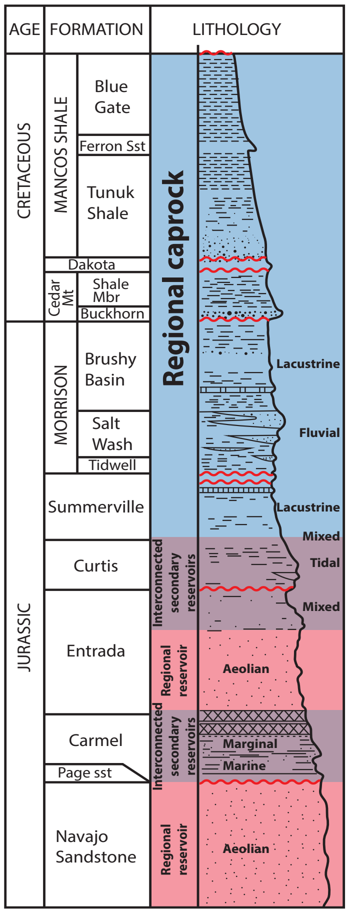


Figure 2.3: Stratigraphic column of Central Utah, modified from Ogata et al. (2014 fig 1D, p. 163).

Parts of the upper Navajo Sandstone intervals, exposed along the southern Uinta Mountains (see geographic location in Figure 1.1), has been described as exhibiting interdune deposits of marine flooding, suggested to announce the Carmel Sea marine incursion (Kocurek and Dott Jr., 1983) (see section below). However, the aeolian Page Sandstone of the San Rafael Group (see section below) was deposited on top of the Navajo Sandstone, on top of the separating Jurassic regional erosional unconformities of J1 (after Pipiringos and O'Sullivan), implicitly reflecting a hiatus between the two deposits (Peterson, 1994 fig. 3, p. 237; Hintze and Kowallis, 2004 fig. 81 p. 59).

2.3.2 San Rafael Group (Middle-Upper Jurassic)

The targeted sedimentary succession in this thesis belongs to the east-central Utah portion of the San Rafael Group. The San Rafael Group has been given its name from the exposures within the San Rafael Swell (Gilluly and Reeside Jr., 1928) and records in central Utah (ascending order) the aeolian Page Sandstone, the marine Carmel Formation, the Entrada Sandstone aeolian erg and wet coastal dune field, the marginal marine Curtis Formation and the Summerville Formation coastal plains (Hintze and Kowallis, 2009).

Peterson (1994 fig. 3, p. 237) postulated a series of Jurassic transgressive-regressive sequences, bounded- and partly interrupted by regional Jurassic erosional unconformities that were described by Pipiringos and O'Sullivan (1978). Accordingly, Peterson (1994) implemented the San Rafael Group through the transgressive-regressive sequences of;

- TR-2, 3 and 4 which altogether covers the Page Sandstone-Carmel Formation - Entrada Sandstone interval, ultimately bounded by the J2- and J3-unconformities (Pipiringos and O'Sullivan, 1978) below and above, respectively, with internal transgressive-regressive interfingering relations resulting in the separation of three sequences.
- TR-5 that covers the transgressive-regressive sequence of the Curtis- and Summerville formations, bounded by the J3- and J5-unconformities (Pipiringos and O'Sullivan, 1978) below and above, respectively.

The San Rafael Group stratigraphic units, with special emphasis given to the Curtis Formation (as it is the main target of this thesis), are introduced below.

Page Sandstone (Middle Jurassic)

The Page Sandstone was deposited in an aeolian erg environment that covered the Navajo Sandstone by the combined erosional unconformities of J1 and J2 (Pipiringos and O'Sullivan, 1978; Peterson, 1994). Due to similar appearance, both visually and structurally, the Page - Navajo sandstones boundary is at places difficult to determine and the Page Sandstone was hence considered a Navajo Sandstone stratigraphic top until year 1979 when characterized by Peterson and Pipiringos (1979) as an individual unit, separated from the Navajo Sandstone by an erosional boundary. Page Sandstone deposits wedge out eastward, and interfingers with- (Peterson and Pipiringos, 1979 fig. 11, p. 13) and grades (Peterson, 1994) northward into the correlative marine Carmel Formation in central Utah.

Carmel Formation (Middle Jurassic)

The Carmel Formation has been described as a marginal marine, epicontinental seaway that extended from the western Canadian border, to the Utah - Arizona border. The Carmel Sea lateral extent was geographically limited by western and southern highlands, and is shaped like an eastward wedge towards the Ancestral Rocky Mountains, the long since eroded predecessors of the modern Rocky Mountains (Hintze and Kowallis, 2009). Lithologic units within the Carmel Formation are laterally diverse, including coarse-clastic deposits from western volcanic activity (Peterson, 1994) (see sub-chapter 2.1 above for tectonic setting), carbonate- and evaporite beds, as well as mudstone and silty sandstone beds (Peterson, 1994; Hintze and Kowallis, 2009). The Carmel Formation western portion grades from intertidal deposits into unfossiliferous, hypersaline deposits, suggested to be products of evaporation of a shallow basin, rather than basin floor topographic restrictions would prevent uniform water circulation (Kocurek and Dott Jr., 1983).

Entrada Sandstone (Middle Jurassic)

The Entrada Sandstone is the most widespread aeolianite of the Western United States, resembling a fossil erg, derived from multiple sources including the Navajo Sandstone (Kocurek and Dott Jr., 1983). The Entrada erg contained large quantities of compound crescentic dune complexes, close to 100 m high, prograding north-west over the Carmel Sea, accompanying its retreat (Kocurek and Dott Jr., 1983). Lower Entrada Sandstone interdune deposits reveal traces of submergence along the Carmel Sea paleocoast areas, suggested to be results of occasional storms and Carmel tidal influence, evidenced by the occurrence of evaporite precipitates in a saline, sabkha-like environment (Crabaugh and Kocurek, 1993).

The Entrada Sandstone in central Utah is divided into two separate units based on its appearance and the interpreted origin of slightly different depositional environments. Representing the main body is the *Slick Rock Member,* that records an arid- to semi-arid aeolian erg deposit. The Slick Rock Member contains compound crescentic dune complexes that outcrops as cross-stratified laterally extensive layers of several meters thick sandbeds (Kocurek and Dott Jr., 1983). The cross-stratified Slick Rock Member sand beds are separated by thinner interdune silt deposits, equally extensive laterally but of lesser thicknesses (Kocurek, 1981). The *Earthy Facies,* presented by Gilluly and Reeside Jr. (1928), sharply overlies the Slick Rock Member but is not officially defined as a separate member of the Entrada Sandstone (USGS National Geologic Map Database - Geolex Search, 2016). The Earthy Facies consists of interbedded deposits of dune- and interdune environments, with occurrence of scattered Gypsum-lenses within the interdune sediments, reflecting wetter depositional conditions than that of the Slick Rock Member (Hintze and Kowallis, 2009).

Crabaugh and Kocurek (1993) suggested that the Entrada erg was a wet aeolean system. By this, they interpret interdune evaporitic sabkha deposits to represent not only coastal flooding from storms, and/or sea level fluctuations, but also periodical inland flooding due to fluctuation of the ground water table. Crabaugh and Kocurek (1993) further stated that it is difficult to define the accurate position of the paleo-coastline due to a low relief coast, and that it thereby is possible to have large inland areas periodically flooded, in addition to suggest that sea level fluctuations may have influenced the relative ground water table.

Curtis Formation (Middle - Upper Jurassic)

The Curtis Formation (after Gilluly and Reeside Jr., 1928) was described as a unit of diverse lithology, resting on the Entrada Sandstone by a channelled surface of as much as ~15 m irregularity at Curtis Point, the formation's type section, approximately 5.3 km south of Dry Mesa (see Figure 1.1B for locality). Gilluly and Reeside Jr. (1928) further described the Curtis Formation as generally 60-80 m thick, pinching out south, at Waterpocket Fold, ~40 km south of Hanksville (see Figure 1.1A for locality), and east towards Moab (see Figure 1.1A). They interpret fossils and consistent presence of ripple marks to reflect deposition during shallow marine conditions, and that a conglomerate in basal incisions may represent a product of marine encroachment onto Entrada Sandstone deposits. Regarding regional geometry, Gilluly and Reeside Jr. (1928) signifies that due to the southerly- and easterly pinch out, combined with its gradual conformable upper transition into the Summerville Formation (see description below), a significantly more extensive unit, the Curtis Sea did not extend further south nor east.

Further research (Kocurek and Dott Jr., 1983) has identified tidal features throughout the Curtis Formation, typically grading up from basal heterolithic beds into trough cross-stratified and tidally bundled (Kreisa and Moiola, 1986) middle sandy intervals, and heterolithic beds towards the Curtis Formation top (Eschner and Kocurek, 1986; Kreisa and Moiola, 1986).

Kreisa and Moiola (1986) investigated Curtis Formation outcrops along highway I-70 through the San Rafael Swell (see Figure 1.1A,B) and documented tidal signatures with special emphasis on sigmoidal tidal bundles (defined by Boersma, 1969) that formed in tidally dominated lagoonal environments. Several other tidal features were considered including flaser- and lenticular bedding, flat-laminated beds with parting lineation and herringbone cross-lamination, only these were barely mentioned and hence not described as thoroughly as the sigmoidal tidal bundles. Their interpretation of sigmoidal tidal bundles were applied to statistically present alternating sedimentation rates during neap- and spring-tides, and they summed up their findings by stating that their result show potentially unreliably high rates of sedimentation, such that different depositional settings should not be ruled out.

Eschner and Kocurek (1986) based their study on outcrops along the southern flank of the Uinta Mountains in northeast Utah (see Figure 1.1A). As Eschner and Kocurek (1986) targeted what they called; "marine destruction of aeolian sand seas", they suggested that the Curtis Sea encroachment eroded the Entrada erg and was thus the sole acting agent on the creation of the J3 erosional unconformity (after Pipiringos and O'Sullivan, 1978). Massive, structureless sandbeds were described as Entrada erg sheet-like mass flow deposits, derived from the Curtis Sea undercutting of Entrada erg aeolian dunes, and hence creating instability as it inundated the land. They further described the Curtis Formation sand content in general to not have been sourced from the Entrada erg, as the Curtis Formation sands are in general coarser than the Entrada Sandstone beds. It should be noted that the Entrada Formation at the Uinta Mountains crops out as thick and laterally extensive layers of aeolian dunes, commensurate with the Slick Rock Member, and that the Earthy Facies is not present this far north (Gilluly and Reeside Jr., 1928). Eschner and Kocurek (1986) identified and described tidal structures as well, lacking identification of tidal bundles, such as the ones described by Kreisa and Moiola (1986) in the San Rafael Swell.

Caputo and Pryor (1991) targeted the depositional environments and stratigraphic relation between the Curtis- and Summerville formations as they based their study on exposures along the San Rafael Swell surrounding flanks as well as localities towards the desert between Green River and Moab (see Figure 1.1A for localities). They suggested a marine inundation that reworked the Entrada Sandstone top during transgression, ultimately resulting in the J3 unconformity (Pipiringos and O'Sullivan, 1978). Further development was described as a storm-influenced, tidal seaway, that deposited ripply sand and dunes, and that trace fossils of burrows and gracing were found in muddier sediment, interpreted to represent calm water conditions. The Curtis - Summerville formations relation was described as being distal- an proximal equals, where the upper Curtis Formation interval represents intertidal platform deposits and that Summerville Formation coastal evaporative sabkha environments developed at the Curtis Sea flanks, prograding northward as the sea receded (Caputo and Pryor, 1991).

Peterson (1994) targeted the transgressive-regressive sequences of the Jurassic sedimentary succession. He described the Curtis Sea marine invasion as depositing glauconitic sands and that the western margin was challenging to identify due to concealment by younger strata, albeit the Curtis Formation was no longer recognized further west. Peterson (1994) further described the basal coarse clastic conglomerates of Gilluly and Reeside Jr. (1928) to represent the first influx of fluviatile sediments derived from the newly elevated Elko highlands (Elko Orogeny, see sub-chapter 2.1 above) west of the sea. Regarding the J3 erosional unconformity, separating the Entrada Sandstone - Curtis Formation, Peterson (1994) describe it as mainly tectonicly eroded, caused by crustal upheaval/base level fall, and that there are additional signs of erosion from the Curtis Sea encroachment. The relation to the Summerville Formation was described as conformable, grading from marine sediments into that of Summerville Formation hypersaline marine conditions, sabkhas and evaporative ponds that developed as the Curtis Sea retreated northwards (Peterson, 1994).

Wilcox (2007) investigated the Curtis - Summerville formations' sequence stratigraphic properties during his field based master thesis study (later published by Wilcox and Currie, 2008). By implementing biostratigraphic samples, Wilcox (2007) developed a depositional model based on outcrops along the San Rafael Swell-, Uinta Mountains- and north-western Colorado (see Figure 1.1A for map), and redefined Curtis Formation age to late Callovian-Oxfordian. Wilcox's findings resulted thus in a correlation between the tide dominated Curtis - Summerville formations of central Utah and the correlative wave-dominated Stump Formation in north-western Colorado and Wyoming. In central Utah, Wilcox (2007) identified a marine flooding event near the Curtis Formation base, and that the depositional trend was upwards shallowing into the Summerville Formation. However, through correlation charts, and assisting gamma ray logs from boreholes in between, Wilcox (2007) identified the same flooding event at the Curtis Formation top, transitioning into the overlying, shelf deposited Stump Formation. Regarding the erosional bounding surfaces of J3 and J5 (Pipiringos and O'Sullivan, 1978), Wilcox (2007) described them both as subaerially exposed during base-level fall. He further describe that the J3-unconformity at places show signs of additional erosion due to marine wave scour.

As demonstrated above, studies have examined and revealed detailed Curtis Formation aspects on variable scale regarding its development and how it relates to its stratigraphically neighbouring units. However, several of these studies have either described locally restricted structures (such as Eschner and Kocurek, 1986; Kreisa and Moiola, 1986) or focused on regional to continental scale development of the designated formations (Caputo and Pryor, 1991; Peterson, 1994; Wilcox, 2007). Each of the studies described above, show different characteristics and suggest alternate interpretations accordingly. On this basis, a thorough sedimentological understanding of the Curtis Formation and how it relates to- and developed relative to its stratigraphically neighbouring units, are targeted through this thesis by interpreting the depositional environments and utilize the associated sequence stratigraphic properties, in a attempt to stitch together small scale litho-facies variations with larger scale depositional development.

Summerville Formation (Middle - Upper Jurassic)

The Summerville Formation has been described by several authors (Gilluly and Reeside, 1928; Kocurek and Dott Jr., 1983; Caputo and Pryor, 1991; Peterson, 1994; Wilcox, 2007) as a coastal equivalent to the Jurassic marine invasion of the Curtis Sea. By this, the Summerville Formation represents a coastal flank of hypersaline sabkha conditions, including evaporative ponds, that resulted in precipitation of gypsum and anhydrite. The Formation extends beyond the Curtis Formation lateral reach and conformably overlies it as further ascending Jurassic stratigraphy represent continentally non-marine deposits. The Summerville Formation top is truncated by the J5 erosional unconformity (after Pipiringos and O'Sullivan, 1978), representing a hiatus that developed as a response to base level fall (Peterson, 1994; Wilcox, 2007), and is thus abruptly overlain by the Upper Jurassic Morrison Formation.

2.3.3 Morrison Formation (Upper Jurassic)

The Morrison Formation is well known for its abundant quantity of dinosaur fossils and represents sediments deposited in a non-marine north-south elongated basin that stretched from southern Canada to northern Mexico, covering the entire states of Wyoming and Colorado, in addition to parts of the neighbouring states and national borders (Hintze and Kowallis, 2009). Central Utah stratigraphy contains the lower Morrison Formation Tidwell- and Salt Wash members, which were deposited in fluvially dominated environments, exhibiting sediments from fluvial flood plains, -crevasse splays and isolated as well as interconnected channels. The mid to upper Morrison Formation Brushy Basin Member overlies the Salt Wash Member and reflects a lacustrine environment (Hintze and Kowallis, 2009).

Chapter 3: Methods

3.1 Sedimentological field work

Methods regarding the collection of data, presented in this thesis, are related to sedimentological field work conducted during two separate periods; two and a half weeks of main field work in June-July 2015 and additional 2 weeks during September 2015 as a field assistant for the Ph.D. candidate *Valentin Zuchuat*. Data collected during field work include (**1**) sedimentary logs (see appendices B-J) recorded on paper at 1:50 and 1:100 scale (see Figure 1.1B for log-trace positions, and corresponding coordinates listed in Appendix A), and (**2**) photos taken at and between log-sites. Additional photographic data provided by Google (maps.google.com) and Bing (bing.com/maps) assist in filling gaps between log traces where possible. (**3**) Paleocurrent measurements were collected at all log sites to record main transport directions across depositional environments, and localities (bulk rose plot diagrams are included in Appendix K). As the majority of the localities lie in remote areas, hardly reachable by car, the log-sites where chosen based on the outcrop exposure quality and reachability, ultimately resulting in alternating lateral spacing between collected logs. Field methods also include lateral tracing of beds and surfaces between outcrops, where possible, in order to improve correlation between log traces.

Data collected and added to this thesis while assisting V. Zuchuat include sedimentary logs from Smith's Cabin North and Crystal Geyser (see Figure 1.1B for localities) and photos from several localities.

Chapter 4: Sedimentology and depositional environments

4.1 Facies descriptions:

Facies A - Cross-stratified sandstone (Entrada Sandstone – Earthy Facies)

Description:

This facies consists of very fine to fine well sorted sandstone beds up to 2 m thick, stacked in up to 7 m thick packages (included parts in this study are generally not more than 2-3 m). Cross-stratification (although various degree of visible stratification due to weathering) with tangential bottom sets is typical. Lower boundary is commonly sharp and straight, and traces of polygonal fractures are observed as imprints at bedform base, seen from below (see Figure 4.1) in Stove Gulch, Humbug Flats (see Figure 1.1C for location). Rusty red colour defines this sandstone in comparison to the yellow and grey Curtis Formation sandstones described below. Facies A is present at all Entrada Sandstone study localities.

Interpretation:

Rusty red sand beds reflect oxidation of iron by subaerial exposure (Boggs, 2006), implying a continental origin of deposition. Coupled with the fine grain size, consistently planar and extensive (far beyond outcrop reach) contacts, very well sorting and the scale (vertical and lateral) of the deposits, Facies A is interpreted as aeolian dunes (James and Dalrymple, 2010), an interpretation that is strengthened by previous work and interpretations conducted by several authors, such as Kocurek and Dott Jr. (1983); Eschner and Kocurek (1986); Peterson (1988); Crabaugh and Kocurek (1993); Hintze and Kowallis (2009). The polygonal fractures appear to be desiccation cracks and may be the same feature as previously described by Kocurek and Hunter (1986) for the Navajo- and Page Sandstones, and later by Carr-Crabaugh and Kocurek (1998) for the Entrada Sandstone as evidence of wet climate and high groundwater level, together with the presence of saline water resulting in evaporite cementation, confirmed by Rimkus (2016) through microscopy analyses to represent calcite cement.

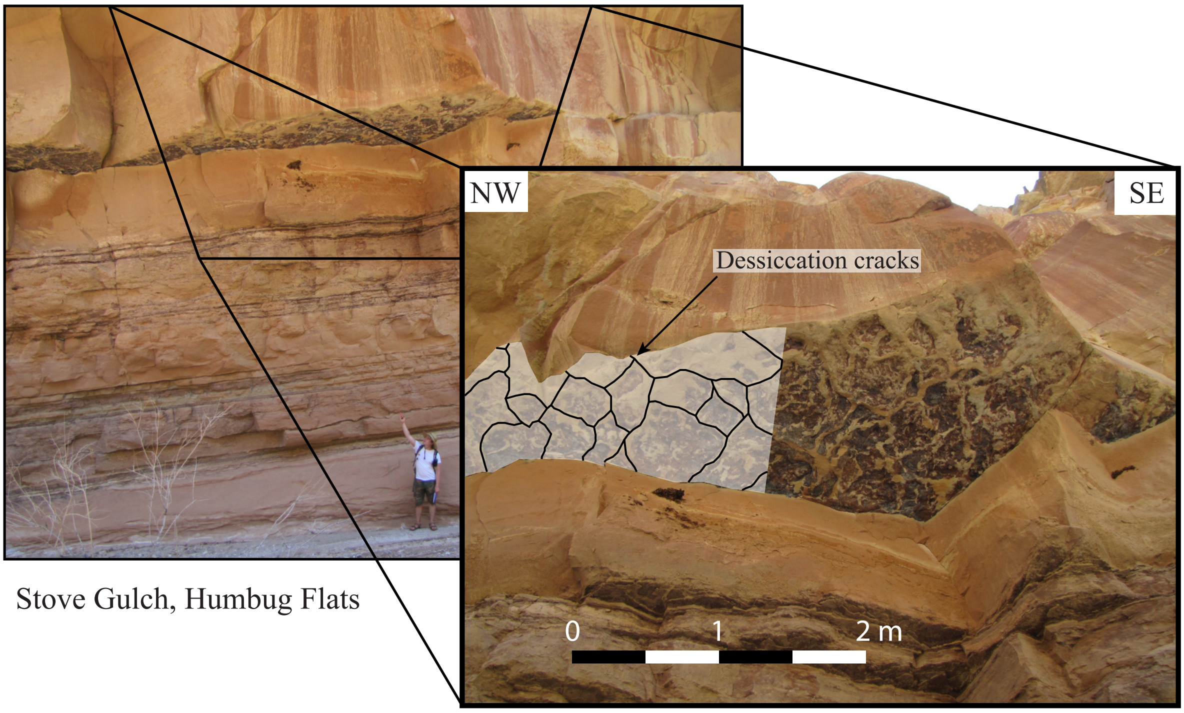


Figure 4.1: Illustrating desiccation cracks (drawn black lines) preserved at Facies A (Cross-stratified sandstone) bedform base. Note person for scale.

Facies B - Parallel laminated mudstone with evaporites (Entrada Sandstone – Earthy Facies)

Description:

This facies is predominated by alternating layers of dark red and pale yellow to white silty mudstone. Up to 7 cm thick layers with highly undulating top and lower boundaries are common as the layers interfinger and pinch out laterally (see Figure 4.2), although at some places, layer boundaries are horizontal with plane parallel lamination. Observed recent *ex situ* evaporite nodules seem to originate from this facies as 2-3 cm thick evaporite layers are found within at scattered localities (see candidate gypsum in Figure 4.2iii). Facies B is most commonly ~1 m thick, but reaches 2.5 m at Neversweat Wash (see log in Appendix F) and Crystal Geyser (see Figure 1.1 for localities).

Interpretation:

Deposition of mud reflects extremely low energy conditions, such as standing bodies of water (Hjulström, 1955). Dark red to brown colour indicates oxidation of iron by subaerial exposure (Boggs, 2006), thus, a continental origin. Presence of evaporites reflects humid and warm conditions, implying high ground water table (James and Dalrymple, 2010) and possibly occasional flooding, as suggested by (Crabaugh and Kocurek, 1993). As Facies B occurs interbedded with Facies A, Facies B is interpreted to have formed in a calm and humid interdune environment that experienced occasional flooding, binding the sediments together by cohesion (Boggs, 2006) as previously described by Kocurek and Dott Jr. (1983); Peterson (1988); Crabaugh and Kocurek (1993).

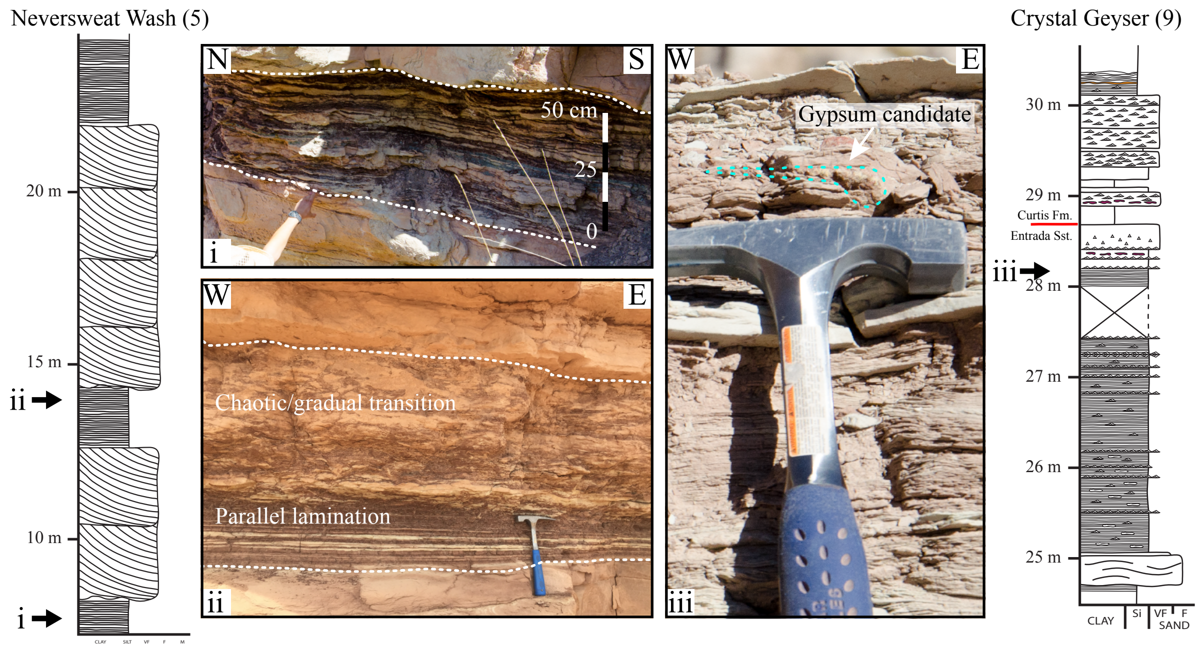


Figure 4.2: Compound figure illustrating appearance of Facies B at Neversweat Wash (**i**,**ii**) and Crystal Geyser (**iii**) (see Figure 1.1 for locations). **i**: Overview of typical outcrop of undulating internal layering of alternating colours. White dotted lines indicate upper and lower boundaries to Facies A. **ii**: Example of a gradual chaotic upper transition into Facies A. Note hammer for scale, white dotted lines indicate lower and upper boundaries. **iii**: Close-up photo of candidate gypsum precipitate at Crystal Geyser (log position indicated to the right).
Photos i,iii: V. Zuchuat

Facies C - Silty sediment (Curtis Formation)

Description:

Grey to green well sorted silt, typically plane parallel laminated with 3-5 mm thick layers of clay at some localities (see Figure 4.3i). This sediment is present at all Curtis Formation intervals, but most dominant at base- and top transitions where both plane parallel lamination and bidirectional current ripples are common (see Figure 4.3i, ii). Iron rich silica concretions are found towards the Curtis Formation top (see Figure 4.3iii).

Interpretation:

Deposition of silt and clay is subject to standing water conditions (Hjulström, 1955), although disturbed at some point by subtle flow activity in the basin, creating gentle current ripples. Gentle layering of clay and silt indicates a slight difference in current velocity during deposition, sorting the sediment. Bidirectional (here, oppositely directed) current ripples may indicate systematic current reversals, such as in environments influenced by tidal activity (Reineck and Singh, 1980; Davis Jr. and Dalrymple, 2012). The grey to green colour has been described by several authors (Hoggan, 1970; Kocurek and Dott Jr., 1983; Eschner and Kocurek, 1986; Kreisa and Moiola, 1986; Wilcox and Currie, 2008) as a result of high *Glauconite* content, implying reducing conditions.

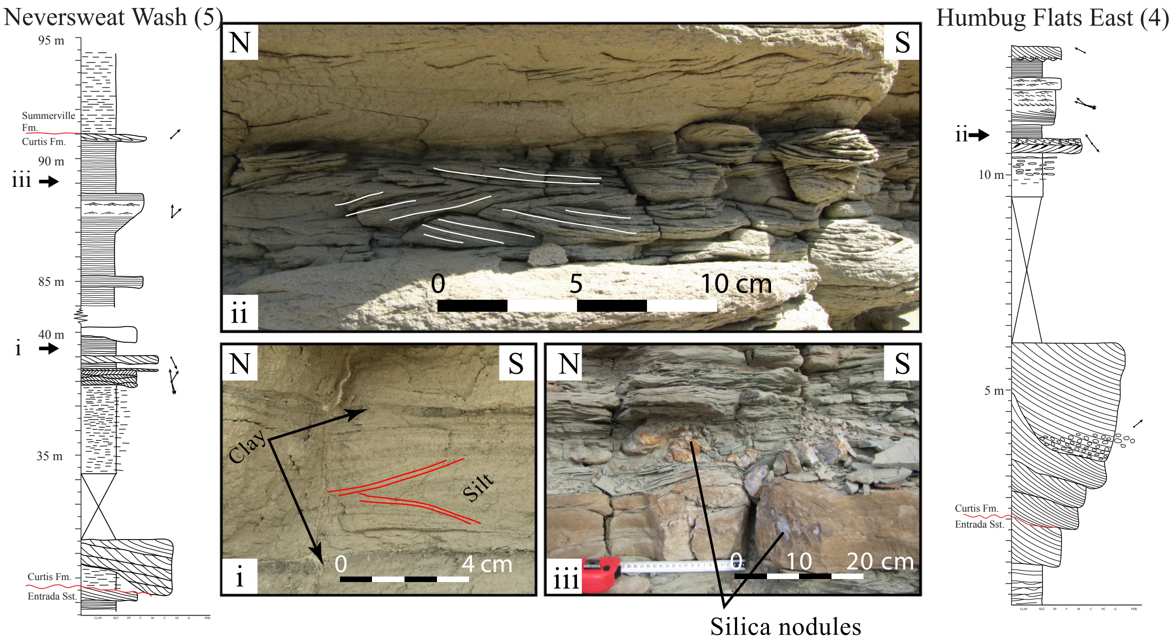


Figure 4.3: **i**, **ii**: Multidirectional current ripples in Facies C, with red and white drawn lines indicating lamination. **iii**: Silica nodules in Facies C and underlying sandbed.See Figure 1.1 for locations.

Facies D - Cross-stratified conglomerate (Curtis Formation)

Description:

This facies consits of poorly sorted medium to granule sandstone with tabular and trough cross-stratification (Figure 4.4). With an apparent erosive base, this unit may contain extrabasinal rounded clasts, mainly chert up to pebble size, at scattered localities, in a matrix-supported conglomerate. The erosive base is commonly packed with mud-clasts (expressed as pits in the sandstone where they are weathered out) up to 15 cm across (see Figure 4.4iii). Unit thicknesses vary between 0.5 to 4 m with internal cross-stratified layers of 0.2 to 1 m. At some localities the tabular cross-stratification occurs as inclined heterolithic stratification with alternating layers of mud/silt and sand of equal thickness (up to 5 cm). Other than isolated oppositely directed foresets and herringbone cross stratification (Davis Jr. and Dalrymple, 2012), the foresets appear to build in northward trending directions. In addition, asymmetrical current ripples may be found at scattered localities, superimposed on the crossbeds. Facies D is observed as laterally extensive layers (beyond outcrop reach, with alternating thickness) towards the Curtis Formation base or as locally restricted lens-shaped bodies a few tens of meters long, typically surrounded by Facies E (Lenticular bedding) and Facies F (Wavy bedding), both described below.

Interpretation:

The coarse grain size and erosion of underlying material indicates deposition during relatively high energy conditions (Hjulström, 1955). Transport of rounded clasts and a cross stratification in mainly one direction may indicate a divergent transport mechanism, such as a fluvial braided stream (Boggs, 2006). However, lack of sorting and presence of herringbone cross-stratification and IHS may indicate a rapid deposition (Nichols, 2009) combined with secondary reworking processes with periodic current reversals, respectively, commonly associated with tidally influenced environments (Davis Jr. and Dalrymple, 2012).

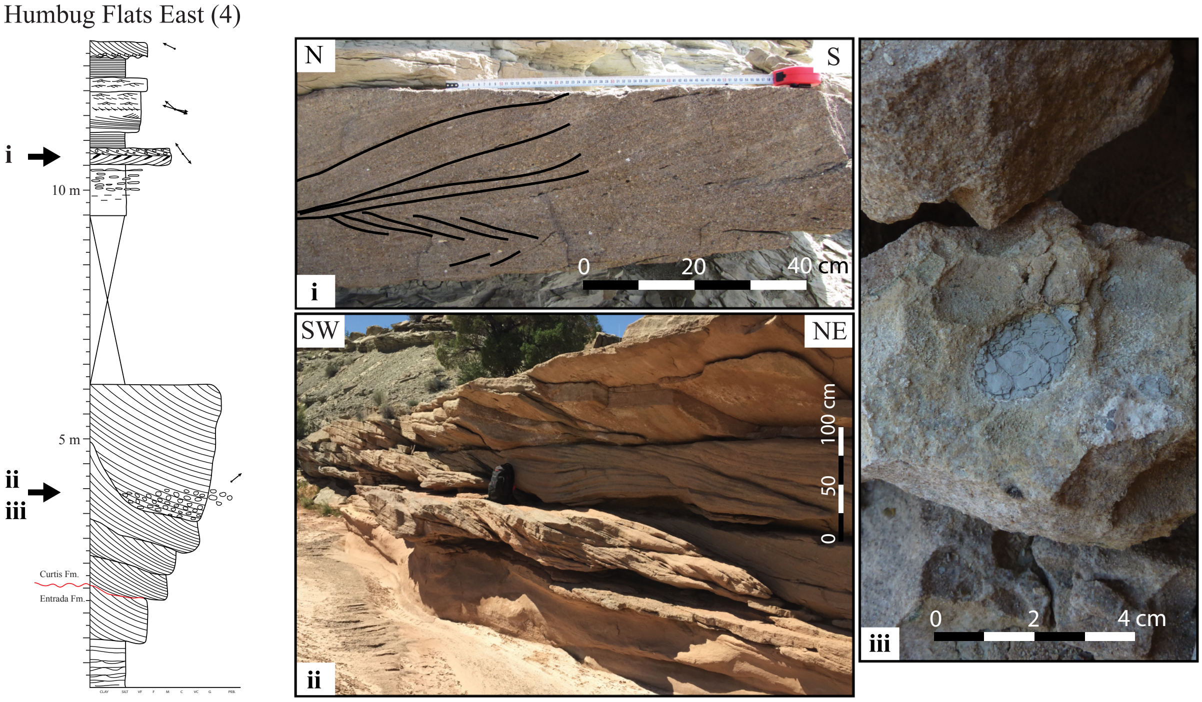


Figure 4.4: Illustration of Facies D outcrop at Humbug Flats East (see Figure 1.1 for location). **i**: Bidirectional cross-stratification, black drawn lines indicate stratification. **ii**: Northeast building cross-stratification with reactivation surfaces, picture taken at *Neversweat Wash* (see Figure 1.1). **iii**: Fresh cut of mud clast from basal bed. *Photo iii: A. Rimkus*

Facies E - Lenticular bedding (Curtis Formation)

Description:

This facies consists of very fine to fine sand lenses containing ripple cross-lamination, isolated by silty mud, interpreted to be the same sediment as Facies C. The sand lenses are 0.1 to 3 cm thick and 2 to 20 cm long (Figure 1.4i) with vertical- and lateral spacing of 0.5 to 10 cm. Herringbone cross-lamination (Davis Jr. and Dalrymple, 2012) is commonly found in the sand lenses, as well as oscillation ripples and several isolated unidirectional current ripples (see Figure 1.4ii), showing sediment transport in several directions. Multiple trace fossils are found, including horizontal burrows and gracing by *Thalassinoides* and *Cruziana* (James and Dalrymple, 2010), respectively (see Figure 4.6), at Smith's Cabin North (see Figure 1.1 for location). Lithology like this is commonly referred to as lenticular bedding (after Reineck and Wunderlich, 1968).

Interpretation:

Interchanging deposition of sand and silt indicates a systematic alternation in energy level (Hjulström, 1955). Oppositely directed current ripples, such as the herringbone structures, reflect an environment with periodic current reversals, such as tidal currents (Davis Jr. and Dalrymple, 2012) depositing rippled sand during tidal flood- and ebb movement and silt/mud in the calm phase between. Oscillation ripples are made during wave motion, thus water depths within half a wavelength (Boggs, 2006), implying near shore water depths, supporting Reineck and Wunderlich (1968) and Reineck and Singh (1980) with definitions of lenticular bedding as either a subtidal or intertidal deposit. Furthermore, observed fossils, lack of observed vertical burrows and the presence of horizontal burrows, may indicate the sublittoral *Cruziana ichnofacies* (James and Dalrymple, 2010), thus a subtidal environment. Moreover, horizontal burrows imply oxygenated water, whereas the lack of vertical burrows may indicate limited oxygen availability deeper into the sediments. This assumption is strengthened by the Glauconite content (as described in Facies C) commonly associated to form in reducing environments (Catuneanu, 2006; James and Dalrymple, 2010).

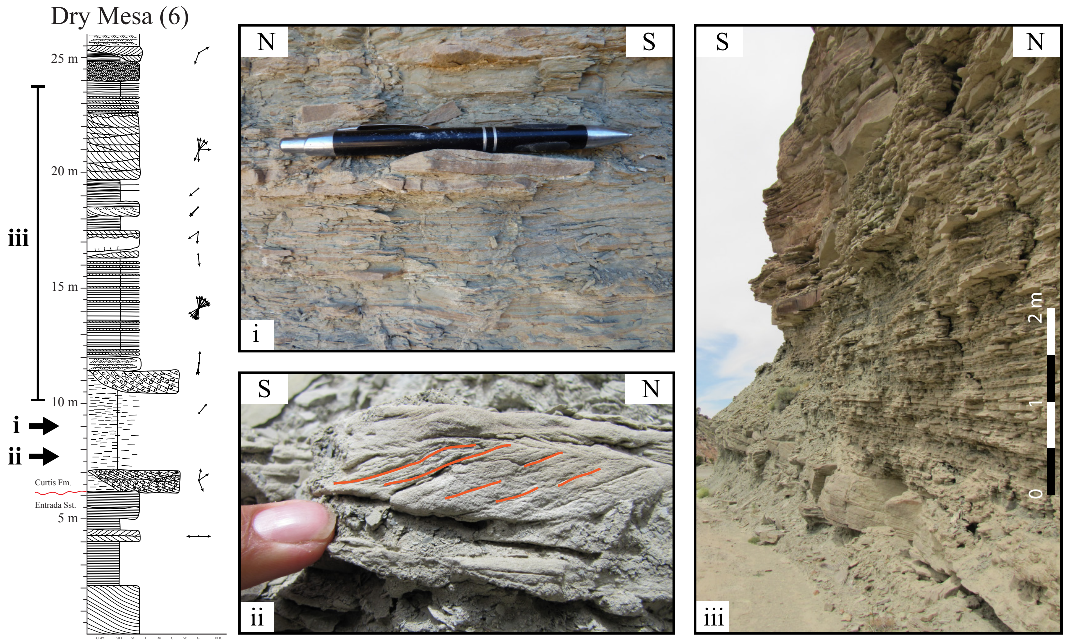


Figure 4.5: Facies E as present at Dry Mesa outcrop (see Figure 1.1 for location). **i**: Overview of thin lenticular bedding. **ii**: Southward-building unidirectional current ripple. **iii**: Part of outcrop at Dry Mesa.
Photo i: A. Rimkus

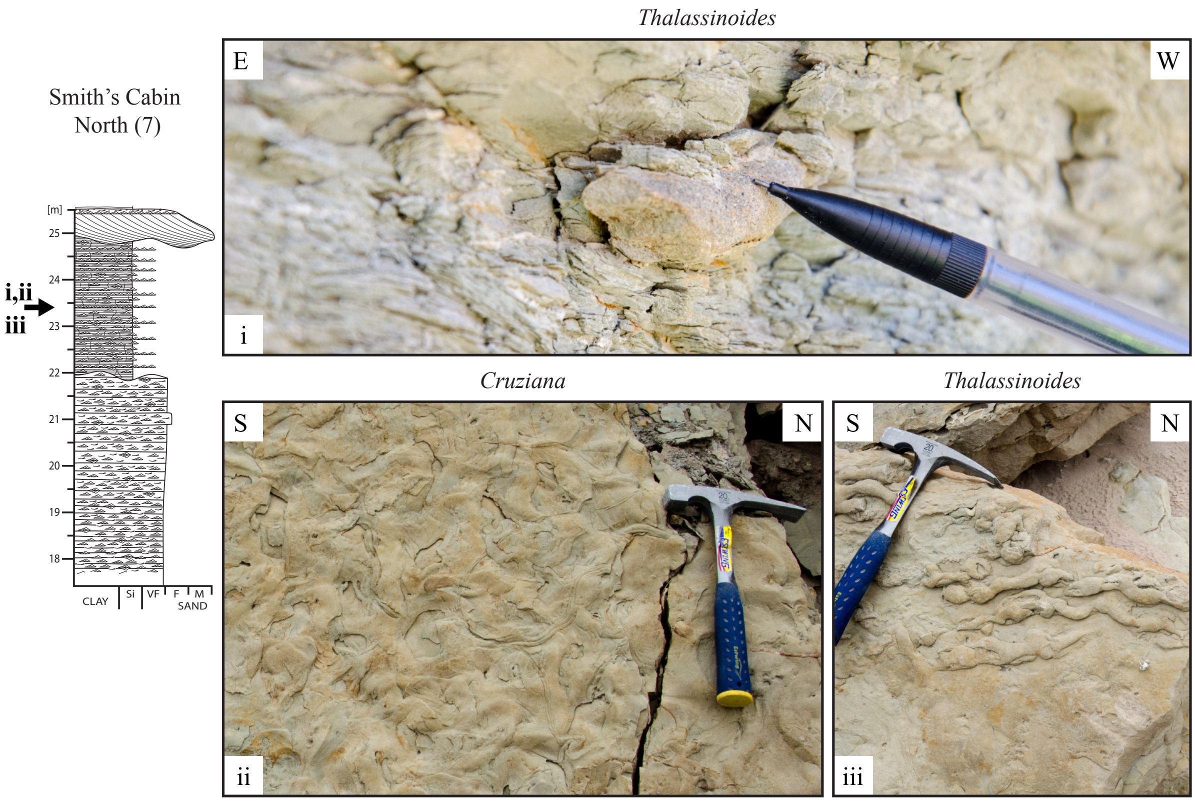


Figure 4.6: Photos from Smith's Cabin North (see Figure 1.1 for locality) showing gracing and burrowing of *Cruziana* and *Thalassinoides*, respectively, occuring in Facies E and Facies F (Wavy bedding) as described below. Note hammer for scale and position in log.
Photos i,ii,iii: V. Zuchuat

Facies F - Wavy bedding (Curtis Formation)

Description:

This is a heterolithic facies consisting of continuous layers of very fine to fine sandstone and layers of Facies C (Silty sediment). Sediment distribution is about 50/50 between sand- and silty layers 2 to 7 cm thick, although sand gets more dominant towards the facies top. Sandstone beds are packed with herringbone cross lamination, multi- and unidirectional current ripples, and oscillation ripples, as well as horizontal burrows and gracing by *Thalassinoides* and *Cruziana* (see Figure 4.6), respectively. Facies F is present towards the lower Curtis Formation and is referred to as wavy bedding after the definition developed by Reineck and Wunderlich (1968).

Interpretation:

As this facies is similar in structures as Facies E, the sediment distribution is closer to 50/50 (between sand and silt). A stronger influence of sand may indicate a slightly different environment, still experiencing current reversals, but at higher and more continuous energy conditions, allowing bedload material (such as sand) to be deposited in continuous layers. Fossils (Log from Smith's Cabin North) indicate the sublittoral *Cruziana Ichnofacies* (see interpretation of Facies E), an interpretation that supports Reineck and Wunderlich (1968) and Reineck and Singh (1980) definitions of wavy bedding as subtidal deposits, although higher sand content may place it in a shallower level than Facies E.

Facies G - Flaser bedding (Curtis Formation)

Description:

Very fine to fine sand with ripple cross-lamination dominates this facies. Silt and clay are scattered throughout the facies as connected- and single lenses commonly found in ripple troughs. Single and double mud drapes (Figure 4.7ii,iii) may occur at scattered localities. The lenses of silt are typically 0.5 to 3 cm thick and 2 to 20 cm long. Structures within the sand include herringbone cross-lamination, multi- and unidirectional current ripples and oscillation ripples. Facies G is commonly found in the middle Curtis Formation sandy interval (see appendices A-J for recorded logs). Lithology like this has been defined by Reineck and Wunderlich (1968) as flaser bedding.

Interpretation:

Although sediment distribution in Facies E (Lenticular bedding) and Facies F (Wavy bedding) is more varied, structures within the sandstone beds are exactly the same as in Facies G. Since silty mud is deposited from suspension during standing water conditions (Hjulström, 1955; Boggs, 2006), the lack of it (in Facies G) may reflect higher- and more continuous energy conditions (than during deposition of Facies E and Facies F), and higher water levels, so that the time needed for silt and mud to reach between current reversals are too short to deposit silt and clay. Double mud drapes (Figure 4.7ii,iii) are deposited during two standing water events, separated by one current flow event, typical for subtidal to lower intertidal environments (Davis Jr. and Dalrymple, 2012). However, flaser bedding may as well be deposited in perennial- (Bhattacharya, 1997) and ephemeral (Martin, 2000) streams, but this is here considered unlikely, as the adjacent strata contain marine trace fossils (see Figure 4.6).

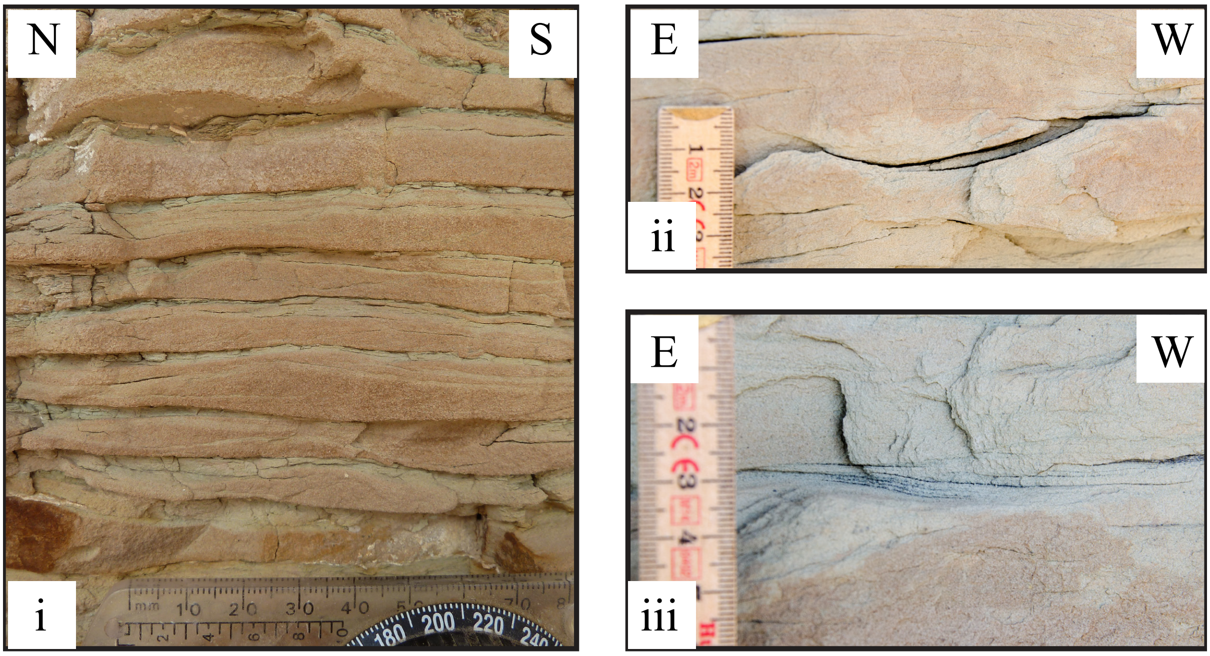


Figure 4.7: Flaser bedding as exposed at Stove Gulch Exposure (**i**), and double mud-drapes Smith's Cabin North (**ii**,**iii**). See Figure 1.1B,C for localities.
Photo i: A. Rimkus
Photo ii,iii: V. Zuchuat

Facies H - Trough cross-stratified sandstone (Entrada Sandstone and Curtis Formation)

Description:

This facies consists of very fine up to medium sandstone (typically uniform grain size, otherwise fining upwards). Trough cross stratification is common (varying from ripple to dune scale) and unit thicknesses vary from 0.5 to 11 m with internal layers 0.2 to 0.5 m thick. Thin (1 mm) layers of dark brown and green bottomset mud drapes are found at scattered localities (see Figure 4.8i). At Humbug Flats East and Dry Mesa (Figure 4.8iii) together with some localities in Stove Gulch, Humbug Flats (Rimkus, 2015) (Figure 4.8ii), what looks like desiccation cracks and gypsum crystals are recorded in less than 1 cm thick coating of silt on top of each sand trough. Recorded transport directions are mainly northwards, although oppositely directed foresets occur.

The road cut exposure at Dry Mesa (see Figure 1.1 for locality) exhibits an up to 50 cm thick cross-bedded sandstone of very fine to fine 20 cm thick dunes separated by undulating erosional contacts (see Figure 4.8v). This facies occurs at 28-30 m in the log (see log in Appendix G), situated on top of Facies F (Wavy bedding) and underneath Facies J (Planar- to low angle cross stratification, see description below).

Facies H is recorded throughout all Curtis Formation intervals, at all localities as well as in the Entrada Sandstone west of Sulphur Canyon (see Figure 4.8vi), Humbug Flats (Rimkus, 2015) and at Crystal Geyser (see Appendix J for log and Figure 1.1B for localities), where mud clasts and candidate mud drapes are found along foresets and bottomsets, respectively, as well as sorted foresets (see Figure 4.8vii).

Interpretation:

Deposition of clean sand represents stable energy conditions (Hjulström, 1955). However, bottomset mud drapes reflects deposition during slack water conditions, indicating systematic alternation between flowing and standing water. Dunes/ripples are deposited as trough cross stratification during sinuous turbulent flow, creating 3D dunes/ripples that erodes into underlying dunes/ripples (Nichols, 2009). Oppositely directed foresets may represent deposition during reversed currents, such as in tidally influenced environments (Davis Jr. and Dalrymple, 2012). Furthermore, a predominance of unidirectional measurements may suggest deposition during flood or ebb tidal currents. Considering such conditions, sediment reworking ought to be expected, thus, the erosional internal contacts at Dry Mesa are interpreted as surfaces reactivated by tidal reworking mechanisms. In addition, traces of subaerial exposure and evaporation such as desiccation cracks and precipitation of gypsum, respectively, may reflect deposition at a level barely submerged below sea level, and left to dry during low tide.

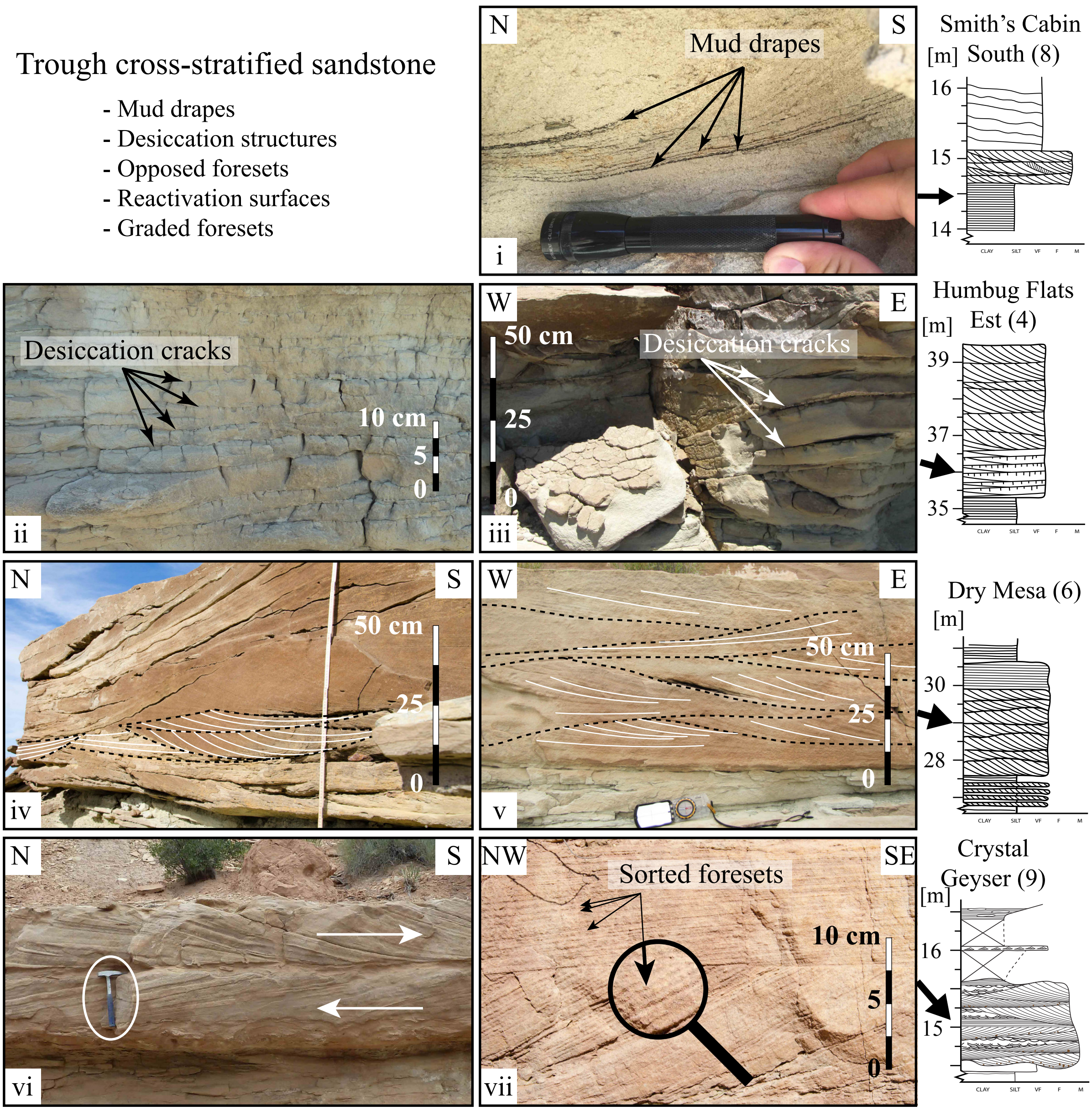


Figure 4.8: Compound collection of Facies H various structures. **i**: Toeset mud drapes from Smith's Cabin South. **ii**: Candidate desiccation cracks in Stove Gulch (Rimkus, 2015). **iii**: Candidate desiccation cracks in top trough silt coating at Humbug Flats East. **iv**: Trough cross-stratification at close to Neversweat Wash. **v**: Tidal reactivation surfaces in trough cross-stratification at Dry Mesa. **vi**: Facies H as it occurs within the Entrada Sandstone Earthy Facies. Note opposed flow directions. Hammer for scale. **vii**: Facies H in Entrada Sandstone Earthy Facies, 13 meters below Curtis Formation at Crystal Geyser. Black arrows indicate foreset sorting.
Black dotted drawn lines indicate trough separation, white drawn lines indicate stratification. See Figure 1.1B,C for associated localities and appendices A-J for full sedimentary logs
Photo ii,vi: A. Rimkus

Facies I - Sandstone with climbing ripples (Curtis Formation)

Description:

This facies consists of very fine to fine sandstone beds with defined climbing-ripple cross-lamination (see Figure 4.9). Ripple stoss-sides are preserved as each ripple builds on top of the next, but further stoss-side accumulation is rare. Hence, angle of climb is commonly close to the stoss side angle. This facies is present at multiple localities (see. Logs 2, 3, 7 and 8 in Figure 1.1) up to 40 cm thick.

Interpretation:

Climbing ripples are typically associated with environments of large sediment input (Allen, 1971) and rapid deposition of suspended material, relative to bedload material (Lanier et al., 1998; Nichols, 2009, p. 53). Moreover, fast deceleration of the transportation fluid velocity will lead to faster sedimentation by suspended sediments relative to bedload transported sediments (Lanier et al., 1998). When sedimentation rate exceeds the rate of accumulation, ripple stoss-side is preserved, causing ripples to accumulate in both stoss- and lee-sides (Nichols, 2009). Hence, if in such conditions the fluid's flow velocity decelerates, thus sedimentation rate of suspended material accelerates, it should be visible through steepening of the ripples' angle of climb (Allen, 1971; Lanier et al., 1998).

Arguably, Figure 4.9 shows a trend of sedimentation rate acceleration where the lower part exhibits a ripple angle of climb similar to the stoss-side angle, while for a few centimetres in the middle, the angle of climb steepens and several paralleled stoss-sides are preserved. The uppermost ripples are more chaotic and shows oppositely directed foresets, indicating at least one current reversal episode.

Considering the apparent acceleration trend and current reversal(s), together with the stratigraphic position with overlying mud draping and herringbone cross-stratification (see log from Smith's Cabin North, Appendix H), climbing ripples such as these may originate from a crevasse splay in a tidally influenced lagoon, or a minor channel on an estuarine tidal flat, both suggested by Yokokawa et al. (1995) and Lanier et al. (1998) for tidally influenced modern- and paleoenvironments in Japan, France and Kansas, USA, respectively.

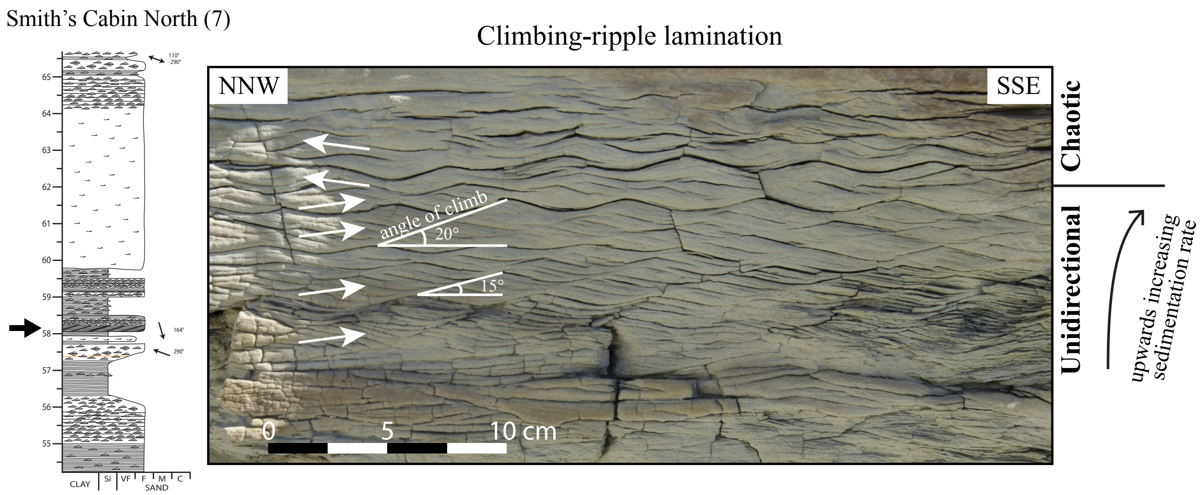


Figure 4.9: Climbing ripples as observed at Smith's Cabin North shows an upwards increase in angle of climb (white illustration) which turns into more chaotic directions and angles towards the top. See Figure 1.1B for locality

Facies J - Planar- to low angle cross-stratified sandstone (Curtis Formation)

Description:

This facies consists of very fine to fine sandstone containing planar- to low angle cross-stratified internal layers 0.2 to 10 cm thick (see Figure 4.10i). Bidirectional current ripples are common locally, as shown in logs from Stove Gulch East, Humbug Flats East and Neversweat Wash (see appendices for logs) (see Figure 1.1 for localities), some places together with oscillation ripples. Structures are otherwise scarce and vague. Although scattered, gentle current ripples of up to 3 cm may be found inside the layering at all localities, as well as up to 10 cm thick gentle cross-beds. This facies is present at all Curtis Formation log-sites (see Figure 1.1 for localities), except Crystal Geyser, commonly in the middle sandy intervals as up to 15 m thick units. Soft sediment deformation is present at 76.5 m and 56 m in the logs from Neversweat Wash and Dry Mesa, respectively (see Figure 4.10ii).

Interpretation:

Very fine to fine sand is deposited in relatively low energy environments (Hjulström, 1955). However, bidirectional current ripples may indicate several transport components such as along-shore currents, river outlets and/or tidal influence with current reversals (Davis Jr. and Dalrymple, 2012). As described by James and Dalrymple (2010), planar- to low angle cross-stratification is common in beach deposits, made by the strong back-and-forth motion of near shore wave action. Dipping gently towards the basin, the low angle cross stratification may locally contain current ripple cross-lamination as a result of basinward, channelized rip currents and oscillation ripples by intrabasinal wave motion (Boggs, 2006). Soft sediment deformation is subject to high pore fluid content, resulting in instability during sediment overburden or irregularities in near proximity, such as an incision of some sort, causing the unstable sediment to slide out and deform. Thus, based on structures, composition and scale, Facies J is interpreted to represent beach deposits with adjacent rip current channels and soft sediment deFormation.

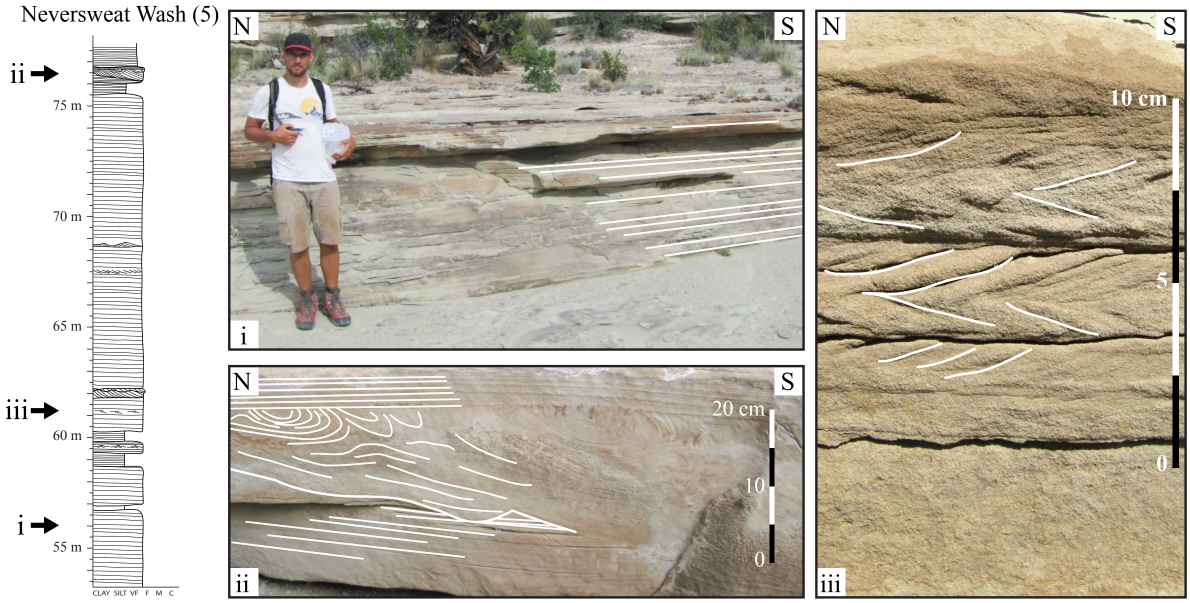


Figure 4.10: Facies J as present at Neversweat Wash (see Figure 1.1 for locality). **i**: Overview of planar to low angle cross-stratification. **ii**: Internal lamination collapse due to water escape. **iii**: Close-up of herringbone cross-lamination. White drawn lines indicate internal structures. Photo positions are marked in attached log.

Facies K - Plane parallel-laminated sandstone (Curtis Formation)

Description:

This facies consists of very fine to fine grained sandstone with plane parallel lamination. Structures are scarce and vague, but some scattered current ripples and herringbone cross-lamination may occur. The sandstone bedding surface is commonly rusty red, while a fresh, newly cut surface is grey-green. Facies K is present in the Curtis Formation upper half intervals at all study localities (see Figure 1.1B,C for localities). Towards the Curtis - Summerville formations transition zone lamination becomes flaky and is expressed as separate layers, with curving geometry, less than 1 cm thick.

Interpretation:

Very fine to fine sand is deposited during relatively low energy conditions (Hjulström, 1955). Plane parallel lamination may be deposited during rapid flows such that ripples are not deposited (Nichols, 2009, p. 139). Presence of current ripples and herringbone cross-lamination at scattered localities, however, reflect deposition during flowing water and current reversals, respectively, such as in a tidally influenced environment (Davis Jr. and Dalrymple, 2012). The grey-green colour of a freshly cut surface, in contrast to the rusty red bedding surface, reflect oxidation, where Fe^{2+} transforms into Fe^{3+} (Boggs, 2006) (in this case by recent surficial weathering). The flaky layers to the top are considered secondary exfoliation features as there are no recorded changes in grain size.

Facies L - Fluvial ripple-laminated sandstone (Summerville Formation)

Description:

Situated as the lowermost Summerville Formation lithological unit, the outcrop at Sulphur Canyon (see Figure 1.1 for locality and Figure 4.11 for picture), exhibits a very fine, 30-40 cm thick red bedded sandstone, packed with unidirectional, well defined, ripple-lamination (see Figure 4.11). Gently fining upwards from fine to very fine sand, the ripples accumulated in the underlying ripple troughs, with no apparent erosion, resulting in a wavy and undulating geometry, preserving the internal structures of each ripple.

Interpretation:

Red coloured sandstone commonly reflects oxidation by subaerial exposure (Boggs, 2006). Fining upwards sorting indicates a decrease in current flow velocity (Hjulström, 1955). Based on the unidirectional nature of the ripples, well defined ripple foresets, a gentle fining upwards trend and apparent evidence for oxidation by subaerial exposure, these ripples are interpreted as fluvial, substantiated by previous Summerville Formation interpretations as supratidal lower coastal plain and salt marsh deposits with small rivers (Kocurek and Dott Jr., 1983; Kreisa and Moiola, 1986; Peterson, 1988; Hintze and Kowallis, 2009).

Figure 4.11: Picture of unidirectional current ripples at Sulphur Canyon (see Figure 1.1C for locality). White drawn lines indicate lamination.

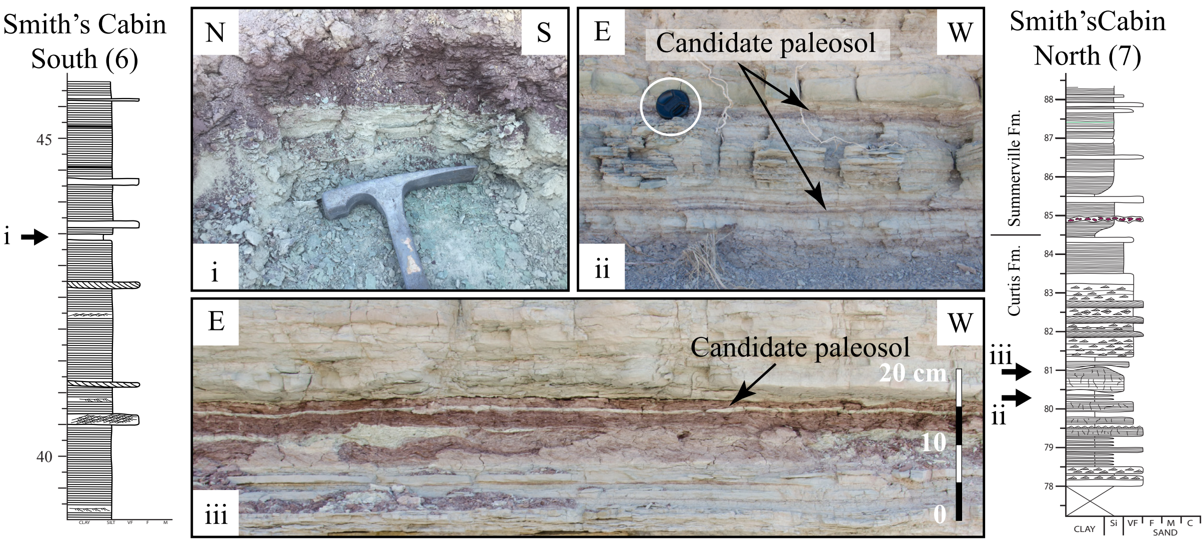


Figure 4.12: Picture of paleosol candidates at Smith's Cabin South (**i**) and North (**ii**,**iii**). Note hammer and lense-cap for scales. See Figure 1.1B for localities.

Facies M - Plane parallel-laminated mudstone (Summerville Formation)

Description:

This facies consists of dark red, plane parallel laminated mudstone, commonly represented as flaky, easily broken, paper-thin layers. Gentle colour variations may occur, including some pale white spots apparently randomly scattered throughout the unit. Up to 10 cm thick layers of dark red to purple loose silt may occur together with green loose silt (see Figure 4.12) in the Curtis – Summerville formations transition zone at several localities (Smith's Cabin North, -South and Crystal Geyser, see Figure 1.1B for localities).

Interpretation:

Grain size and plane parallel-lamination reflects deposition during calm, undisturbed conditions. Dark red colour implies oxidation of iron by subaerial exposure, thus, a continental origin (Boggs, 2006). Presence of isolated, elongate evaporite deposits at scattered localities is interpreted to be remnants of pits and ponds, occasionally flooded, followed by drought in an otherwise arid environment. Occurrences of up to 10 cm thick dark red to purple loose silt may according to Kraus (1999) be candidates for paleosol deposits, hence, a continental origin.

Facies N - Iron rich ripple- and parallel-laminated sandstone (Summerville Formation)

Description:

Fine grained, heavily cemented, siliceous sandstone beds up to 30 cm thick define this facies, coloured dark red to brown. Gentle ripple cross-lamination may occur (though too vague to measure paleocurrent directions with confidence), otherwise plane parallel-lamination, as well as surficial desiccation cracks (see FA 6 below for picture), represented in Smith's Cabin North (see Figure 1.1B for locality) log, . Chert concretions are observed at Dry Mesa roadcut and Mine Canyon (see Figure 1.1B for locality). Facies N occurs as laterally extensive (beyond outcrop reach) layers interbedded with Facies M and is present at all Summerville Formation study localities.

Interpretation:

As dark red to brown colour indicates oxidation by subaerial exposure (Boggs, 2006), it implies a continental depositional origin. Parallel lamination together with unidirectional current ripples may indicate deposition during unidirectional transportation. According to scale, lateral spreading and lack of channel-shape, the sediments are interpreted to originate from sudden channel overbank flooding events, followed by drought. Considering the stratigraphic position as interbedded with Facies M (Plane parallel-laminated siltstone), several authors (Kocurek and Dott Jr., 1983; Caputo and Pryor, 1991; Hintze and Kowallis, 2009) agree with this interpretation.

Table 4.1: Facies table for the Jurassic Entrada-, Curtis- and Summerville formations (see Figure 2.3 for stratigraphic column)

Facies	Description	Structures	Grain size	Interpretation	Formation
A	Cross-stratified sandstone	Unidirectional tangential cross-bedding, sharp boundary, rusty red	VF - F	Aeolian dune deposits	Entrada Sst
B	Parallel-laminated mudstone with evaporites	Dark red silty mud with pale yellow to white lenses, plane parallel laminated, evaporite content	Si - Cl	Aeolian interdune deposits with occational flooding	Entrada Sst
C	Silty sediment	Plane parallel lamination, bidirectional current ripple cross lamination, grey to green	Si - Cl	Gentle flow activity, current reversals → tidal activity	Curtis Fm
D	Cross-stratified conglomerate	Erosive base, mud clasts, extrabasinal rounded chert clasts, tabular- and trough cross stratification	M - Gr	High energy conditions, fluvial transport, modified by tidal currents	Curtis Fm
E	Lenticular bedding	Rippled sand lenses surrounded by Facies C sediment. Herringbone cross stratification and current ripples	Si - F	Current reversals in lower subtidal zone	Curtis Fm
F	Wavy bedding	Multidirectional current ripple cross-laminated sand layers and layers of Facies C	Si - F	Current reversals in subtidal zone (shallower than Facies E)	Curtis Fm
G	Flaser bedding	Ripple cross-lamination, herringbone cross-lamination, mud lenses and double mud drapes	VF - F	Upper subtidal	Curtis Fm
H	Trough cross-stratified sandstone	Trough cross-stratification, mud drapes, desiccation cracks, evaporites	VF - M	Tidally influenced dunes and channel infill	Entrada Sst and Curtis Fm
I	Sandstone with climbing ripples	Climbing ripple cross-lamination	VF - F	Tidal channel overbank spill on tidal flat	Curtis Fm
J	Planar- to low angle cross-stratified sandstone	Planar- to low angle cross-stratification, herringbone cross-lamination, single current ripple and oscillation ripple-lamination	VF - F	Beach with tidal influence	Curtis Fm
K	Plane parallel-laminated sandstone	Plane parallel-lamination, current ripples	VF - F	Upper intertidal sand	Curtis Fm
L	Fluvial ripple-laminated sandstone	Dark red, unidirectional current ripple-lamination	VF - F	Fluvial channel deposit	Summerville Fm
M	Plane parallel-laminated mudstone	Dark red, plane parallel-lamination, pale white lenses, evaporites	Si	Supratidal plain	Summerville Fm
N	Iron rich ripple- and parallel-laminated sandstone	Dark red to brown, gentle ripple cross-lamination, desiccation cracks	F	Fluvial overbank flooding deposits	Summerville Fm

4.2 Facies associations

4.2.1 Facies association 1 (FA 1) – Coastal aeolian dune field:

Description:

FA 1 consists of interbedded units of Facies A (Cross-stratified sandstone) and Facies B (Parallel-laminated mudstone with evaporites), representing the Entrada Sandstone, Earthy Facies, hence, the stratigraphic base of this study. Sharp erosional contacts defines the Facies A - Facies B relationship, both between and within the units, as they alternate in thicknesses. However, Figure 4.2ii shows a gradual transition from Facies B to Facies A (Stove Gulch, Humbug Flats). Thin (2 cm) evaporite lenses (potentially gypsum, see Figure 4.2iii) are found in Facies B at scattered localities.

At Crystal Geyser (see Appendix J for log) and west of Sulphur Canyon, Humbug Flats (Rimkus, 2015) (see Figure 1.1B for localities), Facies H (Trough cross-stratified sandstone) is documented inside FA 1 containing northward-, and oppositely directed foresets, respectively, with tangential bottomsets (see Figure 4.8vi). Facies H occurs at Crystal Geyser ~13 meters below the Entrada Sandstone top and exhibits mud clasts along the foresets, candidate double mud drapes and sorted foresets alternating between coarser and finer sand (see Figure 4.8vii). Facies H is recorded as less than 1.5 m thick and is bounded by Facies A and Facies B.

Interpretation:

Interbedding of aeolian dune- and interdune deposits indicates aeolian desert environments, as interpreted and described by several authors (Kocurek and Dott Jr., 1983; Blakey et al., 1988; Peterson, 1988; Hintze and Kowallis, 2009). Traces of evaporites inside Facies B indicate evaporation in the Entrada Sandstone interdunal areas, which may reflect occasional flooding, high ground water level or humid climate conditions (or combinations), as described by Crabaugh and Kocurek (1993). In addition, according to Catuneanu (2006), a rise in relative ground water level may come as a product of marine transgression. Further, as sand becomes wet, grains stick together by cohesion (Boggs, 2006), resulting in a higher resistance against transport and erosion by flowing currents. Thus, humid conditions may favour the preservation of interdunal sediments as the migrating sand dunes may get stuck in interdune ponds (as suggested by Crabaugh and Kocurek, 1993), instead of eroding the sediments. This is why the rock record of such alternating deposits may be represented as interbedded, continuous layers of cross-bedded dune- and flat-bedded interdune strata (Boggs, 2006) (FA 1 is represented in Figure 4.13).

Regarding the presence of Facies H at Crystal Geyser and west of Sulphur Canyon, well defined tangential foresets and a general transport direction may lead towards an interpretation as sediments deposited by flowing water, such as by a river. However, candidate double mud drapes (illustrated by picture in Figure 4.8vi,vii), oppositely directed foresets and systematic foreset sorting as repeating alternations between coarser- and finer sand may indicate a coastal environment influenced by tidal currents (Davis Jr. and Dalrymple, 2012). Such an interpretation is substantiated by Hicks et al. (2012) as they described Entrada Sandstone tidal features at several localities in east-central and southern Utah.

Consequently, based on the presence of candidate tidal features and the stratigraphic context, it is considered likely that FA 1 resembles a coastal aeolian dune field, rather than exclusively an inland wet aeolian dune field of high ground water level.

4.2.2 Facies association 2 (FA 2) – Fluvio-tidal transition

Description:

Northward from Dry Mesa (see Figure 1.1B for localities) FA 2 overlies FA 1 by an erosional boundary (the J3-unconformity after Pipiringos and O'Sullivan, 1978), some places as an angular unconformity (see Figure 4.13) dividing the Entrada Sandstone and Curtis Formation. Lithology changes abruptly from rusty-red, Facies A (Cross-bedded sandstone) and Facies B (Parallel-laminated mudstone with evaporites) in FA 1, to grey-green Facies C (Silty sediment) and Facies D (Cross-stratified conglomerate) in FA 2. Facies D appears amalgamated with undulating internal contacts at Stove Gulch and Neversweat Wash (see Figure 1.1C for localities) and is typically represented in FA 2 by laterally continuous (far beyond outcrop reach) erosive layers alternating between overlying Facies C sediments and FA 1 directly. FA 2 is present at all Humbug Flats adjacent localities (Sulphur Canyon, Stove Gulch and Humbug Flats East), as well as Neversweat Wash and Dry Mesa (see Figure 1.1B-C for localities).

Interpretation:

As Facies D is interpreted to represent fluvial deposits with tidal modification, its stratigraphic position above Facies C as well as FA 1 directly, indicates that Facies D was deposited into the Curtis Sea at an early stage transgression. Based on average grain size, sorting and amalgamated geometries with undulating troughy internal contacts, Facies D is here interpreted to represent a braided river system that flows into the Curtis Sea. Peterson (1994) described these fluviatile deposits and interpreted them to be the first visible influx of sediments derived from newly elevated Elko highlands to the west (see Chapter 2: Geologic framework). Note that an alternate interpretation of Facies D presence may be that it represents fan-deltas that were deposited into the Curtis Sea, however, it seem unlikely as the measured paleoflow directions indispensably trends north, and not diverging as would be expected from a fan deltaic setting. In addition, as the lack of grain sorting and coarse average grain size reflects rapid deposition (Nichols, 2009) during high energy conditions (Hjulström, 1955), respectively, deposition by ephemeral streams governed by flash floods are considered.

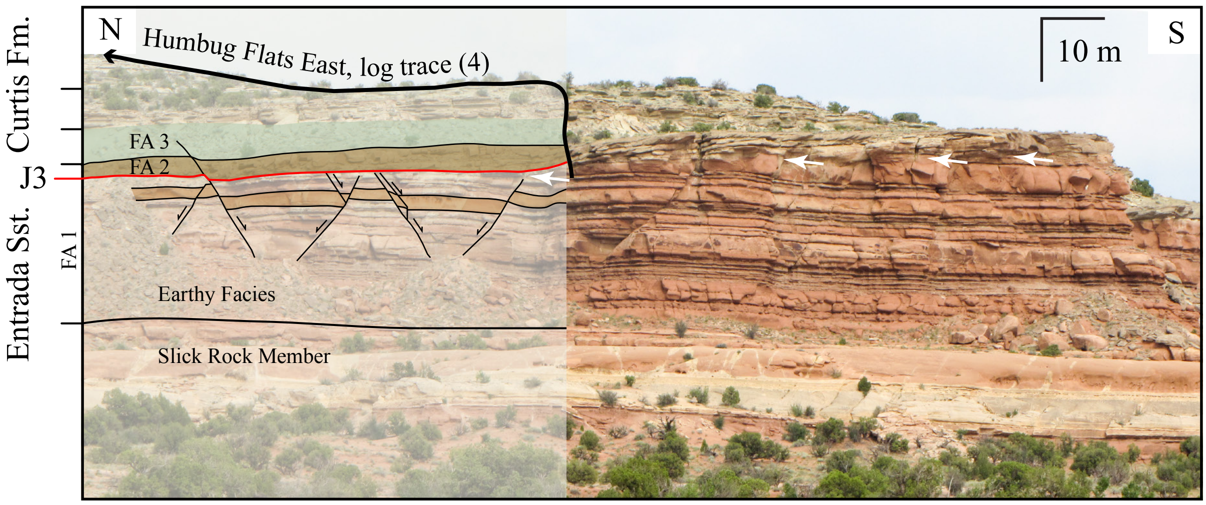


Figure 4.13: Illustration of FA1 - FA 2 - FA 3 - relation at Humbug Flats East (see Figure 1.1 for locality) (log-site 4). The J3-unconformity (drawn in red) acts as an angular unconformity between the Entrada Sandstone and Curtis Formation. Drawn black lines indicate faults and layer boundaries. White arrows indicate Entrada Sandstone top truncations.

4.2.3 Facies association 3 (FA 3) – Subtidal heterolithic mix

Description:

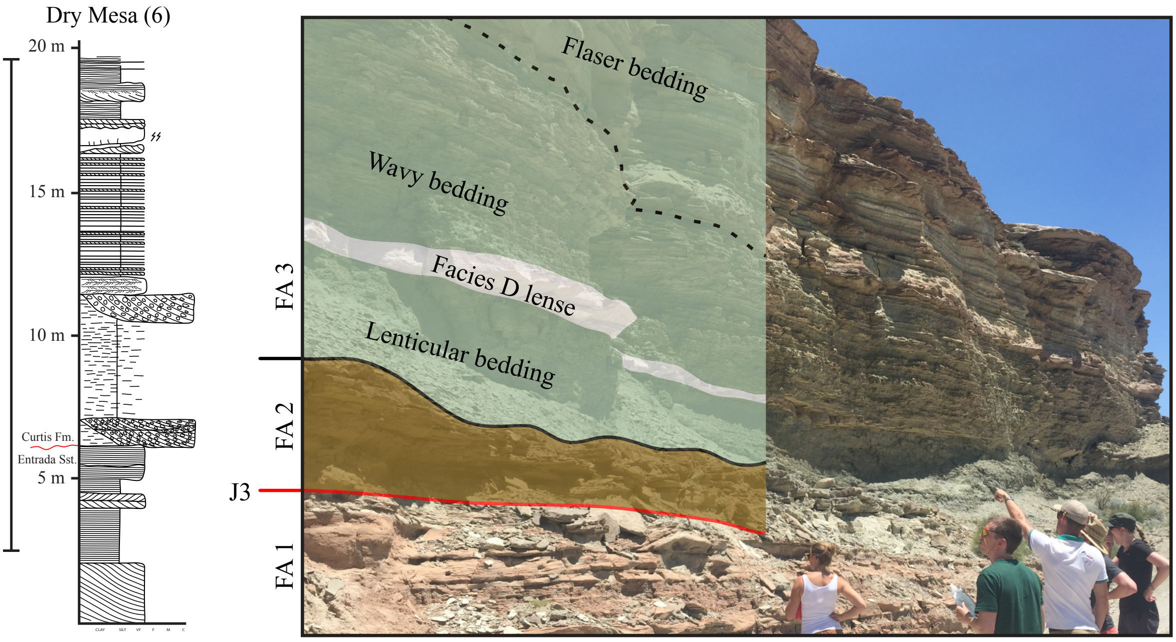
FA 3 overlies FA 2 by a sharp conformable boundary (at localities where FA 2 is present), otherwise unconformably overlying FA 1, dividing the Entrada- and Curtis formations. Lithology changes gradually upwards from Facies C (Silty sediment) to Facies E (Lenticular bedding) and Facies F (Wavy bedding), along with locally restricted wedge- and lens-shaped bodies, a few tens of meters long, of Facies D (Cross-stratified conglomerate) which occurs at scattered localities, documented by logs from Stove Gulch East, Humbug Flats East, Dry Mesa and Smith's Cabin North (see appendices B, E, G for logs and Figure 1.1B for localities).

The contact between FA 3 and FA 1 acts the same way as between FA 2 and FA 1 (see description of FA 2 above) as the J3 (after Pipiringos and O'Sullivan (1978)) separates the Entrada Sandstone and Curtis Formation by an erosional unconformity. Highly various in thicknesses, ranging between 2-25 m, FA 3 is present at all localities except Crystal Geyser (see Figure 1.1 for locality).

Interpretation:

Lithology, sedimentary structures, paleocurrent measurements and the change in development from Facies E to Facies F point towards an increase in energy conditions, for a tidally influenced deposit, as described by Eschner and Kocurek (1986); Kreisa and Moiola (1986). However, while they describe the sediments to originate from intertidal environments, Caputo and Pryor (1991); Wilcox and Currie (2008) utilise sequence- and biostratigraphy to suggest a subtidal origin, thus shallowing upwards (as energy conditions increase and decrease basinward in intertidal- and subtidal zones, respectively (Davis Jr. and Dalrymple, 2012)). Nevertheless, the development from FA 2 to FA 3 and FA 1 to FA 3 was caused due to filling inn accommodation space created by a rise in relative sea level, inundating both FA 2 and FA 1 by marine transgression.

The presence of isolated Facies D wedge- and lens-shaped bodies (see figure) are interpreted as sediments reworked from fluvial deposits of FA 2 (see interpretation of FA 2 above) into tidal bars and basin floor ridges by tidal scouring and modification as the Curtis Sea level rose.



4.2.4 Facies association 4a (FA 4a) – Sub- to intertidal sand mix

Description:

Overlying FA 3, FA 4a is represented by the middle sandy Curtis Formation intervals. The lower boundary is typically gradual as the lithology gets sandier, but at scattered localities, the contact appears sharp and erosion may have occurred. Predominated by Facies G (Flaser bedding), FA 4a is complemented by Facies C (Silty sediment) and Facies H (Trough cross-stratified sandstone). Herringbone cross-lamination, unidirectional current- and oscillation ripple lamination and mud drapes are common.

Interpretation:

Grain size, sorting, sedimentary structures (ripple lamination and mud drapes) and measured paleocurrent directions indicate an environment dominated by periodic current reversals, such as an intertidal environment (Reineck and Singh, 1980; Davis Jr. and Dalrymple, 2012). Sand dominance may be related to depositional energy conditions, placing FA 4a in a higher energy environment than FA 3. Depositional energy conditions increase basinward in intertidal zones (James and Dalrymple, 2010; Davis Jr. and Dalrymple, 2012) as tidal currents are able to influence the sediments for a longer time period (and stronger currents build up); hence, FA 4a is interpreted to represent the upper subtidal- to lower intertidal zone.

4.2.5 Facies association 4b (FA 4b) – Beach with tidal inlets

Description:

FA 4b is defined as a subgroup together with FA 4a due to the stratigraphic context, surrounded by FA 4a both laterally and vertically. FA 4b consists of Facies H (Trough cross-stratified sandstone) and Facies J (Planar- to low angle cross-stratified sandstone), bound together as apparent lens-shaped bodies enclosed by FA 4a. Log-site 3 from Sulphur Canyon, Humbug Flats (see Figure 1.1 for locality), exhibits a representative relation as Facies J changes into Facies H laterally over a distance of less than 40 meters (see Figure 4.14), showing significant lateral variation of the strata. Facies I (Sandstone with climbing ripples) occurs at Stove Gulch West and Smith's Cabin North and South (see Facies I for description and Appendix C, I and H for logs).

Interpretation:

As Facies J is interpreted to represent foreshore beach deposits, the close lateral relation to Facies H implies that there has been a channel cutting through the beach, allowing water to flow through a barrier-like environment towards a bay or lagoon during tidal flood- and ebb currents. Facies J changes laterally into Facies H over a distance of less than 40 meters, showing that significant lateral variations ought to be expected. Considering this coastal setting, a highly various and undulating coastline is suggested, which Caputo and Pryor (1991); Wilcox and Currie (2008) bring forth and visualise by their paleoenvironment reconstruction models.

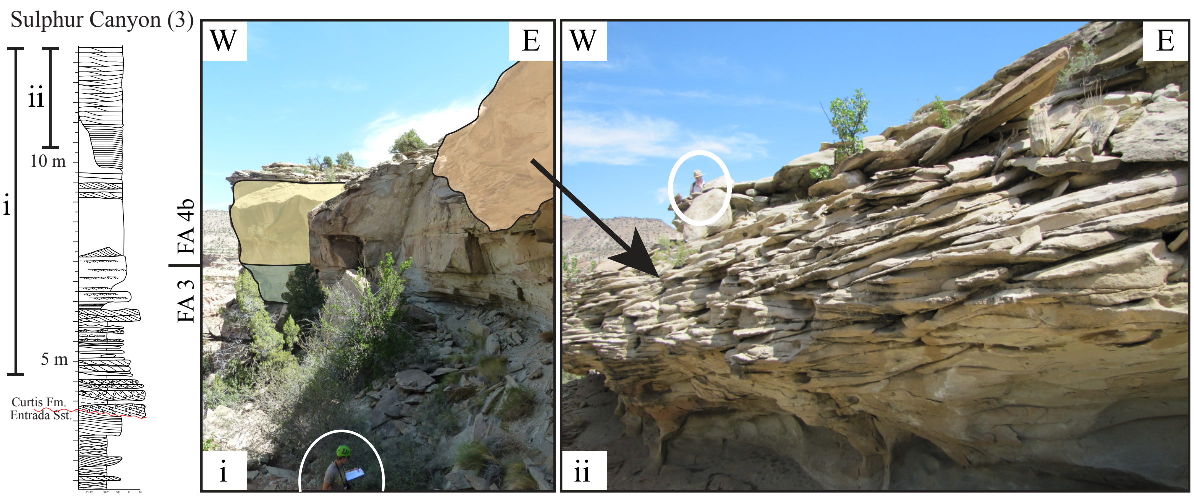


Figure 4.14: Local lateral variation in tidal sub-environments, illustrated at Sulphur Canyon as FA 4b planar- to low angle cross-stratified sandstone (Facies J) interfingers laterally with trough cross-stratified sandstone (Facies H). Note persons for scales. See Figure 1.1C for locality.

4.2.6 Facies association 5 (FA 5) – Upper intertidal mixed flat

Description:

FA 5 covers the topmost Curtis Formation heterolithic interval (picture shown in Figure 4.15i,ii). By a gradual transition, FA 5 overlies FA 4 (either a or b, depending on locality) as the succession gets muddier in an heterolithic interbedding of Facies C (Silty sediment) and Facies K (Plane parallel-laminated sandstone). 10-40 cm thick layers in systematic alternation are common as the layers typically extend beyond lateral outcrop reach (see Figure 4.15i,ii). Internal structures include asymmetrical current- and wave ripple-lamination at all localities, both in Facies C and Facies K (see corresponding descriptions in sub-chapter 4.1 above), while herringbone cross-lamination are present at scattered localities. FA 5 is present at all log-sites where the Summerville Formation is preserved on top, otherwise FA 5 is easily eroded, except at Humbug Flats East where it is preserved and represents thus the succession top.

Interpretation:

Alternating heterolithic deposits such as in FA 5 are closely related to systematic energy level fluctuations, from quiescent water conditions where mud and silt (Facies C) are deposited, to medium energy conditions of sand deposition (Facies K) (Hjulström, 1955). Presence of herringbone cross-lamination reflects current reversals, such as in tidal environments (Davis Jr. and Dalrymple, 2012). Typical sediment distribution within tidal environments are generally (but not restricted to) intertidal mud- and sand-flats, with increasing sand content basinward as the tidal energy increases (Davis Jr. and Dalrymple, 2012). The stratigraphic context is further considered essential as FA 5 is situated on top of (FA 4a/b) sub- and intertidal deposits and is overlain by subaerially exposed continental deposits (FA 6 see description below). As follows, FA 5 is interpreted to represent an intertidal mixed flat of heterolithic character, commensurate with previous Curtis Formation interpretations (e.g. Kocurek and Dott Jr., 1983, see Chapter 2: Geologic framework). Regarding the occurrence of herringbone cross-lamination only at some localities, it may reflect that the degree of preservation of intertidal sedimentary structures may deviate between different depositional systems (Davis Jr. and Dalrymple, 2012), or it may be due to alternating locality outcrop quality, such as regarding exposure cutting angle, degree of cementation, weathering, etc.

4.2.7 Facies association 6 (FA 6) – Supratidal lower coastal plain

Description:

FA 6 is the stratigraphic top for this study and consists of interbedded layers of Facies L (Fluvial ripple-laminated sandstone), Facies M (Plane parallel-laminated mudstone) and Facies N (Iron-rich ripple- and planar laminated sandstone). Observed structures are governed by the presence of Facies L and Facies N as lateral variation occurs. Predominated by the dark red to brown mudstones of Facies M, structures are scarce, although desiccation cracks and ripple lamination are found locally (Log 7, Smith's Cabin North, see Figure 1.1 for locality) in Facies L and Facies N (Figure 4.15).

Interpretation:

Grain size, sorting, structures, colours and evaporites suggest a relatively calm, flat, continental environment of Facies M deposits, with occasional flooding and drought, resulting in precipitation of evaporites (James and Dalrymple, 2010). As Facies L and Facies N both originates from fluvial deposits, the stratigraphic relation to Facies M leads to an interpretation as seasonal fluvial overbank flood deposits of varying magnitude.

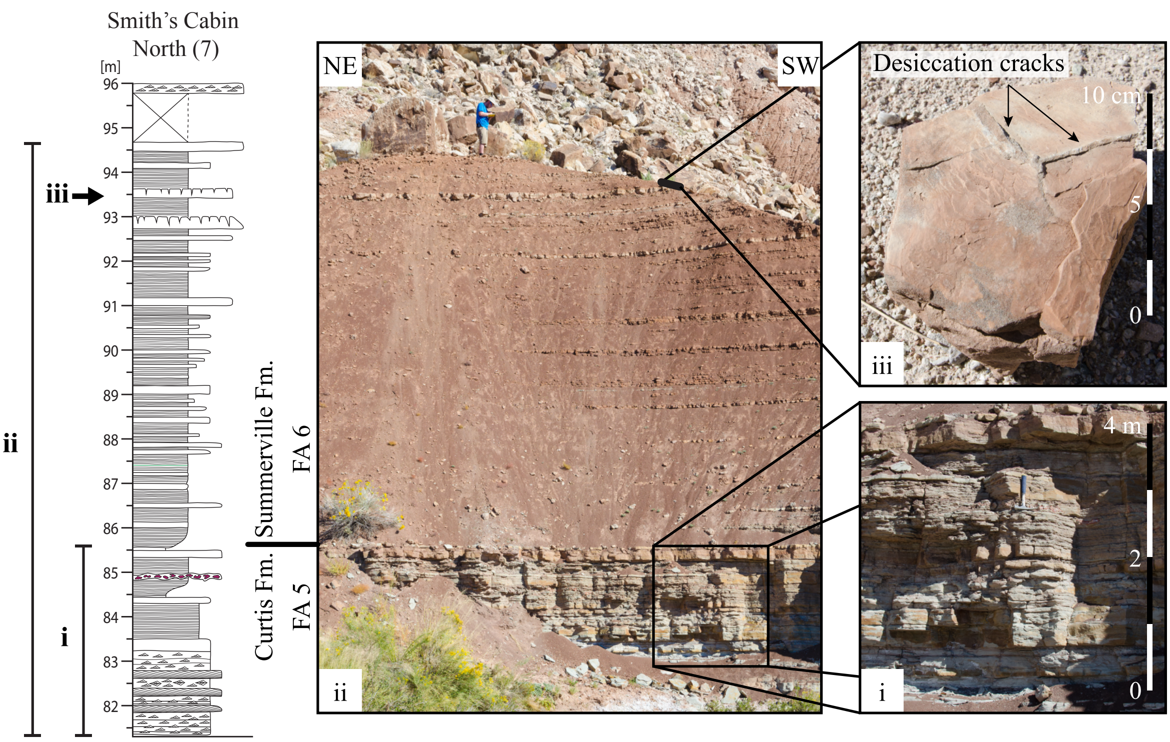


Figure 4.15: Outcrop overview of the Curtis - Summerville formations transition at Smith's Cabin North, log . **i**: Close-up of upper Curtis Formation heterolithic bedding, assigned to FA 5. **ii**: Overview of outcrop, note person at top for scale **iii**: Cemented desiccation cracks of Facies N. Note that the quality of this outcrop is without equal compared to the rest of the localities as the Summerville Formation generally slopes gently due to its easily erodible sediment composition.

Table 4.2: Facies associations for the Entrada Sandstone, Curtis- and Summerville formations, recorded in north-eastern San Rafael Swell, Utah (see Figure 1.1A-B for map). **SB** - Sequence boundary, **TS** - Transgressive surface, **FS** - Flooding surface (sequence stratigraphic surfaces are described in Chapter 5 below).

Formation (Fm.)	**Member/ Unit**	**Architectural element**	**Depositional environment**	**Facies included**	**Sequence stratigraphic surfaces (Exxon Model after Posamentier and Vail, 1988)**
Summerville Fm.		FA 6	Supratidal lower coastal plain	L,M,N	
Curtis Fm.		FA 5	Upper intertidal mixed flat	C,K	
		FA 4b	Beach with tidal inlets	H,I,J	
		FA 4a	Sub- to intertidal sand mix	C,G,H,I	
		FA 3	Subtidal heterolithic mix	C,D,E,F	
		FA 2	Fluvio-tidal transition	C,D	- **FS2** - **FS1**
Entrada Sst.	Earthy Facies	FA 1	Coastal aeolian dune field	A,B	- **SB/TS** (J3)

Chapter 5: Log correlation and sequence stratigraphic surfaces

5.1 Log correlation

There are several ways of correlating sedimentary logs depending on the aim- and available data for the study. The aim for this study is to describe the Curtis Formation sedimentary development in relation to its stratigraphically neighbouring units (Entrada Sandstone and Summerville Formation) based on sedimentology and sequence stratigraphy. Accordingly, aligning the sedimentary logs based on an isochronous surface as horizontal datum line will hinge the sequence stratigraphic interpretation to relative time and thus accentuate the successions relative depositional development. In addition, note that as long as the sedimentation rate has not been determined across the correlation panel, the correlation will only be a chronological approximation.

All recorded logs are included for correlation except the log from Stove Gulch West due to its lack of upper Curtis Formation intervals and close proximity to Stove Gulch East and Sulphur Canyon (see correlation panels below and Figure 1.1 for geographical reference). Note that Crystal Geyser is located at a geographically isolated locality, far from the closest neighbouring log-sites at the Smith's Cabin area, therefore it is not possible to confidently trace the sequence stratigraphic surfaces between the localities. The rest of the recorded successions are readily correlated as they are situated along the eastern flank of the San Rafael Swell which represents a nearly continuous outcrop between log traces.

5.1.1 Candidate datum lines

Sequence stratigraphic surfaces may act as suitable candidate datum lines as they reflect a change in depositional stacking pattern (Miall, 2010). Following are three candidate datum lines presented and discussed, two of which are based on sequence stratigraphic surfaces while one is based on the lithostratigraphic boundary between the Curtis- and Summerville formations.

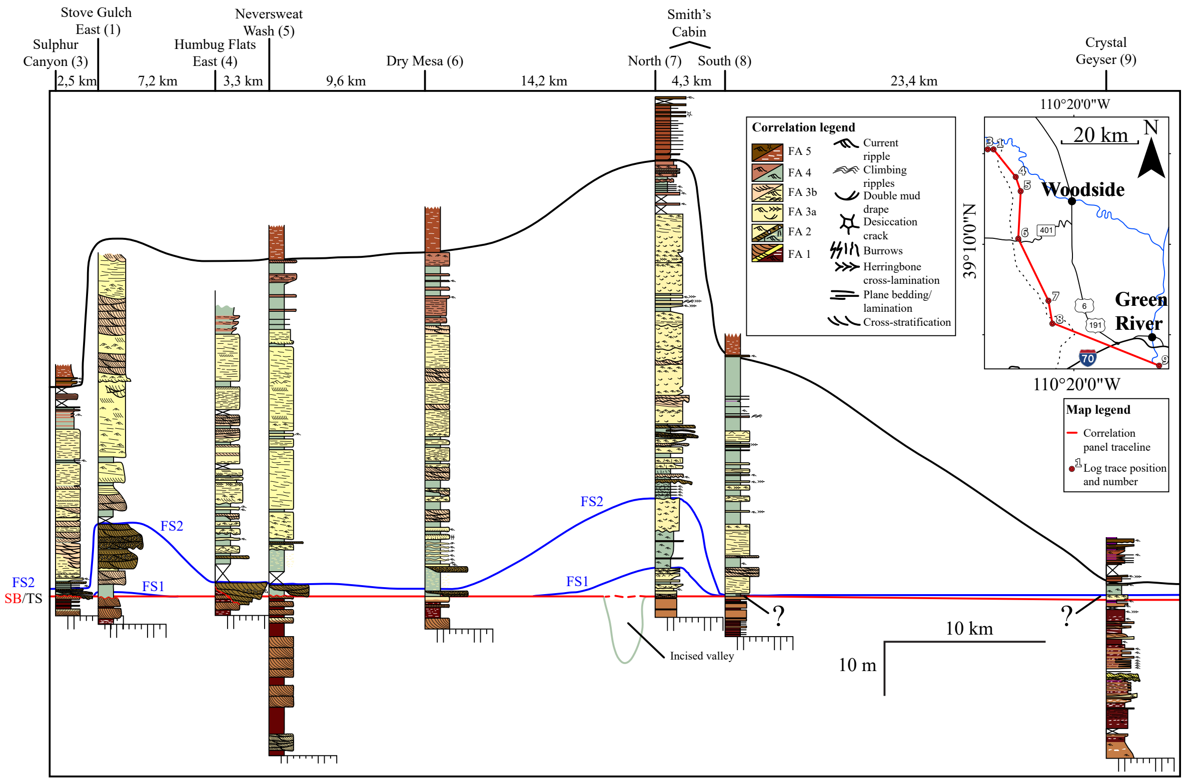


Figure 5.1: Sedimentary correlation panel based on sequence boundary (red line) as candidate datum line. Note legend for symbology & colouring and map for scale and orientation (see Figure 1.1 for complete geographical references). **Incised valley**; see discussion in section 5.2.1 below. **Question marks** (?) indicate uncertainty regarding placement of flooding surface, see discussion in section 5.2.2 below.

Sequence boundary candidate (Curtis Formation base)

One may argue that the sequence boundary (SB) (the Exxon Model after Posamentier and Vail, 1988) (see Figure 1.1 for correlation panel) may act as a suitable candidate datum line for a locally delimited area. Although the SB is erosional, and thus potentially containing a paleotopographic relief, it could in theory be a plain sub-horizontal surface at the time of Curtis Formation deposition, making it isochronous as the whole surface would have been covered by sediments almost at an instance. However, field observations (see Figure 4.13 for angular unconformity) suggest that the SB occurs as an unconformity containing a relief of at least 20 meters, hence the SB is determined diachronous and the correlation panel in Figure 5.1 is thus not considered suitable to establish the Curtis Formation relative time dependant sedimentary development.

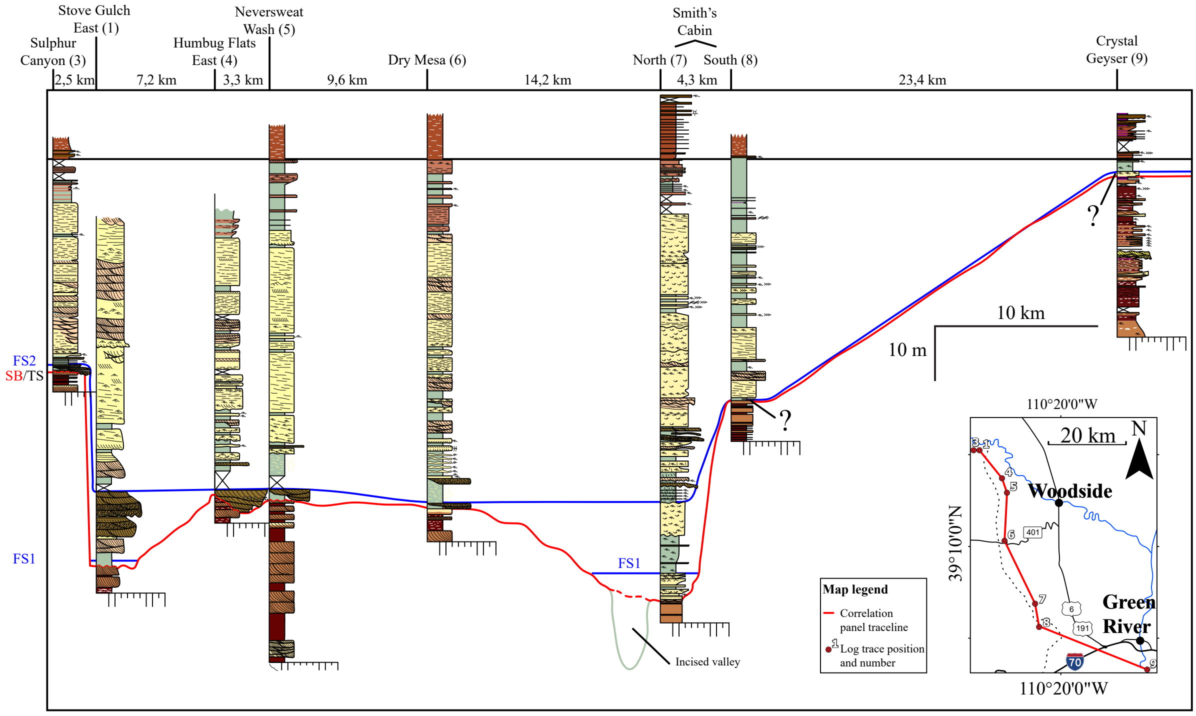


Figure 5.2: Sedimentary correlation panel based on Curtis Formation top boundary as candidate datum line. Note map for scale and orientation (see Figure 1.1 for complete geographical references), see Figure 5.1 for legend on symbology and colouring. Incised valley; see discussion in section 5.2.1 below. **Question marks (?)** indicate uncertainty regarding placement of flooding surfaces, see discussion in section 5.2.2 below.

Curtis Formation top candidate

Utilizing the Curtis – Summerville formations boundary as candidate datum line (see Figure 5.2) results in a Curtis Formation geometry that emphasize on the succession's lateral variation in thickness. The suggested paleotopographic relief along the SB is arguably visible through hinging the logs on the Curtis Formation top boundary, but the FS2 appears undulating. An FS is a sequence stratigraphic surface that represents a point in time where transgression stops and regression starts (Catuneanu et al., 2011) and the FS should in that sense appear strait in a sedimentary correlation panel, such as this, as it is close to isochronous. In addition, the Summerville Formation lower intervals are deposited in a coastal plain environment (see FA 6 description and interpretation in Chapter 4), indicating Curtis Sea regression. Accordingly, regression is considered diachronous and Figure 5.2 is thus not considered suitable to establish the Curtis Formation relative time dependant development.

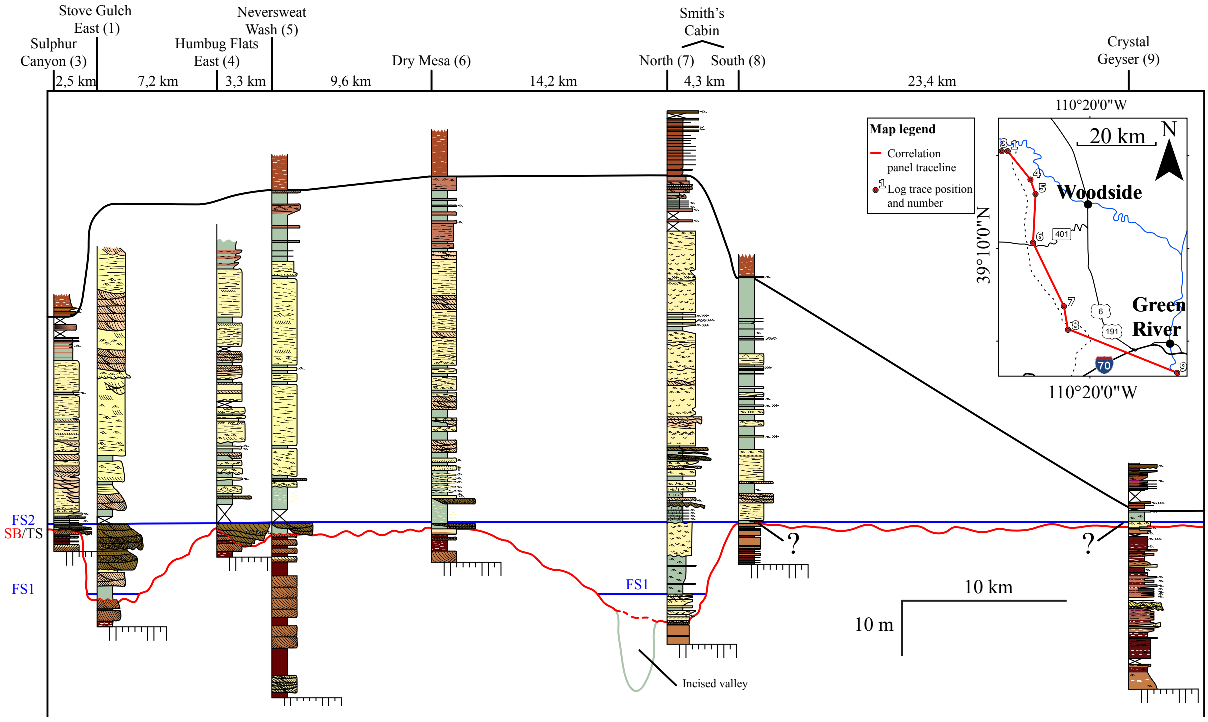


Figure 5.3: Sedimentary correlation panel based on regionally traceable flooding surface (FS2) as candidate datum line. Note map for scale and orientation (see Figure 1.1 for complete geographical references), see Figure 5.1 for legend on symbology and colouring. **Incised valley**; see discussion in section 5.2.1 below. **Question marks** (**?**) indicate uncertainty regarding placement of flooding surface, see discussion in paragraphs below and section 5.2.2 below.

Flooding surface candidate

As a flooding surface (FS) represents a point in time where transgression turns into regression it will act as a suitable candidate datum line as it is close to isochronous (Catuneanu et al., 2011). A sedimentary basin may experience several minor flooding events with FSs that are not necessarily present at all localities (due to e.g. local variations in topography or tectonic activity such as laterally irregular subsidence), hence, the identification of an MFS or regionally traceable FS should be the same for the basin. Such a regionally traceable FS is identified for the recorded logs and suggested suitable for candidate datum line, presented in Figure 5.3. As FS2 is made horizontal (and the logs hinged- and adjusted accordingly) the SB appears undulating, visualizing the previously suggested paleotopographic relief of (here) at least 30 m (as opposed to the formerly suggested 20 meters based on field observations) along the Entrada Sandstone top.

5.1.2 Encountered challenges in correlating the logs

As the sedimentary correlation aims to map out the Curtis Formation relative time dependant development, the vertical scale represents both recorded succession thickness and relative time (based on the isochronous surface datum line alignment). Thus, sedimentation rates may be challenging to account for as these will affect the time dependant correlation vertically. Sedimentation rates across different depositional environments are assumed to be different as governing factors such as energy level and sediment supply may vary. Consider the log from Smith's Cabin South. The distance between Smith's Cabin North and South logs is 4.2 km, and the height difference between the Curtis Formation tops is more than 20 meters (see Figure 5.3). Consequently, as the log from Smith's Cabin South contains more mud and less sand than the log from Smith's Cabin North (and their closely spaced), it is suggested that Smith's Cabin South represents an environment that has lesser energy conditions (thus is more protected) than the log from Smith's Cabin North. Such differences are likely to influence the lateral correlation of sedimentary logs, because of the chronological differences. Accordingly, the correlation panel is merely a representation of development by relative time and not absolute as it would be in a chronostratigraphic correlation panel.

5.2 Recorded sequence stratigraphic surfaces

Sequence stratigraphic surfaces recorded in the field includes one sequence boundary (SB) (the Exxon Model after Posamentier and Vail, 1988) of subaerial erosion, coinciding with a transgressive surface (TS), and at least two flooding surfaces (FS).

5.2.1 Sequence boundary

The SB after the Exxon Model (Posamentier and Vail, 1988) is identified as an erosional unconformity of subaerial erosion and a basinward correlative conformity. Hence, the SB is here interpreted to follow the J3-unconformity (see Chapter 2: Geologic framework), separating the Entrada Sandstone from the overlying Curtis Formation. Eschner and Kocurek (1988) discuss relief along J3 as alternating between inherited relief (partly eroded dunes leaving traces of dune topography, but not the entire dune shape) and erosional relief (completely eroded strata without the preservation of any dune-related topography) with an angular unconformity (as described in Chapter 4 and further discussed in Chapter 6) to the Curtis Formation. The SB has consequently been identified as the boundary beneath the first occurrence of Curtis-like lithofacies, typically occurring as sharp erosional.

Identifying the SB at Crystal Geyser is more challenging as a cross-stratified unit with candidates of tidal features (Facies H - Trough cross-stratified sandstone, see Chapter 4) occurs in the middle of the Entrada Sandstone Earthy Facies (see FA 1, Chapter 4). However, Entrada Sandstone fluvial deposits (Kocurek, 1981) modified by tidal activity (Hicks et al., 2012) has previously been documented for the Entrada Sandstone Earthy Facies. Thus, Facies H is here considered part of the Earthy Facies depositional environment and not the Curtis Formation. Accordingly, the first occurrence of Curtis Formation deposits is documented ~13 meters up the succession (see log from Crystal Geyser, Appendix J), identified by ~3 meters of intertidal sand and mud (see FA 4b, Chapter 4, for description) gradually overlain by the Summerville Formation. Hence, the SB is considered conformable at the Curtis Formation base with no apparent signs of erosion at this certain locality.

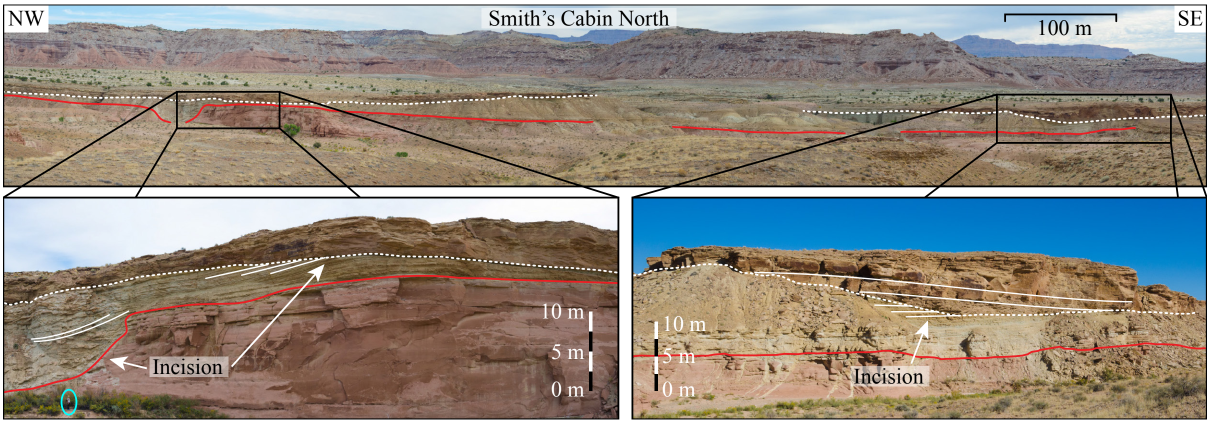


Figure 5.4: Panoramic view of the lower Curtis Formation outcrop at Smith's Cabin North (see Figure 1.1B for locality). Two tidal channel incisions are observed and indicated ~700 m apart in the sandy interval. Basal tidal channel incision are shown in lower left image. Red drawn lines indicate erosive sequence boundary; White drawn dotted lines indicate base of sandy interval; White drawn lines indicate internal layering; Blue circle in lower left points to person for scale.

An incised valley (drawn in green in Figure 5.3) exposed at Cottonwood Wash (see Figure 1.1 for locality) (illustrated in Figure 5.4) is considered an erosional feature derived from a Curtis Sea tidal inlet. Thus, as the J3-unconformity represents the erosional to partly erosional unconformity between the Entrada Sandstone and Curtis Formation it is not solely a result of Curtis Formation erosion (although some degree of Curtis Formation transgressive ravinement and tidal erosion are considered), but rather a product of a pre-Curtis erosive agent. Hence, the J3/SB is drawn across the incision by a dotted line, to highlight the incision (see further discussion in Chapter 6).

5.2.2 Flooding surfaces and candidates for maximum flooding

Flooding surfaces (FS) mark the surface where transgression stops and regression starts (Miall, 2010), and thus generally identified as surfaces under shallowing upwards *parasequences* (after Van Wagoner et al., 1987) (at the base of the stratigraphically most distal sediments). Such changes in lithology may appear abrupt or gradual and may occur at several stages, all of which may act as candidates for maximum flooding. The MFS however, is identified as an FS that represents the event of maximum flooding within a stratigraphic sequence (Catuneanu et al., 2011) (bounded by a lower- and upper SB). Accordingly, the presence of more than one FS ought to be considered different candidates for MFS.

The recorded FSs (see Figure 5.3 for correlation) have been identified on the basis of stratigraphic change in lithology; e.g. as the coarse grained sediments of Facies D (Cross-stratified conglomerate) is sharply and conformably overlain by mud and heterolithic (Facies C and Facies E, respectively) deposits that gently coarsen upwards in the lower Curtis Formation (see FS2 in Figure 5.3). To correlate FSs across the correlation panel, similar facies stacking patterns have been compared to distinguish between regionally traceable- and local FSs. The logs from Stove Gulch East and Smith's Cabin North (Figure 5.3) contain two FSs (one local and one regional), whereas the other logs contain one FS and are thus readily correlated.

There is however a considerable uncertainty regarding (**1**) the FS stratigraphic position at Smith's Cabin South and (**2**) the lateral distance to Crystal Geyser (see Figure 5.3 question marks) accentuating the potential for an alternative interpretation:

- (**1**) Consider an Entrada Sandstone paleotopographic high at Smith's Cabin South, elevated above local sea level at the time of maximum flooding. Subsequent normal regression and the creation of Curtis Basin accommodation space could potentially explain the deposition of Curtis Formation sediments, even without a recordable FS.

- (**2**) The succession at Crystal Geyser is geographically isolated from the other localities and the FS is thus difficult to correlate with the FSs recorded elsewhere (FS1 and FS2, Figure 5.3). In addition, since there is only one recorded FS here, correlation will implicitly indicate Curtis Formation maximum extent, and hence the MFS.

However, note that for a (**1**) subaerially exposed area to be considered, traces of an FS onlapping onto the SB should be observed and documented at adjacent localities to substantiate such an argument, thus, it remains open for further research and discussion.

Recognition of an MFS

Regarding the recognition of an MFS, the recorded sedimentary succession does not include a full stratigraphic sequence, bounded by an upper and lower SB. However, Peterson (1994) signified that the upper sequence boundary is represented by the J5-unconformity (Pipiringos and O'Sullivan, 1978) which truncates the Summerville Formation and in turn states that an MFS should be present within the recorded succession. Moreover, there is little to no lithological difference between to state that one or the other FS represents the most significant flooding event. The MFS should, however, be regionally traceable and hence serve as the most extensive FS within the succession. Consequently, FS2 is considered the most suitable candidate MFS and Crystal Geyser is correlated accordingly. In addition, the MFS marks the separation between a lower transgressive- and upper highstand systems tracts (Miall, 2010) (see annotations in correlation panels above).

Chapter 6: Sedimentary models and geologic development

6.1 Phase one - Aeolian deposits, local tectonic collapse and erosion

6.1.1 Entrada Sandstone - rise in relative ground water level

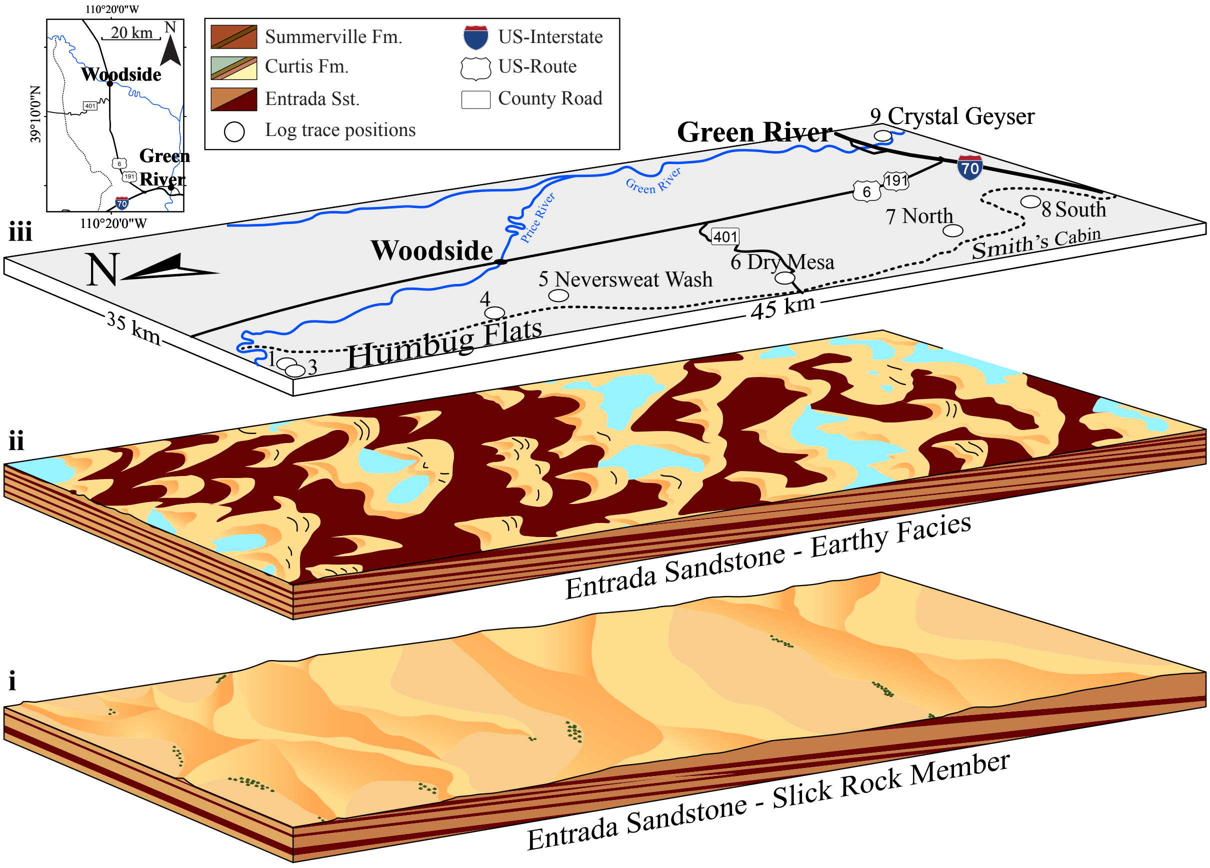


Figure 6.1: **i**,**ii**: Illustrative representation of depositional environments for the Entrada Sandstone Slick Rock Member (**i**) and Earthy Facies (**ii**). **iii**: Geographical reference to study area with corresponding miniature map for location (see Figure 1.1 for full geographic references) and descriptive legend. Note horizontal scales. Vertical scale- and wind-driven sediment transportation direction not intended.

The Entrada Sandstone depositional environments are illustrated in Figure 6.1 for both the Slick Rock Member and the Earthy Facies, along with present day geographical reference points and key localities. The Slick Rock Member was an aeolian sand sea (erg) with compound dunes of various shapes and sizes, separated by areas of interdune sedimentation (Kocurek, 1981). The Slick Rock Member depositional environment (Figure 6.1i) is included to emphasize the change in sedimentation conditions as a rise in relative ground water level resulted in the Entrada Sandstone Earthy Facies (Figure 6.1ii) development (see FA 1 - Coastal aeolian dune field, Chapter 4) (Kocurek, 1981). The Entrada Sandstone Earthy Facies is illustrated as barchanoid dune shapes of variable lateral connectivity and sizes, separated by interdunal areas of dry, evaporative conditions (described further in Chapter 4, FA 1).

6.1.2 Entrada Sandstone regional tilting and faulting

Although structural geology is not a main concern in this study, observed and documented traces of pre-Curtis Formation local tectonic activity, inside the Entrada Sandstone Earthy Facies, are considered keys to understand the relation between the two formations. Sedimentary models in Figure 6.2 and onwards are presented by three separate blocks as field observations suggest that slight structural differences between the localities occur, differences that this study does not intend to resolve.

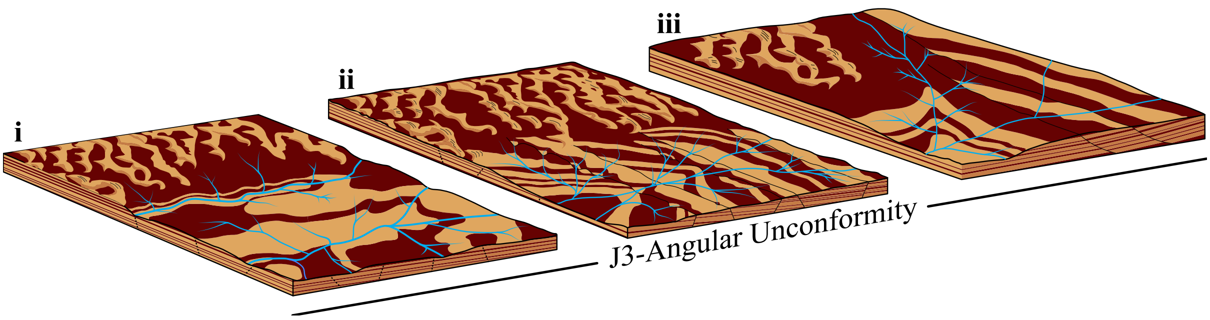


Figure 6.2: **i**,**ii**,**iii**: Illustration of Entrada Sandstone tilt, fault and erosion. Dendritic black lines indicate possible drainage patterns. Solid black lines with layer displacement represent observed faults while dotted lines represents (unobserved) expected faults. See Figure 6.1 for geographical references, descriptive legend, scales and orientation. Vertical scale not intended.

Figure 4.13 (Chapter 4) from Humbug Flats East (see Figure 1.1B for locality) show evidence of a local tectonic disturbance within the uppermost Entrada Sandstone beds. Faulting and resultant tilting of blocks within the stratigraphic unit are evident along laterally continuous outcrops, especially those with North-South orientation. Vertical displacement is in the order of 2-5 m, and the listric faults appear to sole out in the Earthy Facies of the Entrada Sandstone ~10 m below the boundary to the Curtis Formation (Figure 6.3). The origin of the faulting is unknown, and is considered outside the scope of this thesis. However, liquefaction of a buried water-laden sandstone interval, or a deeper mobilisation of evaporite beds may be attributed to the disturbance. A regionally significant change in tectonic stress regimes is not implied here.

One single fault is observed cutting into the lowermost Curtis Formation, but since there are no evident traces of syn-tectonic sedimentation, the fault is considered reactivated more recently and has not in any way contributed to the Curtis Formation development. Based on the angular difference () between the Entrada Sandstone and Curtis Formation layers, the separating boundary is classified as an angular unconformity.

The northern Humbug Flats localities (in Stove Gulch and Sulphur Canyon, see the map in Figure 1.1C) do not show any clear Entrada Sandstone faulting, however, sedimentary log correlation, conducted by Rimkus (2016), aligning the Curtis Formation to appear horizontal, shows that Entrada Sandstone layers are tilted eastward, and hence the model in Figure 6.2i is illustrated accordingly.

Figure 6.3: Entrada Sandstone faults indicated by white drawn lines at Smith's Cabin South (see Figure 1.1B for locality). Red line indicate sequence boundary separating the Entrada Sandstone - Curtis Formation. Note person for scale. The picture is taken at an angle which creates an illusion; the Curtis Formation is actually recorded ~50 meters thick (see Appendix I for log.).
Photo: V. Zuchuat

Tilted Entrada Sandstone layers and extensional faults are also observed at Smith's Cabin South (see Figure 1.1 for locality, picture in Figure 6.3 above and illustration in Figure 6.2iii). The faults dip south and the layers are tilted northward accordingly. Nevertheless, as the Entrada Sandstone layers are tilted and occur at different angles to the Curtis Formation at several key localities, the boundary is considered an angular unconformity throughout the whole study area, containing small scale, local variations (illustrated in Figure 6.2 and depositional models hereafter).

6.1.3 Base level fall and regional erosion

The Entrada Sandstone - Curtis Formation boundary is both sharp and erosional (J3-unconformity), representing a hiatus (Pipiringos and O'Sullivan, 1978). As Figure 6.2 illustrates, faults described in section 6.1.2 above are truncated by this erosional contact, indicating that erosion occurred after the Entrada Sandstone tilt and tectonic collapse (as there is no observed traces of fault related paleotopographic relief). Further, as several authors point out (Pipiringos and O'Sullivan, 1978; Eschner and Kocurek, 1986; Blakey et al., 1988; Eschner and Kocurek, 1988; Caputo and Pryor, 1991; Crabaugh and Kocurek, 1993; Hintze and Kowallis, 2009), the J3-unconformity stretched beyond the Curtis Formation lateral extent, suggesting that the erosion occurred partially (Peterson, 1994) prior to Curtis Formation deposition. The J3 erosional unconformity is accordingly considered governed by mechanisms other than, or in addition to (Peterson, 1994), the Curtis Sea transgressive nature. Hence, the Curtis Formation appears erosive to the Entrada Sandstone but is not necessarily the sole erosive agent (see discussion in section 6.2.1 below).

Subaerial erosion and sediment bypass are both considered effects of a local base level fall (Miall, 2010), which potentially explains the J3-unconformity origin. Such an upheaval-derived erosion was suggested by Pipiringos and O'Sullivan (1978), followed by burial and Curtis Sea inundation within less than 1 Ma.

Eschner and Kocurek (1988) describe and discuss the origin of relief along the J3-unconformity at the Uinta Mountains area (see Figure 1.1 for locality). They suggest that the boundary alternates between inherited- and erosional relief (briefly explained in Chapter 5 section 5.2.1) while Peterson (1994) confirm the eastward decrease of erosion towards the town of Moad (see Figure 1.1A for map). Although erosional relief is the only kind of relief observed in this study, inherited relief is included towards the east of the sedimentary models (Figure 6.2 and Figure 6.4) as an illustrative representation of Eschner and Kocurek (1988) observations.

6.2 Phase two – Aeolian deposits inundated by marine transgression

According to the sedimentary correlation panel in Figure 5.3, and corresponding interpretation, the Curtis Sea transgression over the Entrada Sandstone deposits occurred during at least two stages (based on the presence of at least two flooding surfaces); the first marine inundation of Entrada Sandstone deposits (up until FS2, Figure 5.3), followed by the regionally traceable flooding event of FS2 (shown in Figure 5.3) and the subsequent accumulation of Curtis Formation deposits.

6.2.1 Curtis Sea inundates the Entrada Sandstone

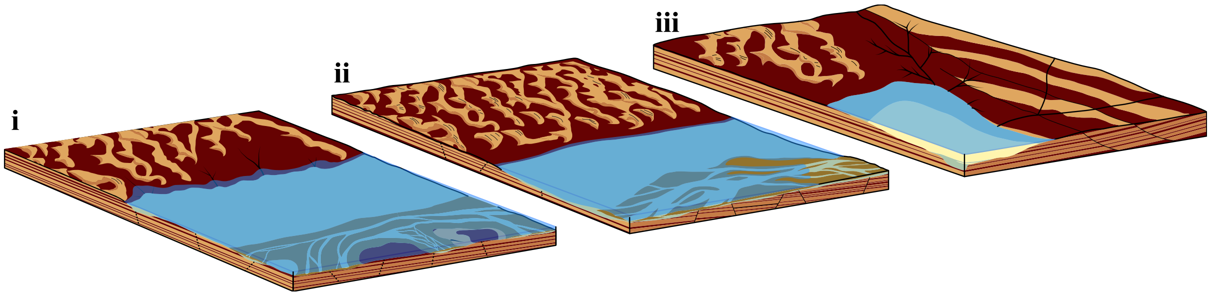


Figure 6.4: i,ii,iii: Illustrative representation of the first recorded rise in relative sea level as the Curtis Sea inundated Entrada Sandstone deposits. Eastern Entrada Sandstone dunes are included as Eschner and Kocurek (1988) describe inherited relief along the J3 unconformity eastern vicinity, discussed in Chapter 5 section 5.2.1 and section 6.1.3 above. See Figure 6.1 for geographical references, descriptive legend, scales and orientation. Vertical scale not intended.

Figure 6.4 illustrates the first recorded rise in relative sea level represented by strata up to right before FS2 flooding (see Figure 5.3 for correlation panel). The successions at Stove Gulch East and Smith's Cabin North exhibits sediments associated by an initial Curtis Sea level rise, represented by FA 2 (Fluvio-tidal transition), FA 3 (Subtidal heterolithic mix) and FA 4a (Sub- to intertidal sand mix) (see Chapter 4 for full descriptions). To deposit sediments at these two localities without deposition in between, a paleotopographic relief is suggested, temporarily leaving elevated Entrada Sandstone areas dry and out of Curtis Sea reach. As illustrated by the correlation panel in Figure 5.3, such a candidate paleotopographic high was present between Stove Gulch East and Smith's Cabin North. However, as the Curtis Sea transgressed further, inundation of this elevated area resulted in the development of FA 2 as rivers from the western hinterland met the Curtis Sea (see Chapter 2 for geologic framework and Chapter 4 for FA 2 description and interpretation). Figure 6.4 illustrates the suggested environment as braided ephemeral streams met the Curtis Sea. Based on the FA 2 interpretation as a fluvio-tidal transition (Chapter 4), it is here suggested that the Curtis Sea channelled through pre-existing

Facies D fluvial channels in an early stage transgression. Note that the Curtis Sea in Figure 6.3i,ii is situated east and not west of FA 2 fluvial deposits based the interpretation by Peterson (1994) as sediments originating from elevated highlands to the west, flowing towards northeast into the Curtis Basin.

Figure 6.4i illustrates what Rimkus (2016) suggest based on local east-west sedimentary correlation at the Humbug Flats northern area (see Figure 1.1C for localities); FA 2 deposits seem to follow J3-unconformity paleotopographic lows (note that this is not directly commensurate with the north-south going semi-regional correlation of this study (Figure 5.3), but might be a result of correlations based on different scales and directions).

As discussed in section 6.1.3 above, most of the J3 erosion was developed subaerially (prior to Curtis Sea inundation). However, the presence of a base Curtis Formation tidal channel incision (see picture in Figure 5.4) recorded at Cottonwood Wash (see map in Figure 1.1B), emphasizes Curtis Sea scouring and modification of the pre-existing J3 erosional unconformity. Consequently, J3 is interpreted to be mainly a product of pre-Curtis Formation erosion with additional Curtis Sea scouring. Such Curtis Sea tidal scours was described by Eschner and Kocurek (1986) for a comparable base Curtis Formation incision, close to the Uinta Mountains, in north-eastern Utah (see Figure 1.1 for geographic overview).

6.3 Phase three - Summerville coastal plain progradation

6.3.1 Development of a highstand systems tract

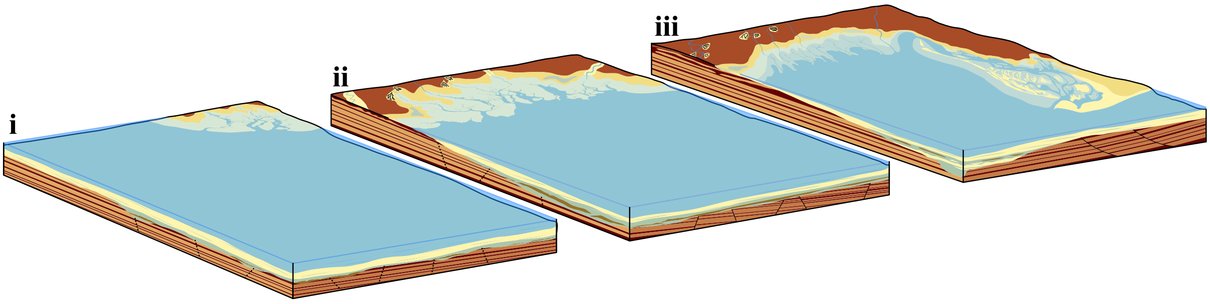


Figure 6.5: i,**ii**,**iii**: Illustrations of Curtis Sea maximum extent within the study area. Note the Curtis Sea south-eastward extent in sub-figure iii, where the Crystal Geyser section records a thin marine succession. See Figure 6.1 for geographical references, descriptive legend, scales and orientation. Vertical scale not intended. Coastline is illustrative with estimated geographical position. Summerville lower coastal plains are illustrated with small rivers, crevasse splays and saline ponds.

FS2, Figure 5.3, represents the latest recorded Curtis Formation flooding surface. Correlation of units above FS2 shows that development of FA 3 (Subtidal heterolithic mix) through FA 4a (Sub- to intertidal sand mix), FA 4b (Beach with tidal inlet), FA 5 (Intertidal mixed flat) and FA 6 (Supratidal lower coastal plain) (see Chapter 4 for facies associations) occurred at all log-sites (except where the Summerville Formation is eroded) except Crystal Geyser where the succession shows a thin marginal Curtis Formation. Accordingly, Figure 6.5 shows the Curtis Sea maximum extent, with well developed eastern tidal flats (artistically presented, exact geographical position not intended), distal subtidal zones and a significant degree of lateral variation visualized by the relief along SB/J3, undulating coastline and a tidally influenced bay or lagoon at Smith's Cabin South (see next paragraph).

The succession at Smith's Cabin South (see Figure 1.1 for locality) is dominated by a higher mud content than at the other study localities (see composite logs correlated in Figure 5.3). Considering the closest neighbouring locality, Smith's Cabin North, the depositional environment of Smith's Cabin South was governed by lesser energy conditions, and hence more protected from the subsequent influx of coarser sediments by stronger currents. Accordingly, it is suggested that the corresponding depositional environment of Smith's Cabin South may resemble a tidally influenced bay or lagoon, as illustrated in Figure 6.5iii.

Regarding the geographical outlier at Crystal Geyser (see Figure 1.1B for locality), the recorded Curtis Formation succession is difficult to hinge on- and correlate to the suggested flooding surfaces (presented in Figure 5.3 and discussed in Chapter 5). However, Figure 6.5iii illustrates the Curtis Sea marginal inundation of this locality (albeit not confidently time-constrained in the depositional environment) as the succession represents a development from FA 1 (Coastal aeolian dune field) to FA 5 (Upper intertidal mixed flat) and FA 6 (Supratidal lower coastal plain). Crystal Geyser is considered likely to represent a locality adjacent to the maximum Curtis Formation extent, and hence maximum flooding, as the succession is ~3 meters thick. Moreover, the Curtis Formation at Crystal Geyser shows a correlated wedge-shaped geometry eastward from the succession at Smith's Cabin South (see Figure 5.3 for correlation panel), indicating eastward Curtis Formation pinch out.

All study localities (except Crystal Geyser) show development of FA 4b (Beach with tidal inlets) in stratigraphic adjacency to FA 4a at different stratigraphic levels for the different localities, resulting in complex interfingering lateral relations. Significant lateral variations in depositional stacking patterns, such as the ones described, are interpreted to reflect a shallow basin readily affected by subtle sea level changes (in addition to fluctuations caused by tidal activity) resulting in significant lateral diversity in depositional environments.

Prograding coastline

Considering that a flooding surface is defined as the surface that represents the point in time where transgression stops and regression starts (Catuneanu et al., 2011), the progradation or at least aggradation of a coastline is thus considered contemporaneous to the development of a highstand systems tract. Based on the Curtis – Summerville formations conformable boundary, showing no apparent sign of erosion, combined with the correlation of Crystal Geyser and Smith's Cabin logs, it is proposed that the Summerville lower coastal plains (FA 6) prograded into the Curtis Sea by normal regression (see Figure 5.3 for correlation panel). As follows, the Summerville Formation lower interval is considered contemporaneous to the upper Curtis Formation, and that they represent proximal and distal equivalents, respectively.

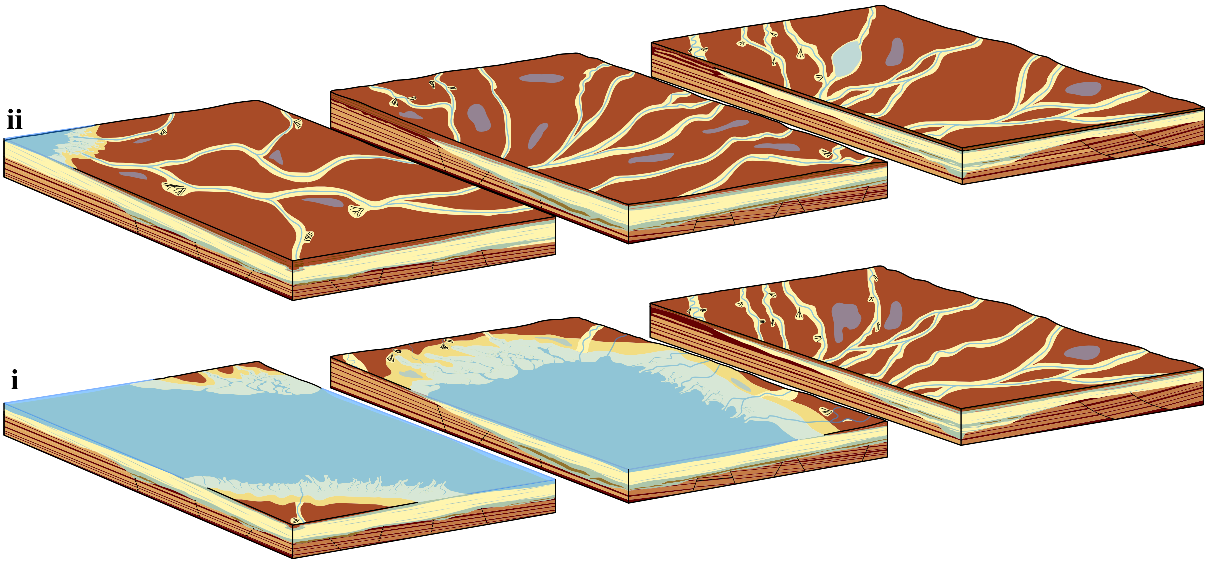


Figure 6.6: **i**,**ii**: Illustration of Curtis Sea north-eastward regression and the associated advancement of Summerville coastal plains. Chronological snapshots presented as stratigraphy; upwards from older (**i**) to younger (**ii**). See Figure 6.1 for geographical references, descriptive legend, scales and orientation. Vertical scale not intended.

Based on the already discussed Crystal Geyser – Smith's Cabin sedimentary development (see paragraph above), the Curtis Basin was filled in by sediments from south to contribute to the Curtis Sea northwards retraction. Furthermore, the prograding western coast (illustrated in Figure 6.6i, north-western corner) is suggested based on correlation-derived interpretation where the Curtis – Summerville formations boundary dips northward from Dry Mesa towards Sulphur Canyon (see Figure 5.3), giving a wedge-shaped geometry similar to the already described Smith's Cabin - Crystal Geyser correlation. Hence, adding this western component to the Curtis Sea retraction, overall regression direction is interpreted north-eastward (see Figure 6.6).

The FA 6 development is illustrated in Figure 6.6, containing rivers of avulsion, merging channels and crevasse splays, flowing into the Curtis Sea through small lakes (described by Kocurek and Dott Jr., 1983) and near-shore saline ponds, drawn on the basis of observed evaporitic lamination in Facies M (Plane parallel-laminated mudstone). FA 6 is illustrated with the purpose of presenting the developing depositional environment and not to imply exact geographical positions of lakes, ponds or rivers.

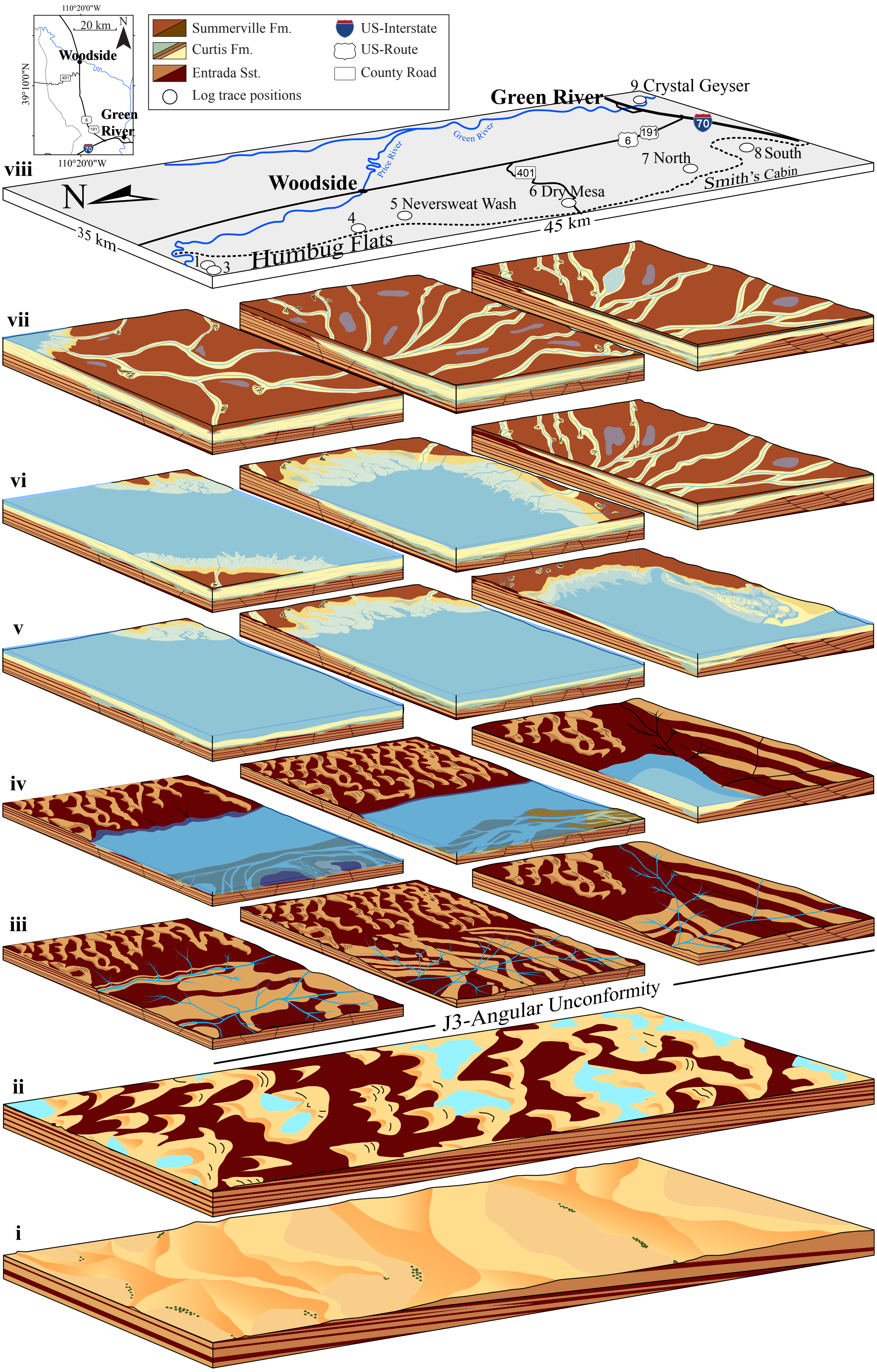


Table 6.1: Stratigraphical illustration of sedimentary development from the Entrada Sandstone Slick Rock Member (**i**) up through the Curtis Formation (**iv**,**v**,**vi**,**vii**) into the Summerville Formation early stage development (**v**,**vi**,**vii**). **viii**: Geographical references regarding study area (see Figure 1.1 for full references), descriptive legend, scales and orientation. Vertical scale not intended. Depositional models are arranged and labelled from oldest to youngest upwards.

Chapter 7: Discussion

7.1 Controls on Curtis Sea development and behaviour

The Jurassic sedimentary succession, exposed in east-central Utah, contains deposits that originates from successively alternating depositional environments (see Chapter 2: Geologic framework). Such rapidly alternating environments give rise to questions on which factors, both external (allogenic) and internal (autogenic), controlled- and contributed to the depositional development. Different factors, mechanisms and processes are discussed below in relation to the Curtis Formation depositional development.

7.1.1 Allogenic mechanisms

Creation of sedimentary accommodation space is controlled by, or a result of interplay between, different allogenic mechanisms such as (**1**) tectonic activity by subsidence and/or (**2**) global eustatic sea level rise (Miall, 2010). (**3**) Climatic factors may control the development of depositional environments and influence autogenic processes related to sediment infill, -supply and drainage patterns by precipitation and temperature (Miall, 2010). As controlling allogenic mechanisms lay different signatures on sequence stratigraphic architecture, investigation of the Curtis Formation sequence stratigraphic properties can give answers on which allogenic factors controlled the depositional development.

The evolution of Entrada Sandstone depositional environments (discussed in Chapter 6), from the Slick Rock Member to the Earthy Facies, reflects a significant rise in relative ground water table. Combined with upper Entrada Sandstone tidal features, identified by Hicks et al. (2012), an approaching marine transgression may be considered. Further, deposition of the marine Curtis Formation, onto the Entrada Sandstone, could naturally serve as an argument of such a development. However, the J3-unconformity (Pipiringos and O'Sullivan, 1978) separates the Entrada Sandstone from the Curtis Formation, as a sequence boundary of subaerial erosion, and marks thus a genetic separation of the two units. This genetic separation reflects a fall in relative base level and the subsequent regional erosion of J3. Accordingly, as the relative ground water table rose during Entrada Sandstone deposition, a significant event occurred causing relative base level fall and the concurrent erosion of J3. Temporary crustal upheaval may serve as a potential explanation to such a development, substantiated by Peterson (1994); Thorman and Peterson (2004) that described significant orogenic activity during Middle-Upper

Jurassic (see Chapter 2: Geologic framework, and interpretation of depositional development in Chapter 6 section 6.1.3). In addition, considering the evident J3 angular unconformity, however potentially local, accentuates tectonic activity in the area, prior to Curtis Formation deposition (as discussed in Chapter 6 section 6.1.2).

The creation of accommodation may be tied to global eustatic sea level fluctuations when sedimentary basins around the world, that are both contemporaneous and independent from one another, are correlated (Miall, 2010). Peterson (1994) signified that the Middle Jurassic Carmel Sea marine encroachment (see Chapter 2: Geologic framework) were confidently correlated to several suggested global eustatic sea level curves. However, the Curtis Formation was not commensurate with the same proposed curves, which consequently suggested that tectonic activity was the main controlling mechanism on the creation of accommodation space, and hence the triggered marine transgression.

This study has not documented any evidence of syn-sedimentary tectonic disturbance within the Curtis Formation, however, regional scale geometry of the San Rafael Group (Kocurek and Dott Jr., 1983) show an evident westward thickening. Combined with the tectonic setting and that Utah was situated in the North American Cordillera retroarc foreland-region, it is suggested that the Curtis Formation belongs to a tectonically controlled foreland basin. Moreover, Lawton (1994) proposed that differential mantle convection flow, due to flattening of the oceanic subducting slab, caused dynamic topography that in turn was the main tectonic control for the Middle Jurassic successive alternation of marine- and continental depositional environments.

Intrabasinal catchment area, drainage, weathering/erosion and the resultant sediment input flux to a basin are controlled by climatic conditions such as precipitation rates and temperature (Miall, 2010). Accordingly, climatic changes that involves these properties are most likely to have an influence on the development of depositional environments. The described Entrada Sandstone development from an arid- to semi-arid aeolian sand sea (Slick Rock Member) to a wet aeolian dune field (Earthy Facies) potentially indicate climate change. However, Kocurek and Dott Jr. (1983) stated that the climate was stable and dry (see Chapter 2: Geologic framework) and Peterson (1994) emphasized the Jurassic climate as getting drier within the trade-wind-belt system. The only climatic conditions that changed during the Middle Jurassic period, was a complication of local wind directions by topographic disturbances. Such stable climatic conditions point towards a tectonically governed rise in relative ground water table during Entrada Sandstone deposition.

Comparison of the Jurassic transgressive-regressive sequences **TR2→4** and **TR5**, postulated by Peterson (1994) (see Chapter 2: Geologic framework), raise questions on their depositional differences in relation to climatic conditions; (**TR2→4**) The development shows an aeolian unit (Page Sandstone) that was inundated by marine transgression (Carmel Formation), subsequently followed by the progradation of another aeolian dune field (Entrada Sandstone) (Kocurek and Dott Jr., 1983). In contrast, the (**TR5**) Curtis Sea transgression over the Entrada Sandstone was not followed by an aeolian dune field, but rather the progradation of Summerville coastal plains. There may hence be some unresolved questions, regarding climatic differences that may have favoured the development of a coastal plain rather than an aeolian unit. Considered that the Entrada erg was described as partly Navajo-sourced (Kocurek and Dott J3., 1983), the Summerville coastal plain development may have been caused by climatic conditions, such as increased humidity and resultant sand grain cohesion, as it could prevent e.g. Entrada erg sediment sourcing. Substance to this argument of development may be found in eastern Utah localities where the Summerville Formation is situated directly on top of the Entrada Sandstone (Hintze and Kowallis, 2009).

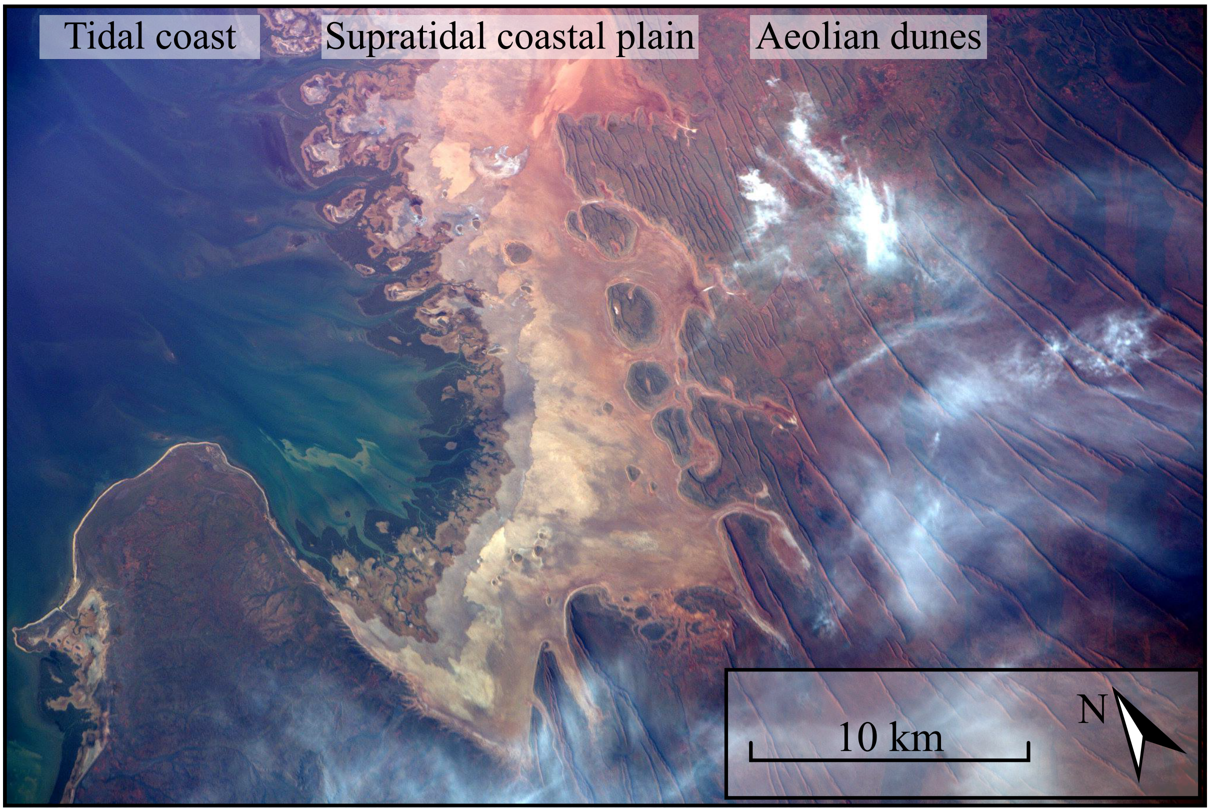


Figure 7.1: Picture of the Exmouth Gulf tidal coast of western Australia, considered a potential analogue to the Curtis-Summerville formations genetic relation.
Photo: NASA (2016)

An alternate explanation to the coastal plain development relates to the strong Curtis Sea tidal influence that potentially favoured the development of an arid supratidal lower coastal plain in contrast to an aeolian dune field. Such an environment is considered analogous to the present day Exmouth Gulf coastal environment of western Australia (see Figure 7.1). The environmental setting of Exmouth Gulf is considered similar to the Callovian Curtis - Summerville paleoenvironment, presented in Table 7.1 below.

Table 7.1: Comparison of present day western Australia and Callovian east-central Utah environments. Note that temperature is challanging to account for other than that Middle Jurassic global mean temperatures may have approached 10°C higher than present (Kocurek and Dott Jr., 1983).

Parameters	Exmouth Gulf, western Australia	Callovian east-central Utah (Curtis-Summerville deposition)
Geographic position	~22° south (southern trade-wind belt)	~18° north (Caputo and Pryor, 1991) (northern trade-wind belt)
Coastal environment	Gulf on open marine coastline	Intracratonic closed seaway (Peterson, 1994)
Topographic restrictions	Generally flat, with westerly rugged terrain	Generally flat, with western, southern and eastern elevated highlands (e.g. Peterson, 1994)

7.1.2 Autogenic mechanisms

Lateral distribution of tidal sub-environments are generally controlled by the interplay between the lateral spacing of distributary channels, their associated sediment input, and hydrodynamic forces, such as tidal currents and waves, reworking and redistributing sediments throughout the basin and hence reshaping the sub-environments morphology (Davis Jr. and Dalrymple, 2012). The amount of control inflicted by these factors, however, may differ between tidal sub-environments, depending on shoreline proximity, basin depth and bathymetry, in relation to the tidal range magnitude (Davis Jr. and Dalrymple, 2012).

Davis Jr. and Dalrymple (2012) described the morphological processes within tide-dominated estuaries as very predictable on a large scale as the rhythmic currents of tides and the seasonal fluvial drainage generally are well-defined and stable. Detailed small scale knowledge was however poor, except regarding the deposition and erosion related to tidal ebb- and flood current pathways within a meandering tidal channel (Davis Jr. and Dalrymple, 2012). Further, Davis Jr. and Dalrymple (2012) stated that the recognition and interpretation of small scale facies distribution within a tidal sub-environment remains speculative and should be further addressed in future studies.

Hunt et al. (2015) investigated intertidal controls on morphology of the meso-tidal Raglan Harbour estuarine environment in New Zealand, to create a generalized model for wave- and wind-contribution relative to tidal forcing. Their research showed that the intertidal impacts on erosion, sand distribution and morphology caused by tidal currents were minor, compared to the irregular patterns of wind-generated waves, especially regarding erosion. Hunt et al. (2015) further suggested that the orbital forcing from wind-generated waves primarily controlled the erosion of intertidal sand bodies and that the shoreline topography, along with the orientation of the estuary, were imperative for magnitude of the wave-induced modification, as topography and orientation may cause wind attenuation. Tidal currents were further signified by Hunt et al. (2015) to control the generation of tidal channels, while wind circulation and waves may modify the sediment transport pathways within channels and thus alter their positions and orientations.

Figure 5.4 shows a panoramic view of the lower Curtis Formation succession at Smith's Cabin North (see Figure 1.1B for locality). The apparent basal incised tidal channel was here able to erode the J3 unconformity, due to the initial rise in sea level and the associated tidal scouring. The same applied for the two overlying sandier channels that incised the heterolithic Curtis Formation beds below. Exact geographical position of tidal channels are however entirely controlled by autogenic mechanisms of sediment supply and tidal activity (Davis Jr. and Dalrymple, 2012) albeit wind-driven wave motion may have contributed to the scouring as Hunt et al. (2015) described for the intertidal Raglan Harbour, New Zealand.

Regional correlation of the Curtis Formation sandy interval, presented in Figure 5.3, is challenging as the sub- to intertidal environments (FA 4a & 4b, Chapter 4) interfinger complexly across both longer and short distances. As the Curtis Formation was deposited in a shallow basin of low angle regional relief (Kocurek and Dott Jr., 1983; Caputo and Pryor, 1991), the lateral variation of tidal zones reflect the autogenically controlled distribution of tidal sub-environments in a basin where depositional environments shifted dynamically during deposition, e.g. by tidal channel avulsions.

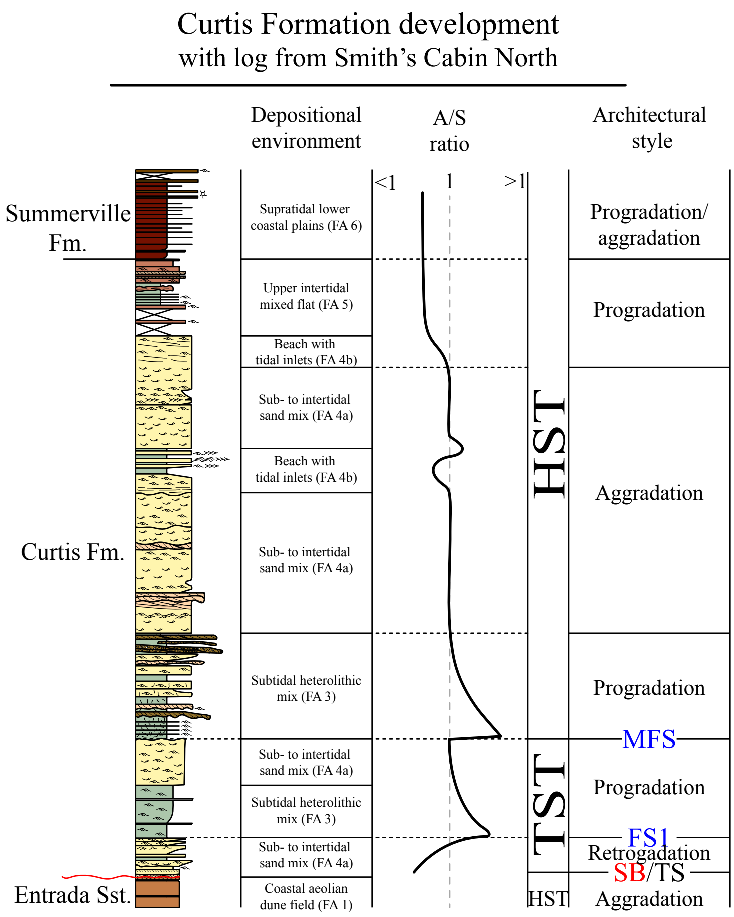


Figure 7.2: Curtis Formation depositional development at Smith's Cabin North in relation to A/S ratio. See Figure 1.1B for locality and Appendix H for full log.

As controlling allogenic- and autogenic mechanisms have been discussed above, the interplay between them was what ultimately controlled the Curtis Formation depositional development. This interaction may be presented as rate of creation of accommodation space over the rate of sediment infill (or A/S, see Figure 7.2). Representative interpretation from Smith's Cabin North are as follows;

- The SB/TS - FS1 interval is classified as a retrogradational architectural style, as the environment evolved from continental to marine, towards a flooding surface. The deposited sediments indicate a noteable sedimentation rate, however not high enough to significantly affect/match the rate of creation of accommodation.

- The architectural style of the FS1 - FS2 (MFS) interval is progradational as the subtidal heterolithic beds (FA 3) evolve into sub- to intertidal sand (FA 4a). A development like this reflects an upwards decrease in relative sea level, and hence normal regression. The rate of sediment input was thus higher than the rate of creation of accommodation space.

- The highstand systems tract that followed the maximum flooding surface is evidenced by the evolution from FA 3 (Subtidal heterolithic mix) reflects a rate of sediment input that was higher than the rate of creation of accommodation space, and hence a brief progradational architectural trend.

- Further development of the highstand systems tract appears aggradational, where the rate of sediment input balances the rate of accommodation creation.

- As sediment distribution in tide-dominated basins are different from wave- or fluvial-dominated basins, the upper fining heterolithic Curtis Formation interval reflects progradation of intertidal environments, and the followed gradual progradational; potentially aggradational, lower Summerville Formation.

- Even though not more than the lower Summerville Formation is recorded, the architectural development further up is considered progradational to aggradational as the rest of the stratigraphic sequence is represented by Summerville Formation deposits (Peterson, 1994).

7.1.3 Basin character and paleobathymetry

In addition to allogenic- and autogenic controls on the Curtis Formation depositional development, the basin type and associated paleobathymetry are considered imperative to the regulations of autogenic mechanisms such as hydrodynamic forces, controlling the lateral distribution of tidal sub-environments.

Basin character

Based on the overall contractional tectonic regime during the Jurassic North American Cordillera (see Chapter 2), it was suggested by Willis (1999) that the Curtis Formation may resemble a foredeep-, or back-bulge basin deposit. However, foredeep basin deposits are typically associated with great asymmetrical thickness distribution due to the uneven basin subsidence that is caused by orogenic growth which in turn isostatically forces the craton downwards by flexural loading (Miall, 2010). Based on Curtis Formation dimensions, a foredeep-type basin is not considered likely. In contrast, the Middle Jurassic sedimentary basin was considered by Lawton (1994) to have changed from a foredeep- to a back-bulge basin by dynamic topography due to alternating mantle flows related to flattening of the subducting oceanic slab. The successive alternation between continental and marine strata testifies an intracratonic depositional setting, such that a sag basin should not be ruled out. However, it is noted that the proposed Middle Jurassic Elko orogeny (Thorman et al., 1990 cited by Thorman and Peterson, 2004) (see Chapter 2 on tectonic setting) may provide answers to the San Rafael Group basin character as it was suggested to represent a lesser orogeny with hence an associated smaller scale foreland basin.

Paleobathymetry and tidal activity

Tidal signatures are present throughout all Curtis Formation intervals, raising questions on how and why tidal fluctuations were able to influence Curtis Sea sedimentation in such a degree. The low angle profile on which the Curtis Formation was deposited, is considered a good candidate to explain the amount of tidal influence as even micro-tidal fluctuations would have caused the periodical coverage of considerable areas. In addition, the previously described paleotopographic relief along the J3-unconformity, acted as bathymetry to the initial Curtis Sea, and is thus considered essential to the early stage distribution of tidal sub-environments as paleotopografic lows may have favoured the development of both subtidal zones, and the evolution of tidal channels.

7.2 Sequence stratigraphic indicators to relative sea level fluctuations

As relative base level fluctuations are the main control on sequence stratigraphic architecture (Miall, 2010), investigation of the Curtis Formation sequence stratigraphy reveal evidence for when deposition occurred regarding relative sea level fluctuations.

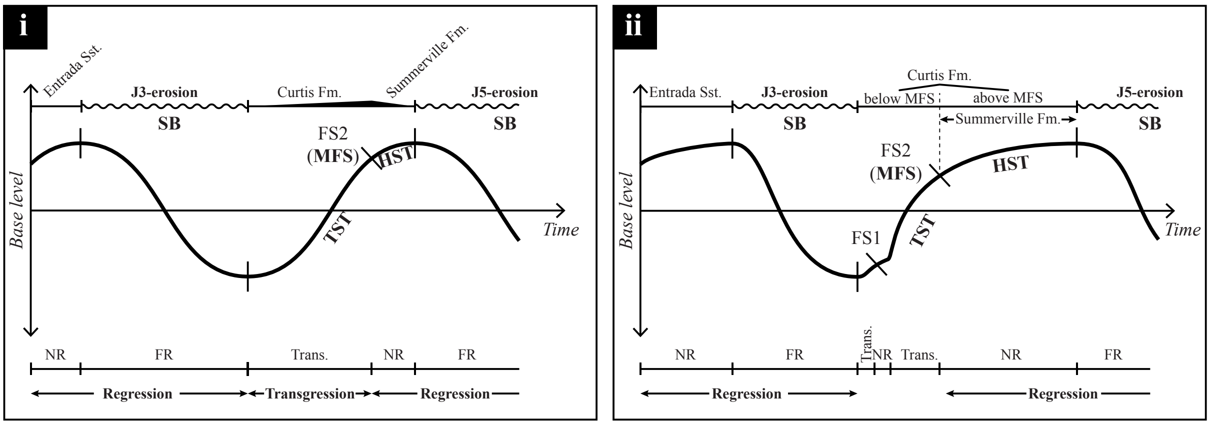


Figure 7.3: **i**: Chart of local base level fluctuations with time, modified from Catuneanu (2006, Fig. 3.19, p. 91) to explain Curtis Formation deposition. Base level is drawn as a symmetrical sine curve for simplicity, and is relative based on a constant rate of sedimentation. **ii**: Continuation of sub-figure **i**, modified to represent a more realistic, complex interpretation of depositional history. Including FS1 results in a more complex interplay between base level and sedimentation rate. **Abbreviations**: NR: *Normal regression*; FR: *Forced regression*; Trans: *Transgression*; MFS: *Maximum flooding surface*; TST: *Transgressive systems tract*; HST: *Highstand systems tract*; SB, FS1-2: *Sequence boundary* and *Flooding surface* 1-2 from Figure 5.3.

Figure 7.3i is a modification of Catuneanu (2006, Fig. 3.19, p. 91) figure on relative base level fluctuations, adjusted to fit, and graphically explain, the Curtis Formation deposition. Figure 7.3i and ii are based on the following sequence stratigraphic properties:

- The sequence boundary (J3 unconformity) marks a base level fall that led to Entrada Sandstone top subaerial erosion (see Chapter 6 section 6.1.3).

- The stratigraphic position of the MFS (see FS2 in correlation panel of Figure 5.3), situated in the lower third portion of the Curtis Formation succession, testifies that the maximum flooding event occured rapidly relative to sedimentation rate, as the majority of Curtis Formation sediments was deposited during a high stand systems tract with only a vague transgressive systems tract (see annotations in Figure 5.3).

- Sedimentation rate exceeded the rate of relative sea level rise, hence the occurrence of an MFS, and triggered normal regression and the contemporary progadation of Summerville lower coastal plains. Upper Curtis- (above MFS) and lower Summerville formations are hence considered contemporaneous as distal and proximal equals, respectively.

- The J5-unconformity is the upper boundary of the Curtis - Summerville stratigraphic sequence (TR-5 by Peterson (1994)) which marks a fall in relative sea level and thus the end of the Curtis- and Summerville formations.

As Figure 7.3i is a simplified sketch to illustrate relative base level fluctuations during constant sedimentation rate, Figure 7.3ii is altered to better represent the complexity and chronological development of the Entrada Sandstone, Curtis- and Summerville formations succession.

7.3 Comparison to previous Curtis Formation work

Sheet-like Entrada-derived mass flow deposits (Eschner and Kocurek, 1986) were not identified during this study, nor were there any confident recognitions of tidal bundles (Kreisa and Moiola, 1986). Accordingly, these thoroughly described Curtis Formation features are considered locally restricted.

Peterson (1994) described the fluviatile Curtis Formation (here Facies D) sediment source and the formation's transgressive-regressive relation to the Summerville Formation. Regional depositional models were made by interpretation of depositional environments (Caputo and Pryor, 1991) and the utilization of sequence- and biostratigraphy (Wilcox, 2007). In addition, by collecting biostratigraphic samples, Wilcox (2007) was able to accurately date the Curtis Formation to Late Callovian - Oxfordian age. Neither Caputo and Pryor (1991), nor Wilcox (2007) did however address the allogenic- and autogenic controls, or other influencing parameters on the Curtis Formation deposition, whereas the San Rafael Group tectonic control was suggested by Thorman et al. (1990 cited in Thorman and Peterson, 2004) to relate to the Middle Jurassic Elko orogeny, and to dynamic topography (Lawton, 1994).

Regarding the J3-unconformity (Pipiringos and O'Sullivan, 1978) origin, e.g. Eschner and Kocurek (1986) suggest a Curtis Sea erosional origin, whereas others (Peterson, 1994; Wilcox, 2007 and others) state that there was tectonically controlled erosion prior to Curtis Sea invasion, and additional modification due to Curtis Sea tidal scour.

As summarized above, multiple studies have revolved around the depositional nature of the Curtis Formation, and its relation to stratigraphically neighbouring units. However, there is no encountered study that reveals the two stage transgression described in this thesis, nor how the coarse grained, fluviatile, cross-stratified conglomerates of Facies D relates to the early stage Curtis Sea development, except what Peterson (1994) described as fluviatile sediments sourced from the Elko highlands. Moreover, it seems that there is insufficient research addressing the apparent Entrada Sandstone local tectonic collapse (described in Chapter 6, section 6.1.2), as the only encountered remark was a few-lined comment by Keach II et al. (2013) in a report to Utah Geological Survey, targeting Entrada Sandstone petroleum resources by seismic attribute analysis.

Chapter 8: Conclusions

- The late Callovian-Oxfordian Curtis Formation was deposited during an unconformably bounded, full transgressive-regressive sequence, containing evidence of consistently tide-dominated shallow-marine conditions. The Entrada Sandstone top, on which the Curtis Formation was deposited, experienced subaerial erosion as an outcome of relative sea level fall prior to Curtis Formation deposition. The eroded top of the Entrada Sandstone hence serves as a lower sequence boundary for the investigated stratigraphic sequence.

- During tectonically controlled subsidence, associated with the North American Cordillera, the Curtis Sea inundated the Entrada Sandstone by a low angle regional relief and modified the pre-existing Entrada Sandstone top erosional surface additionally by tidal scouring, evidenced by Curtis Formation basal tidal channel incisions. The Curtis Formation is considered to have been deposited in the back-bulge region of the suggested North American Cordillera retroarc foreland basin, due to its gentle wedge-shaped geometry that thickens towards west, and pinches out towards east.

- The Curtis Sea transgression is recorded to have occurred during two stages, with two preserved flooding surfaces; one local- and one regionally traceable maximum flooding surface. Northern localities show that the initial marine inundation was partially filled in by fluviatile conglomerates derived from western highlands, subsequently followed by the maximum flooding event. The Curtis Sea extended south beyond Waterpocket Fold, Utah, and east between Green River and Moab, Utah. The western margin is challenging to map farther than the western flank of the San Rafael Swell due to concealment by younger strata, but is considered to not have extended significantly farther.

- Sedimentation rate exceeded the rate of relative sea level rise and gave rise to normal regression and the contemporary progradation of supratidal lower coastal plain deposits, contained within the Summerville Formation. Hence, it is proposed that the upper Curtis Formation (above MFS) and the lower Summerville Formation were deposited contemporaneously as distal and proximal equals, respectively, during the development of a highstand systems tract.

- The Curtis Formation architectural style development, following the maximum flooding surface, is represented by a slight progradational stage that was followed by an interval of prolonged aggradation as the deposits reflect balance between rate of sedimentation and rate of accommodation creation. The final stage involves the progradation of intertidal mixed flats and supratidal lower coastal plains (Summerville Formation) that gradually prograded into the Curtis Basin, contributing to its northwards retreat.

- Curtis Formation architectural geometry during the aggradational stage shows an interfingering sub- to intertidal regional zonation. This lateral variation reflects the autogenically controlled lateral distribution of tidal sub-environments in a basin where environmental conditions dynamically shifted during deposition, e.g. by tidal channel avulsions.

- Finally, the Summerville Formation top boundary display a subaerially eroded surface, an unconformity that acts hence as another sequence boundary, enclosing the investigated transgressive regressive-sequence.

Considering the high resolution outcrop quality along the laterally extensive eastern flank of the San Rafael Swell, Utah, the lateral spacing of Curtis Formation tidal sub-environments, presented through this thesis, may serve as an analogue for other tidally influenced environments, especially those that reflect deposition in shallow basins or in general during aggradational depositional development.

Recommendations on further research

The work presented in this thesis has revealed aspects of the Curtis Formation depositional development that has yet not been thoroughly described and interpreted. Further research is hence needed to resolve unanswered questions with a special emphasis on:

- The Curtis Formation basal transgressive systems tract, the lateral extent of the initial relative sea level rise and how it relates to the influx of fluviatile sediments, and do these associated conglomeratic fluvial channels occur within the Summerville Formation?

- The evidenced Entrada Sandstone intra-formational local tectonic collapse, its origin, extent and potential contribution to initial Curtis Sea inundation.

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Appendices

Appendix A - Log trace localities coordinates

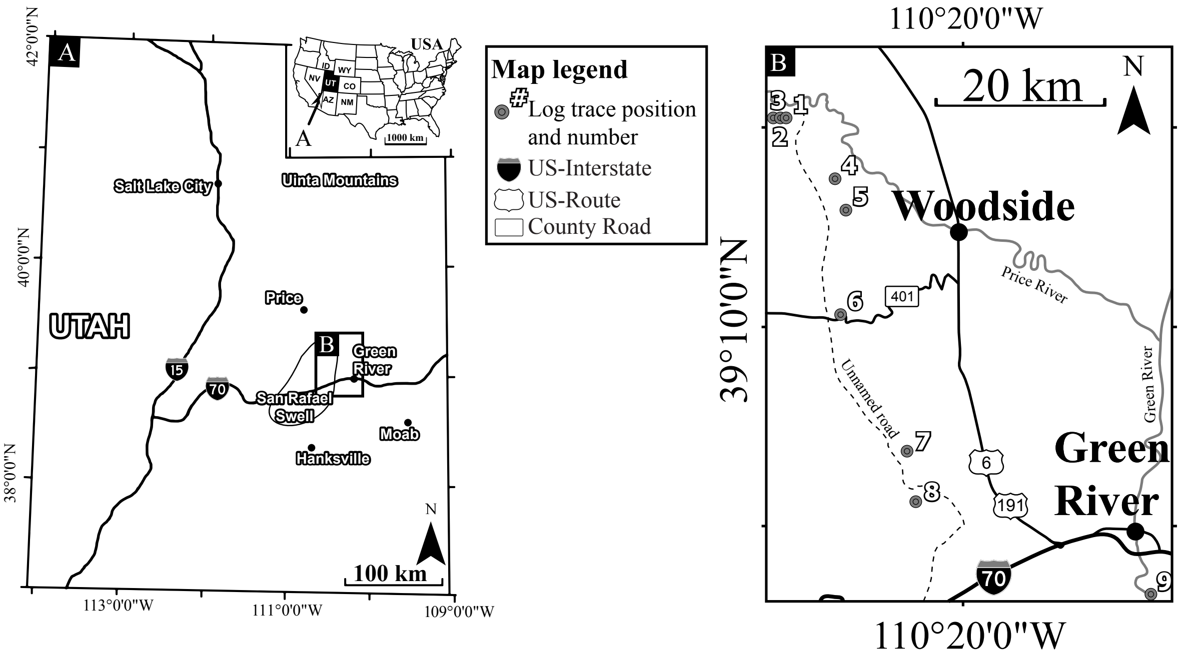


Figure A: **USA mini map**: Overview of the contiguous USA showing location of Utah (**UT**) and bordering states; Idaho (**ID**), Wyoming (**WY**), Colorado (**CO**), New Mexico (**NM**), Arizona (**AZ**) and Nevada (**NV**) **A**: Map of Utah with key cities, towns and roads. **B**: Map of the designated study area with local towns, roads and log trace positions. See legend for symbology, log trace coordinates are listed in Table A below.

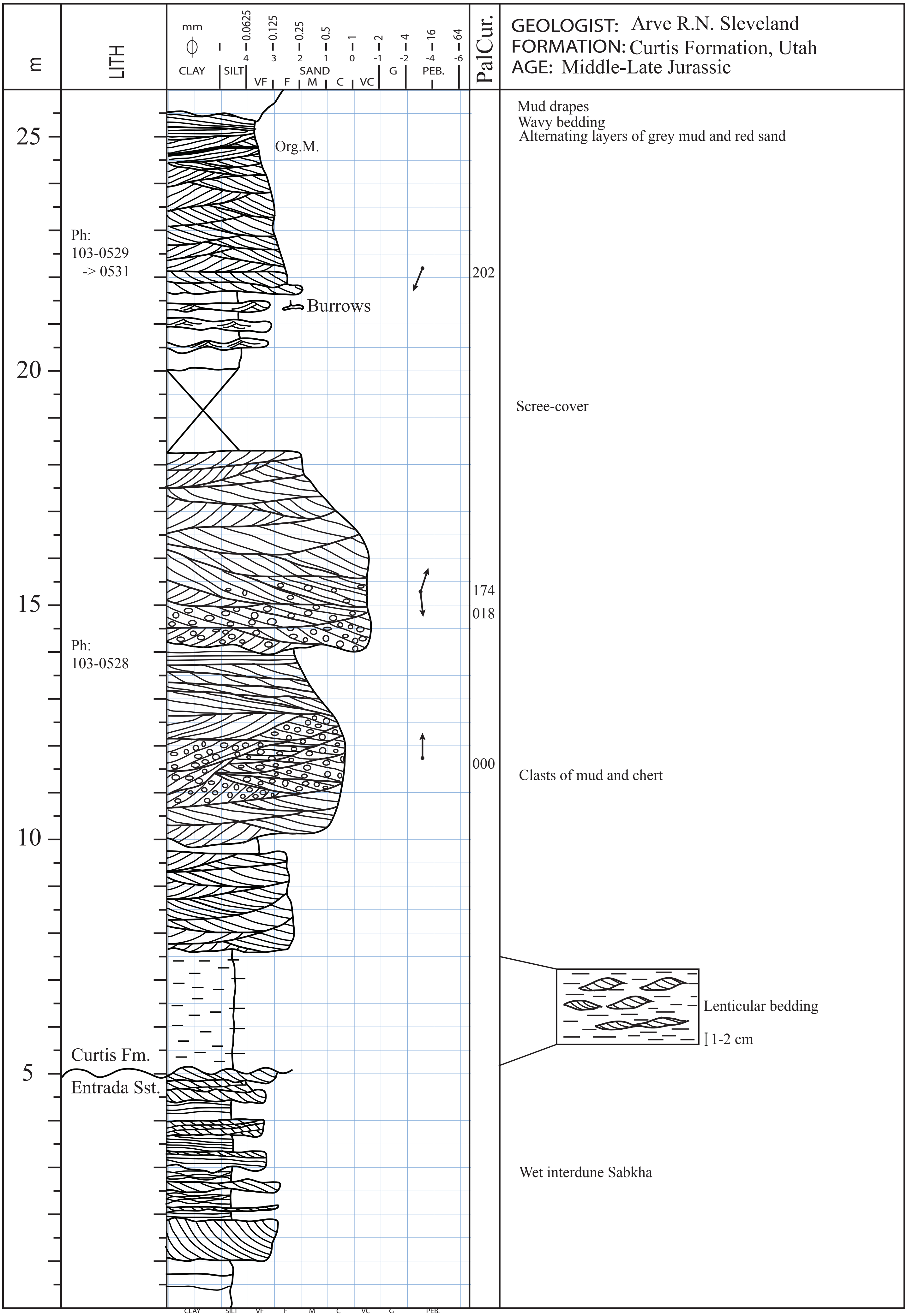
Table A: UTM coordinates for log trace localities associated with this thesis see Figure A above for geographical references.

Locality	Date	UTM - Coordinates		
		Zone	**Easting**	**Northing**
1. Stove Gulch East	23.6.2015	12 S	541150 m E	4354677 m N
2. Stove Gulch West	26.6.2015	12 S	540412 m E	4354758 m N
3. Sulphur Canyon	27.6.2015	12 S	538598 m E	4354691 m N
4. Humbug Flats East	30.6.2015	12 S	545496 m E	4349054 m N
5. Neversweat Wash	1.7.2015	12 S	546582 m E	4345984 m N
6. Dry Mesa	2.7.2015	12 S	546370 m E	4336290 m N
7. Smith’s Cabin North	22.-23.9.2015	12 S	552531 m E	4323706 m N
8. Smith’s Cabin South	3.7.2015	12 S	553584 m E	4319583 m N
9. Crystal Geyser	18.-19.9.2015	12 S	575060 m E	4310623 m N

Appendix B - Log from Stove Gulch East

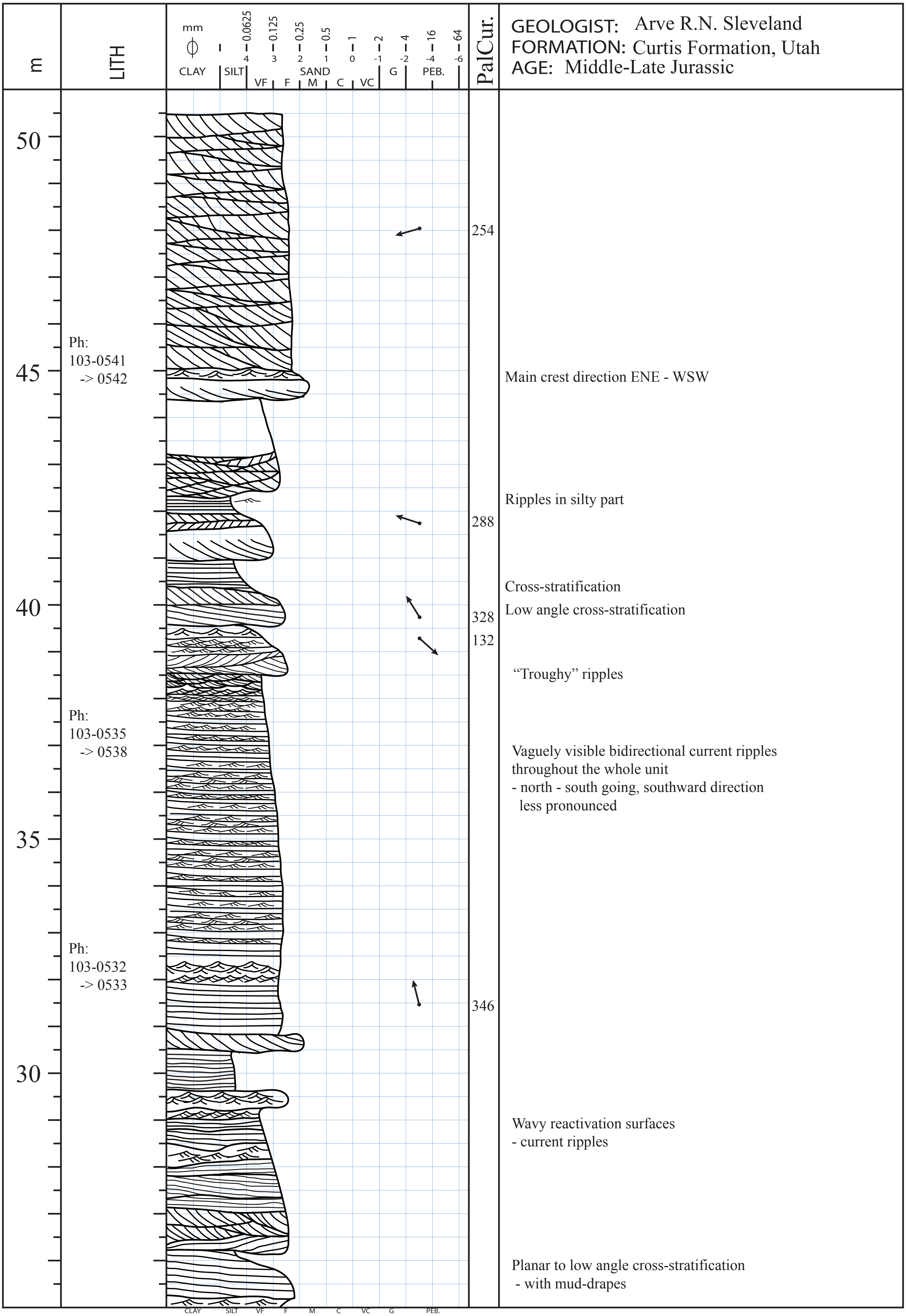
Log 1 - Stove Gulch East

LOCALITY 39°20'26.2"N 110°31'21.5"W SHEET 1 OF 3 DATE: 23.6.15 SCALE: 1:100



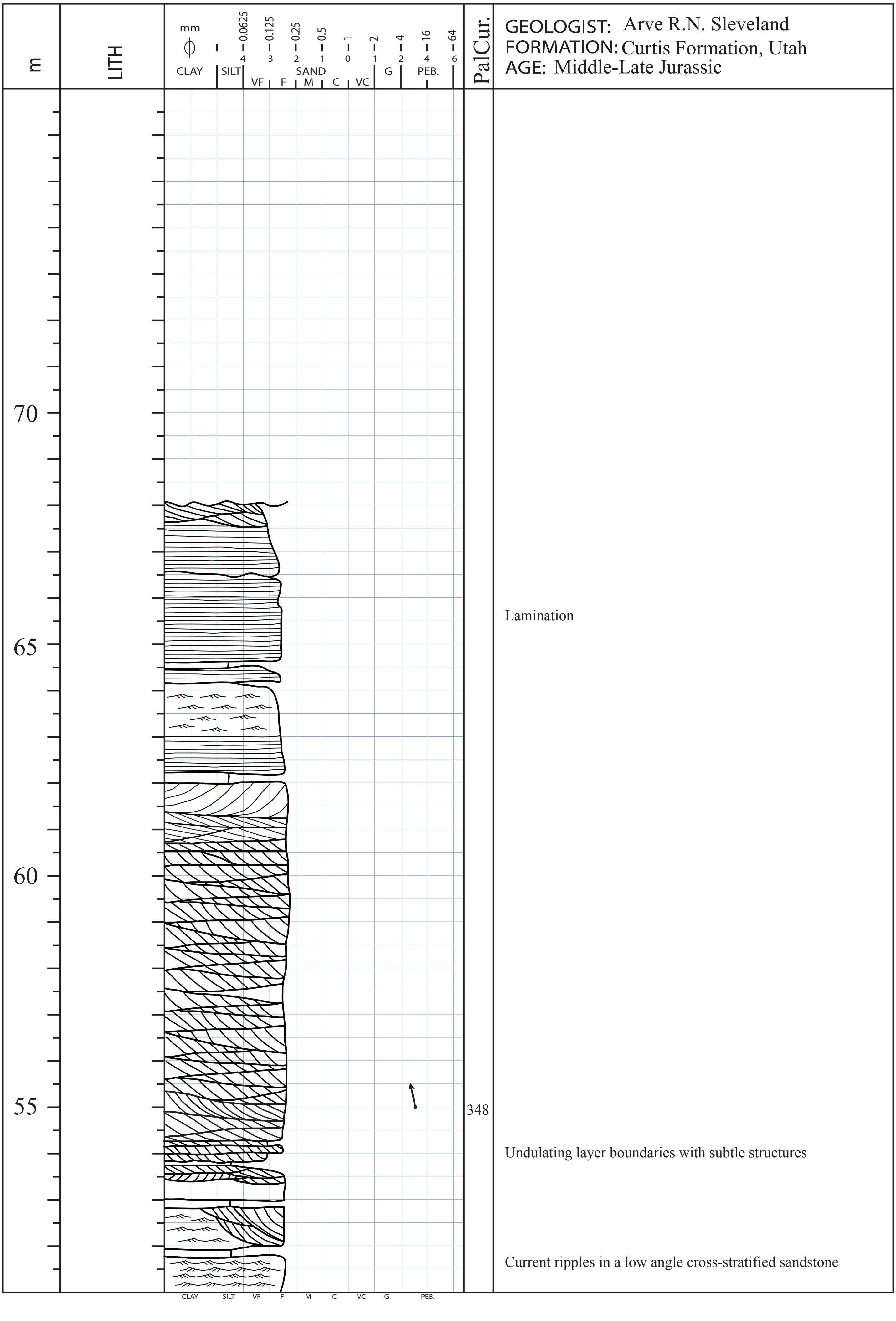
Log 1 - Stove Gulch East

LOCALITY 39°20'26.2"N 110°31'21.5"W SHEET 2 OF 3 DATE: 23.6.15 SCALE: 1:100



Log 1 - Stove Gulch East

LOCALITY 39°20'26.2"N 110°31'21.5"W SHEET 3 OF 3 DATE: 23.6.15 SCALE: 1:100

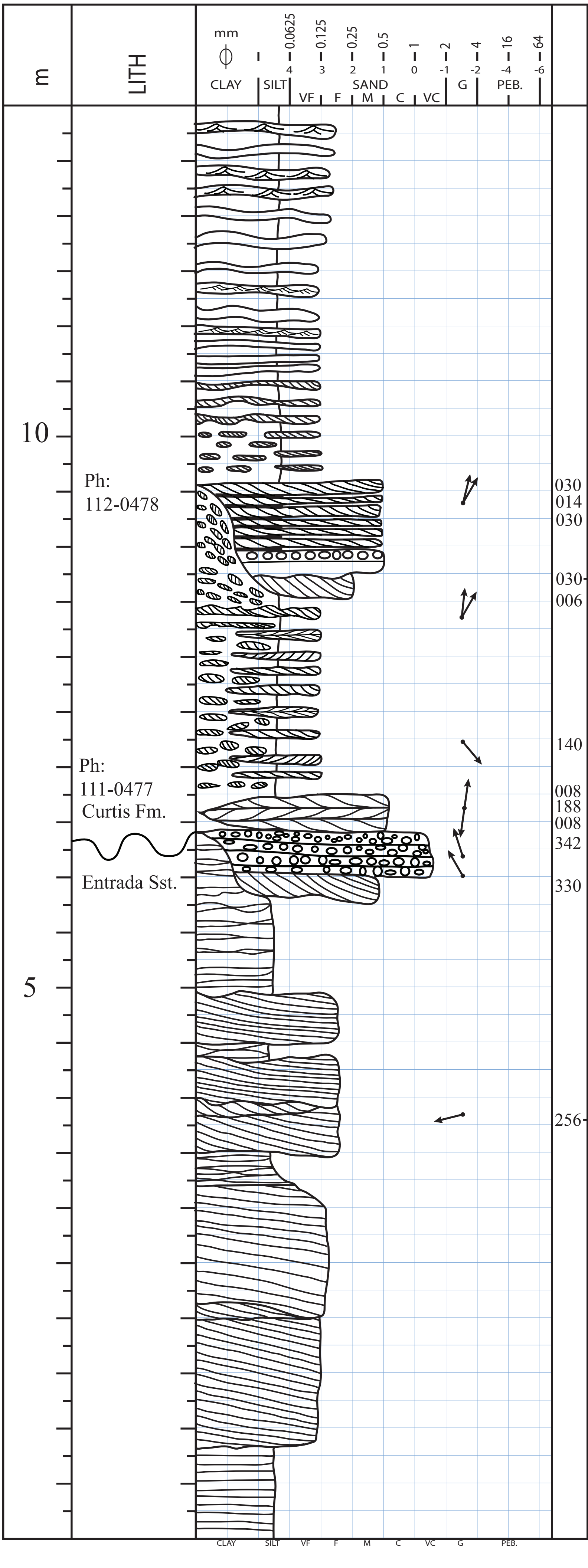


Appendix C - Log from Stove Gulch West

Log 2 - Stove Gulch West

LOCALITY 39°20'29.0"N 110°31'51.8"W SHEET 1 OF 3 DATE:26.6.15 SCALE: 1:50

GEOLOGIST: Arve R. N. Sleveland
FORMATION: Curtis Formation
AGE: Middle-late Jurassic



Wavy bedding

with wave ripples crest : 140 °

Lenticular bedding

Inclined Heterolithic Stratification?

clasts up to 4 cm accross

ripple in lense

Lenticular to wavy bedding

Herringbone structure

Grainsupported

Interdune sabkha, evaporite strings in layers

Bleached dune

Wet sabkha interdune

Bleached dune

2D

Evaporite strings in topmost part of interdune

Gradual transition from dune to interdune

Bleached dune with low angle cross stratification

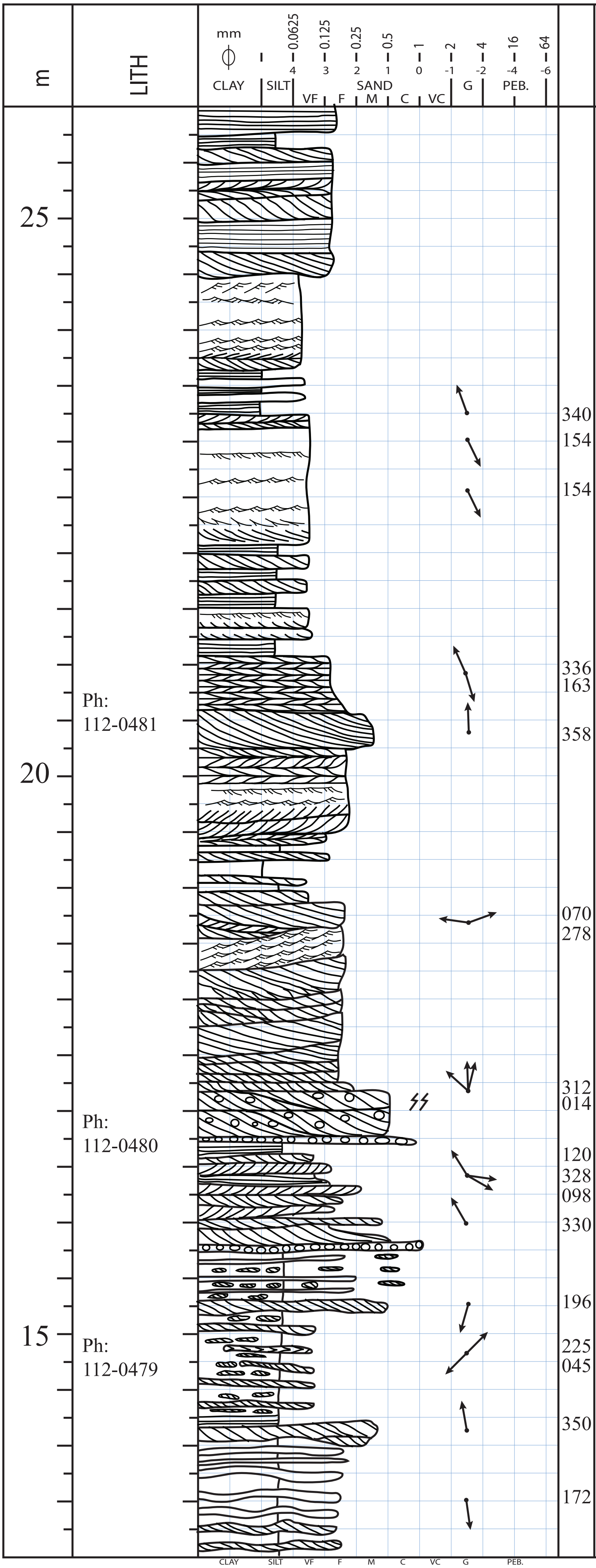
Dune with low angle cross stratification

Planar stratified interdune

Log 2 - Stove Gulch West

LOCALITY 39°20'29.0"N 110°31'51.8"W SHEET 2 OF 3 DATE: 26.6.15 SCALE: 1:50

GEOLOGIST: Arve R. N. Sleveland
FORMATION: Curtis Formation
AGE: Middle-late Jurassic



Cross stratified units separated by planar to low angle cross stratification

Herringbone

Lots of reactivation surfaces
- by tidal erosion and sediment reworking

Double mud-drapes

Herringbone with mud-drapes in between

Mud-drapes

Herringbone

mud-draping

Herringbone

Ripples

Cross-stratification with double mud-drapes
Unit contain rip-off clast lenses of green mud
Upwards thickening

Some scattered clasts, unit pinches out southward

Matrix supported konglomerate - clasts 5 cm accross

Herringbone in lenses

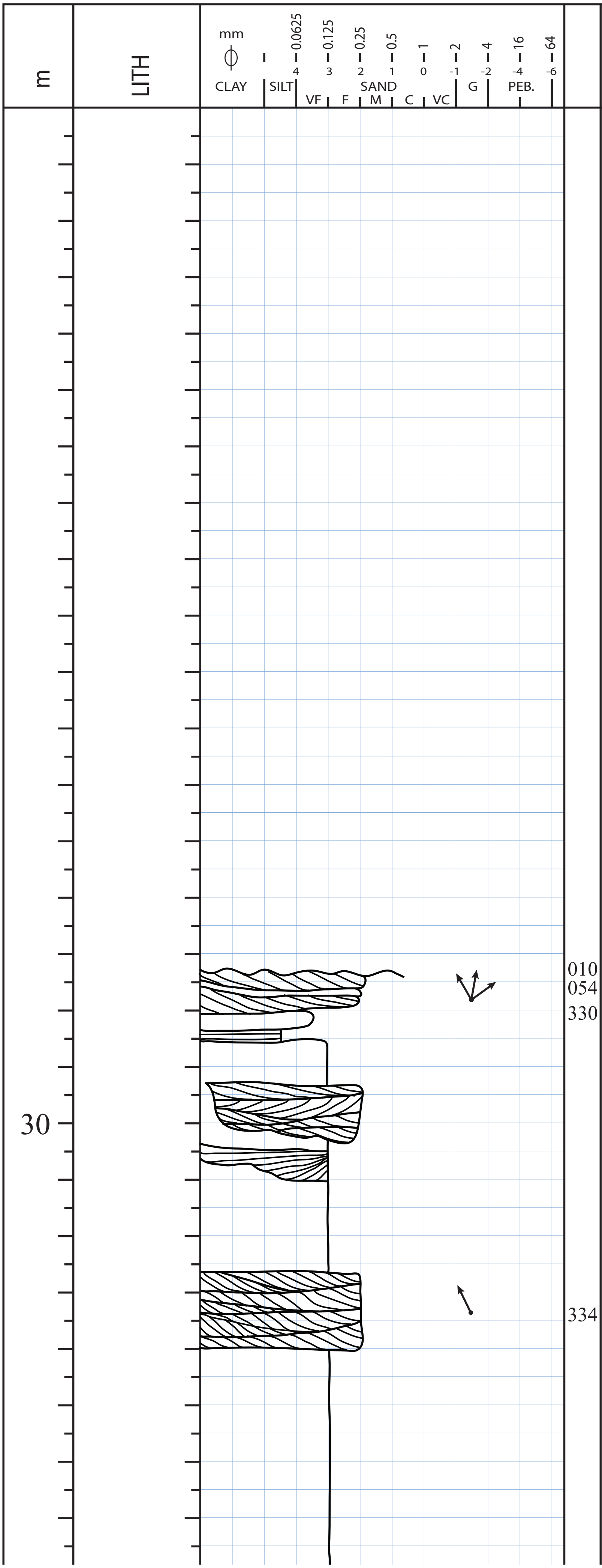
Clasts get up to 5 cm accross

Unit thickens southward

Log 2 - Stove Gulch West

LOCALITY 39°20'29.0"N 110°31'51.8"W SHEET 3 OF 3 DATE: 26.6.15 SCALE: 1:50

GEOLOGIST: Arve R. N. Sleveland
FORMATION: Curtis Formation
AGE: Middle-late Jurassic



wave ripples on top-surface - crest 080°

Tidally influenced channel?, recent erosion

Tidally influenced channel?

Diverging cross stratification

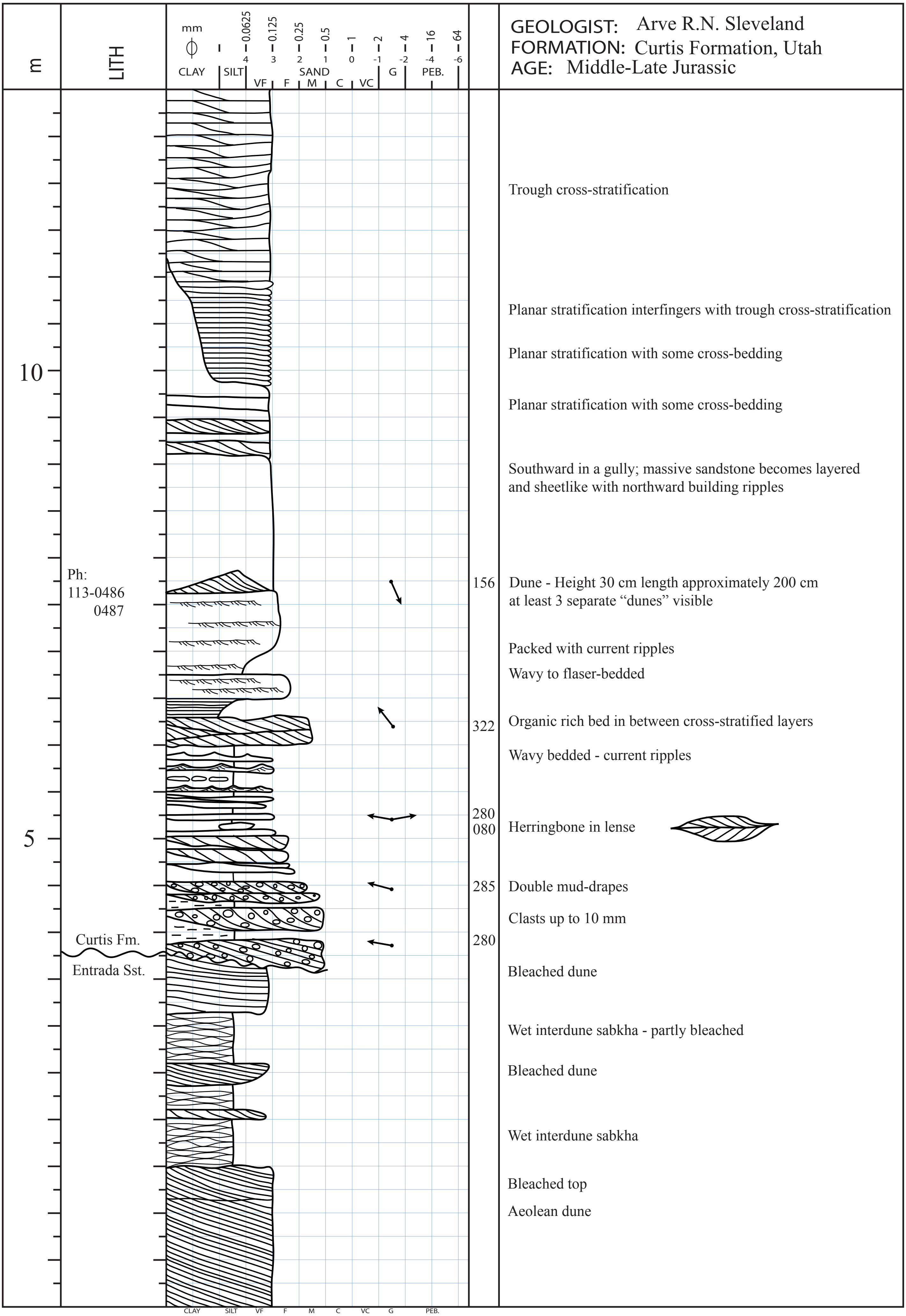
Some planar lines/ structures

Weathered surface, hardly any visible structures

Appendix D - Log from Sulphur Canyon

Log 3 - Sulphur Canyon

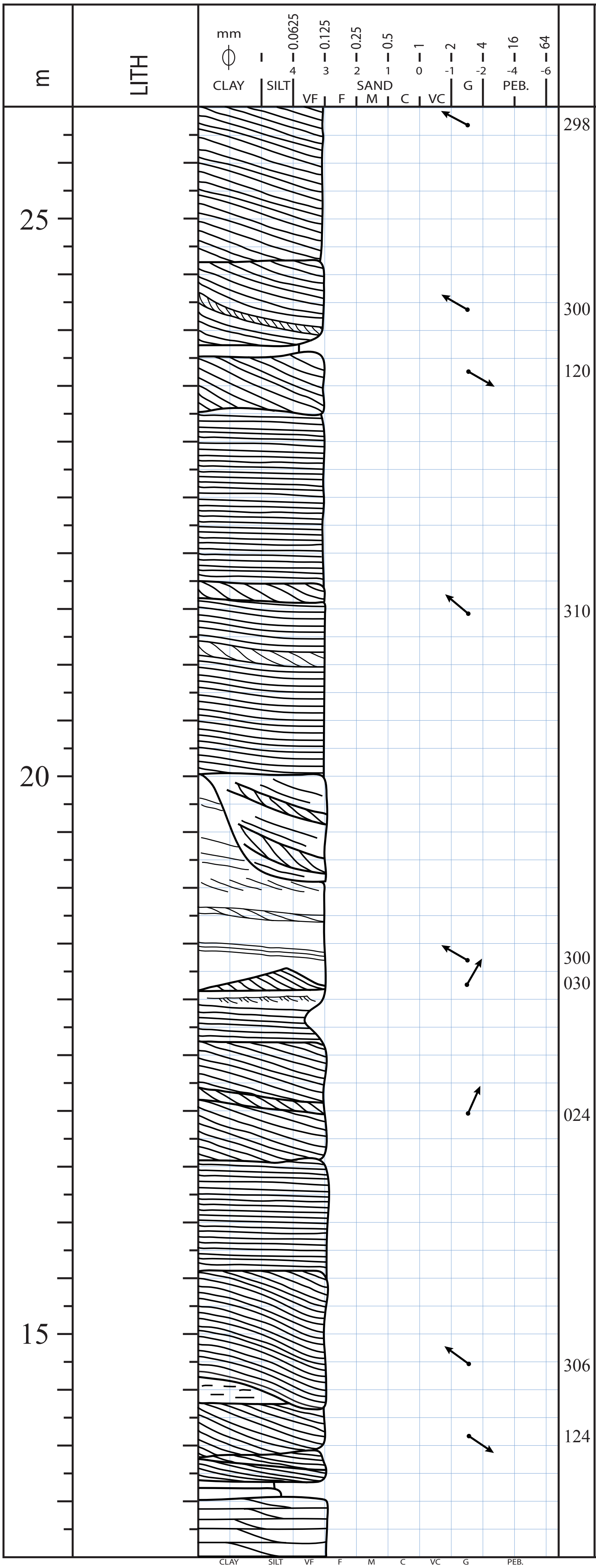
LOCALITY 39°20'29.9"N 110°33'07.5"W SHEET 1 OF 4 DATE: 27.06.15 SCALE: 1 : 50



Log 3 - Sulphur Canyon

LOCALITY 39°20'29.9"N 110°33'07.5"W SHEET 2 OF 4 DATE: 27.06.15 SCALE: 1 : 50

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



Gracing trace
Laminar flow
Low angle cross-stratification

Low angle cross-stratification

Quite massive sandstone with some subtle structures

Low angle cross-stratification

Cross-stratification

Planar- to low angle cross-stratification

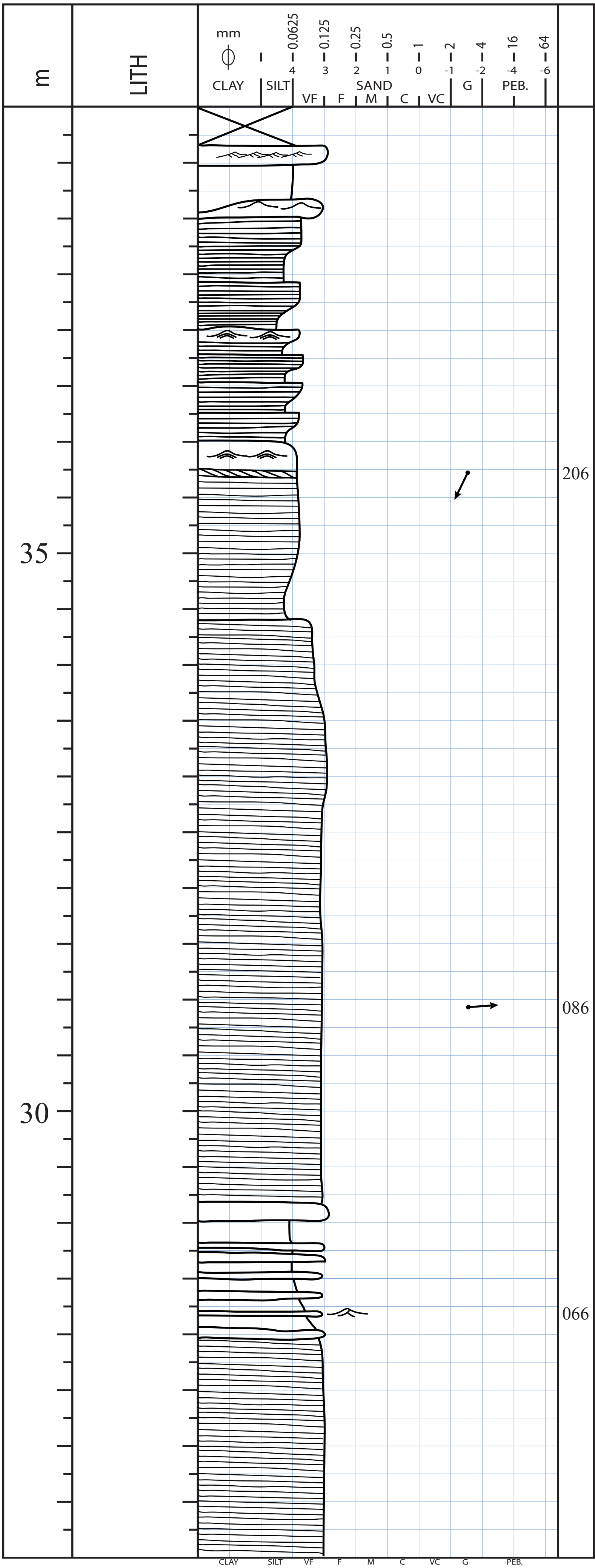
Log 3 - Sulphur Canyon

LOCALITY 39°20'29.9"N 110°33'07.5"W SHEET 3 OF 4 DATE: 27.06.15 SCALE: 1 : 50

GEOLOGIST: Arve R.N. Sleveland

FORMATION: Curtis Formation, Utah

AGE: Middle-Late Jurassic



wave ripples - vaguely visible, hard to measure

Silty-shale with laminae up to 0,5mm in thickness

Muddy

Layers are thinning upwards

Low angle cross-stratification

Measured on overhang current

Wavy- to flaser-bedded

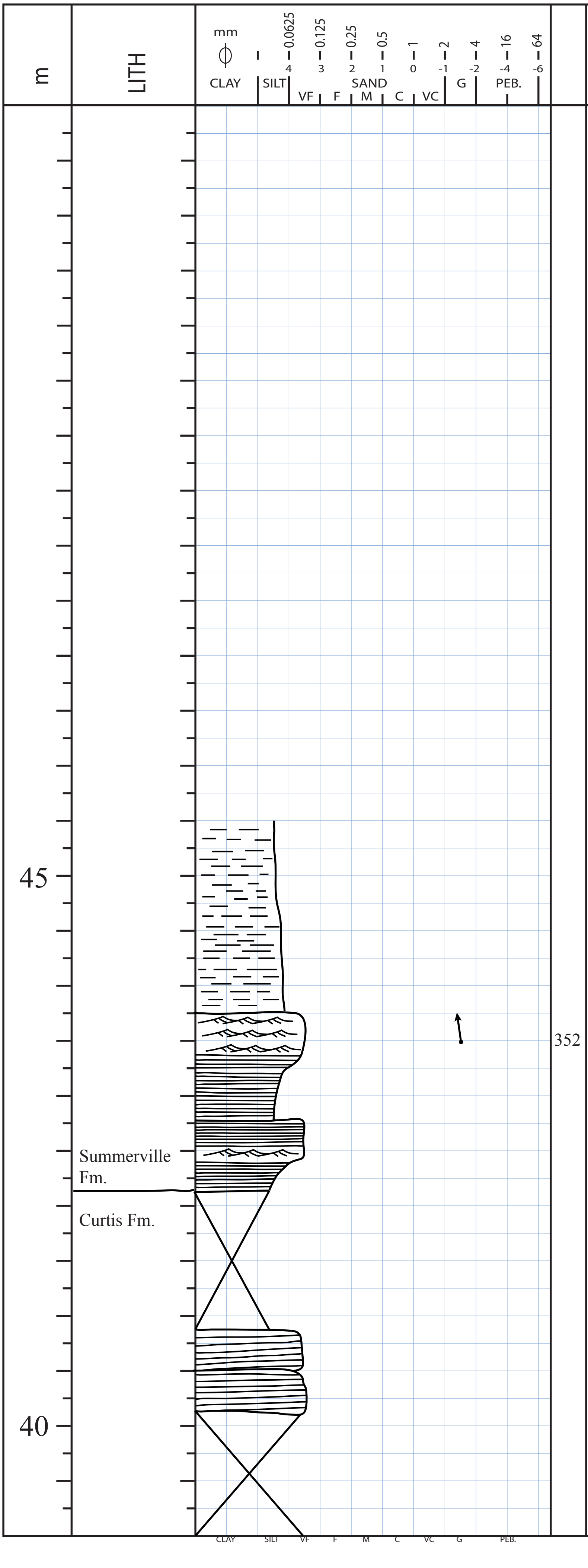
Wave ripple crest direction

Planar- to low angle cross-stratification

Log 3 - Sulphur Canyon

LOCALITY 39°20'29.9"N 110°33'07.5"W SHEET 4 OF 4 DATE: 27.06.15 SCALE: 1 : 50

GEOLOGIST:
FORMATION:
AGE:



Rusty red - Fluvial flood plain?

Herringbone

Brown - red color

Flaser - laminated

5-10 mm thick laminae

Scree-cover - possibly mud

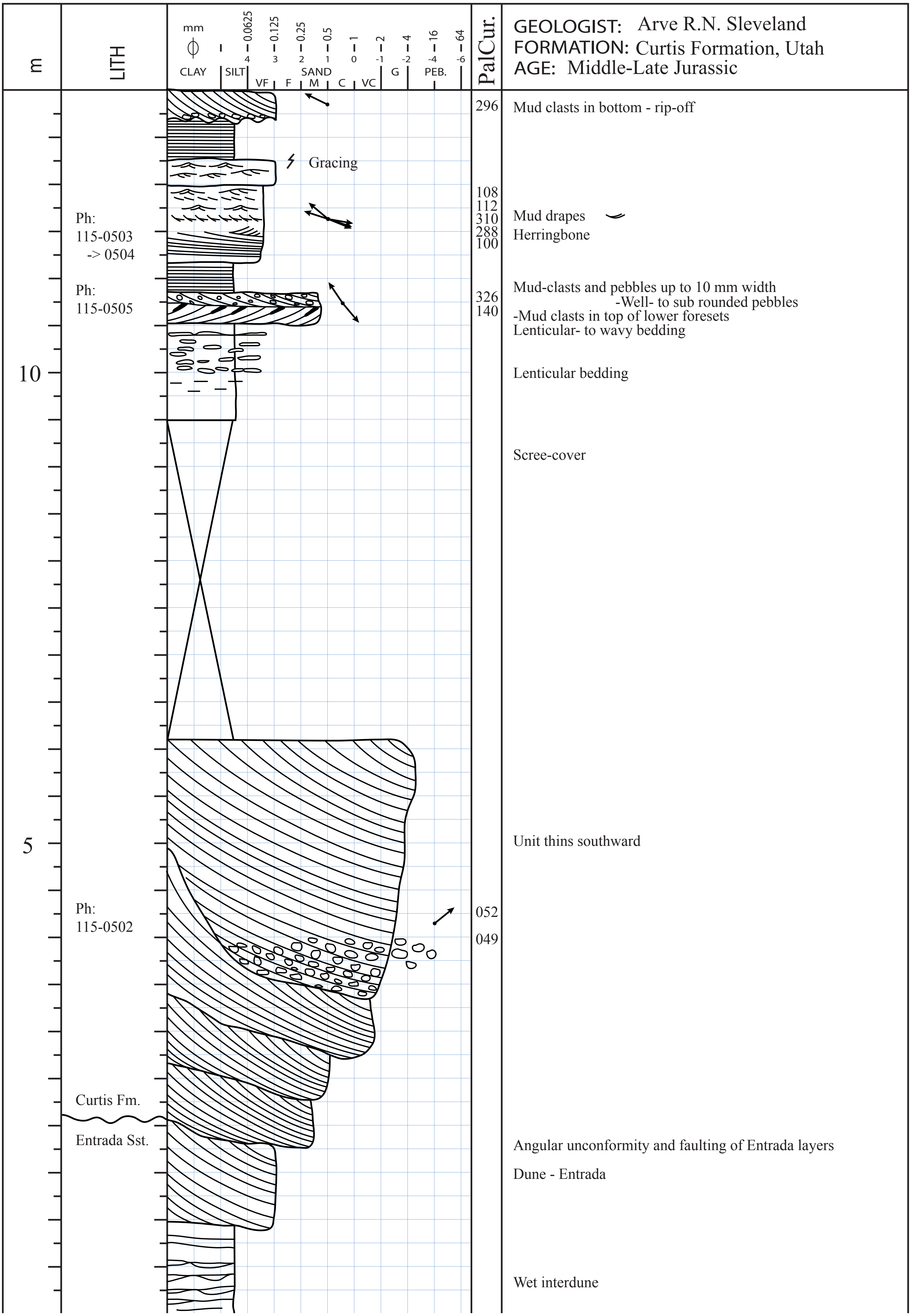
Clean sandstone with gently inclined layering

Scree-cover - possibly mud

Appendix E - Log from Humbug Flats East

Log 4 - Humbug Flats East

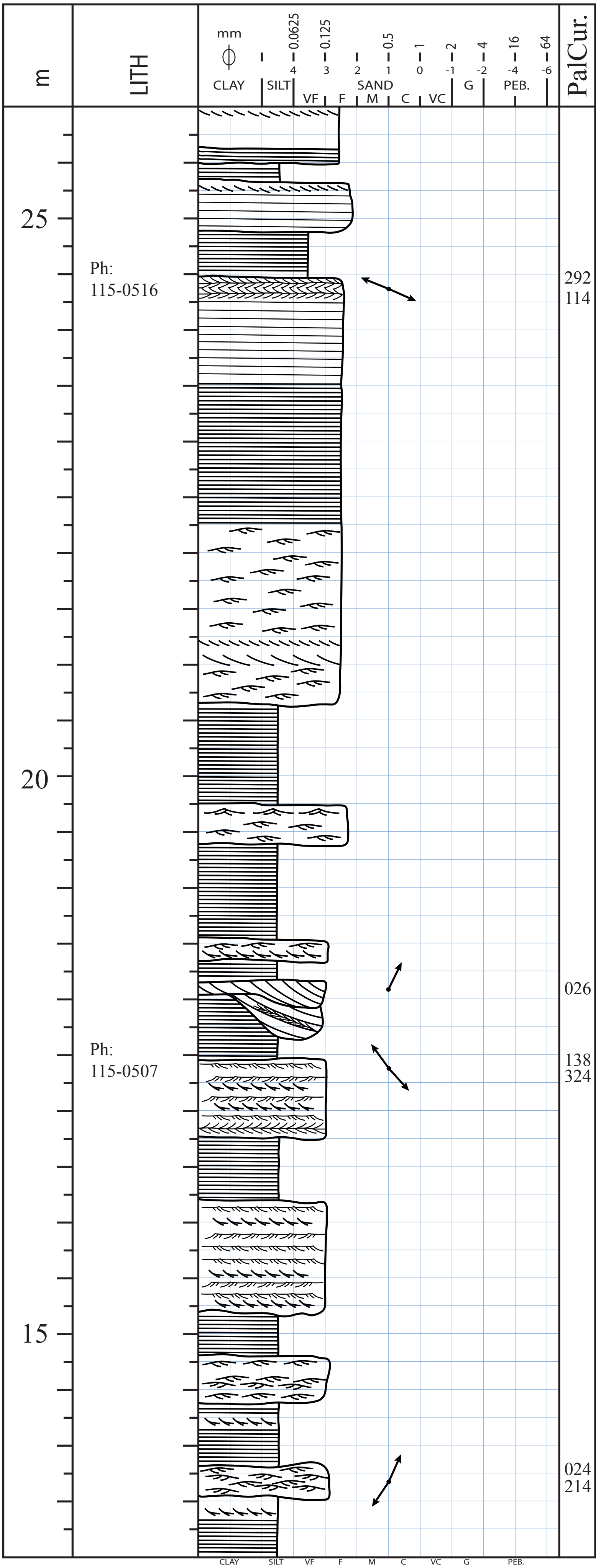
LOCALITY 39°17'25.0"N 110°28'18.4"W SHEET 1 OF 5 DATE: 30.6.15 SCALE: 1:50



Log 4 - Humbug Flats East

LOCALITY 39°17'25.0"N 110°28'18.4"W SHEET 2 OF 5 DATE: 30.6.15 SCALE: 1:50

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



Laminated fine sandstone

Planar to low angle cross stratification with some vague ripples

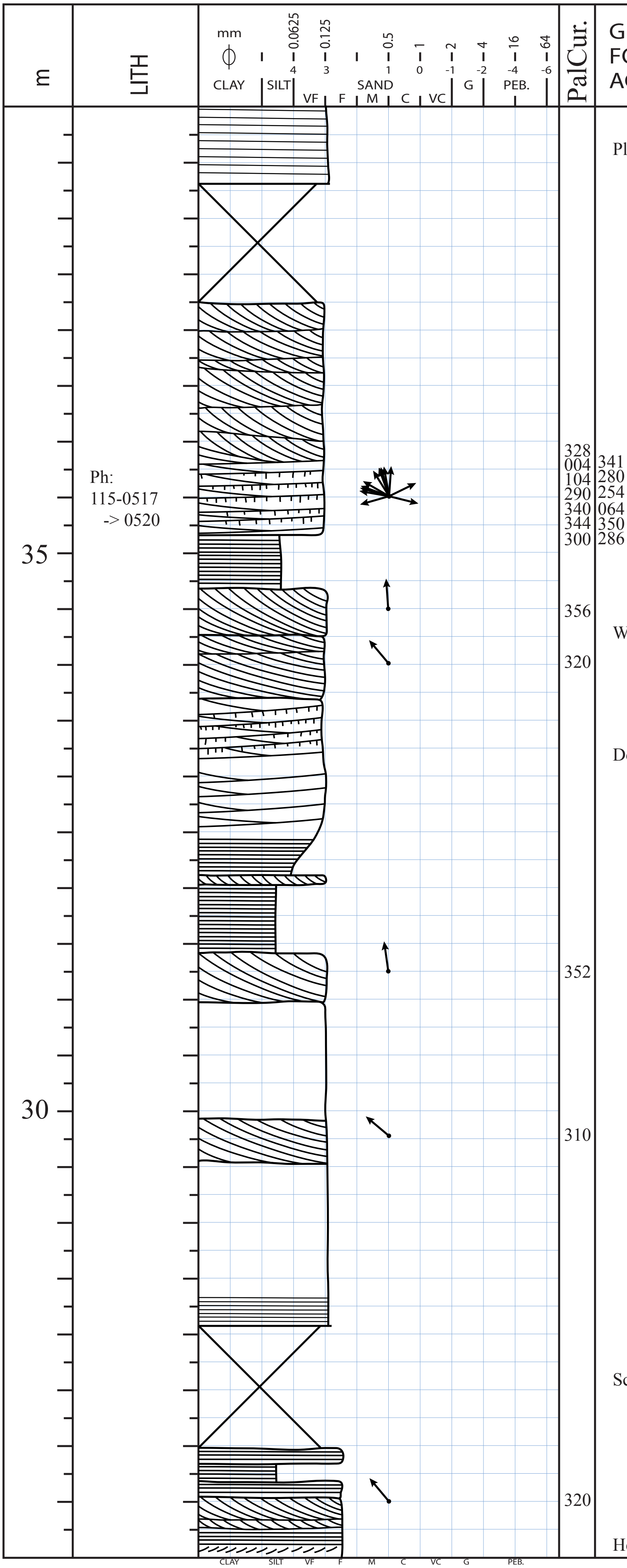
Traces of mud-clasts inside - carved out

Multidirectional current ripples - hard to measure

Log 4 - Humbug Flats East

LOCALITY 39°17'25.0"N 110°28'18.4"W SHEET 3 OF 5 DATE: 30.6.15 SCALE: 1:50

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



Planar- to low angle cross stratification

Sheet like massflows? Small lobes?

Dessication cracks on top of each lobe

Wave ripple crest on layer surface 012°

Dessication cracks

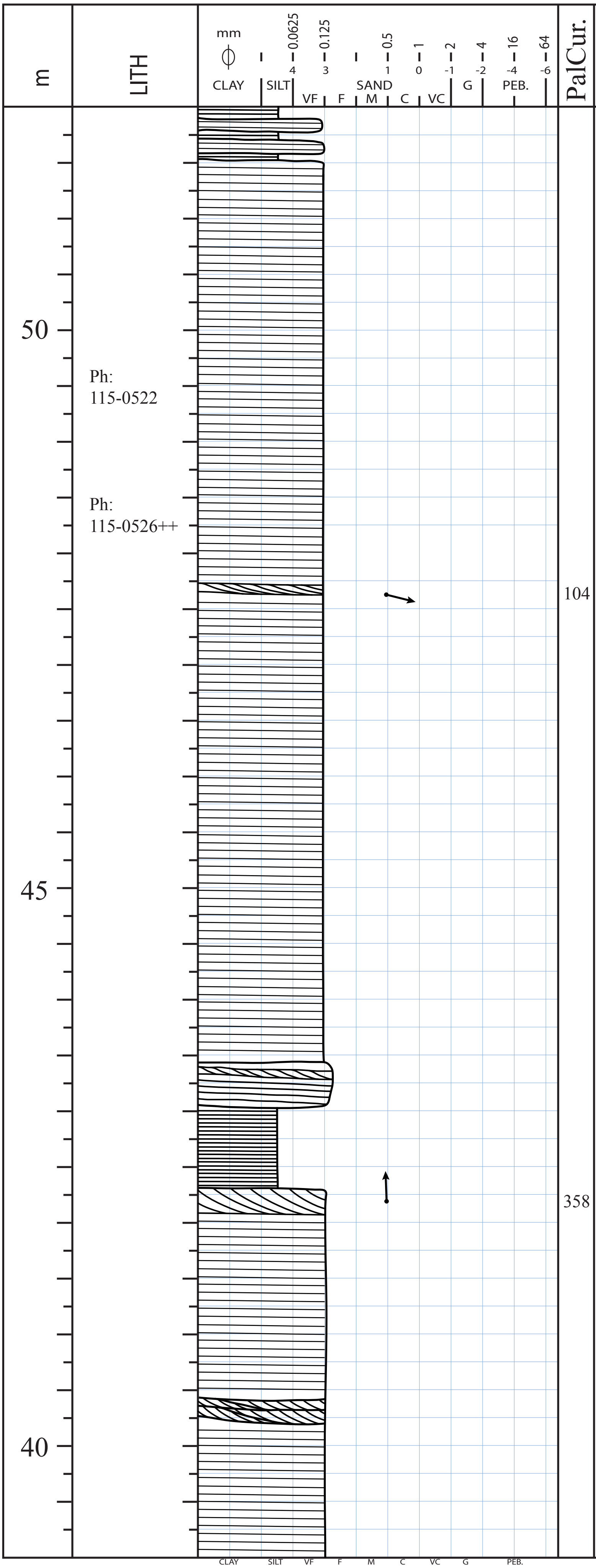
Scree-cover

Herringbone

Log 4 - Humbug Flats East

LOCALITY 39°17'25.0"N 110°28'18.4"W SHEET 4 OF 5 DATE: 30.6.15 SCALE: 1:50

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



Some vague current ripples

Planar- to low angle cross bedding to lamination

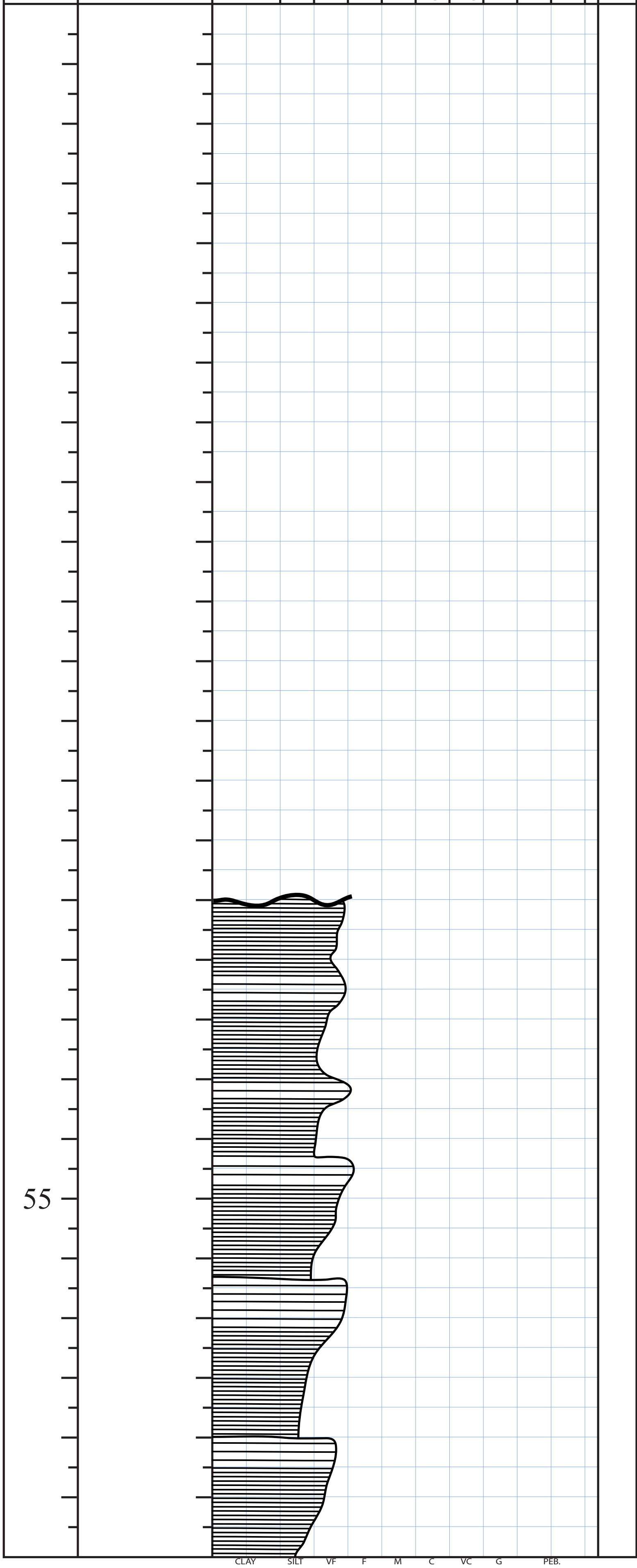
Planar- to low angle cross stratification

Planar- to low angle cross stratification

Log 4 - Humbug Flats East

LOCALITY 39°17'25.0"N 110°28'18.4"W SHEET 5 OF 5 DATE: 30.6.15 SCALE: 1:50

m	LITH	mm: 0.0625, 0.125, 0.5, 1, 2, 4, 16, 64; φ: 4, 3, 1, 0, -1, -2, -4, -6; CLAY, SILT, SAND (VF, F, M, C, VC), G, PEB.	PalCur.	GEOLOGIST: Arve R.N. Sleveland FORMATION: Curtis Formation, Utah AGE: Middle-Late Jurassic



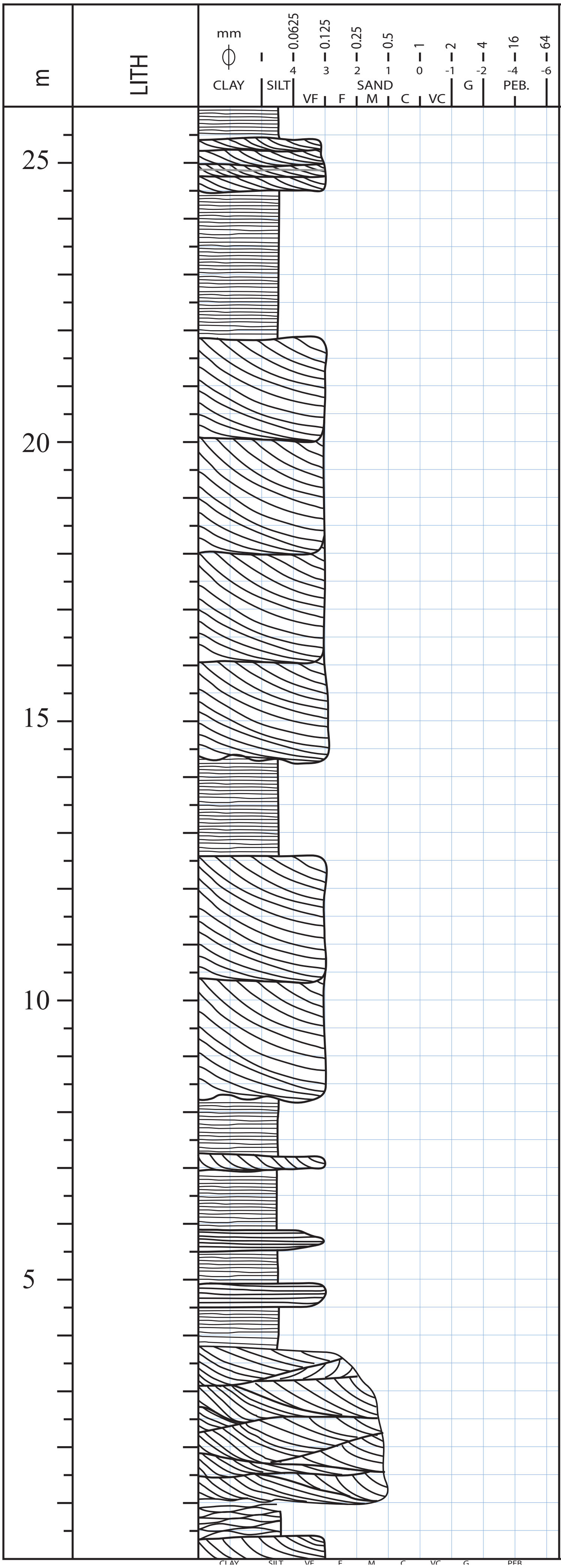
Extremely flakey exfoliation-like wavy geometry weathering along surface boundaries.
Layers of 1-2 cm thicknesses

Appendix F - Log from Neversweat Wash

Log 5 - Neversweat Wash

LOCALITY 39°15'56.0"N 110°28'07.5"W SHEET 1 OF 4 DATE: 1.07.15 SCALE: 1:100

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



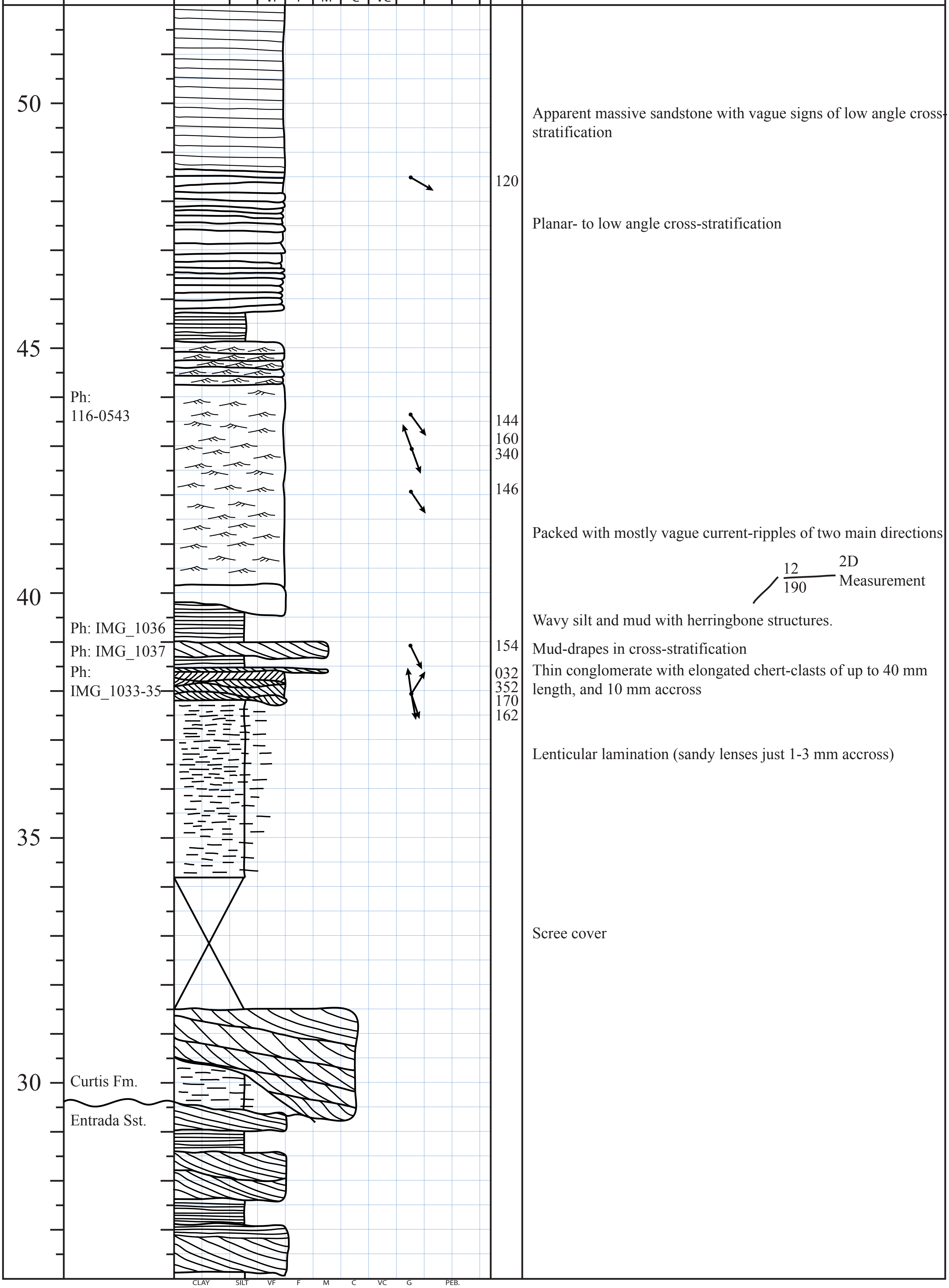
Bleaching contact

Entirely bleached unit
Collapsed? Packed with deformation bands

Log 5 - Neversweat Wash

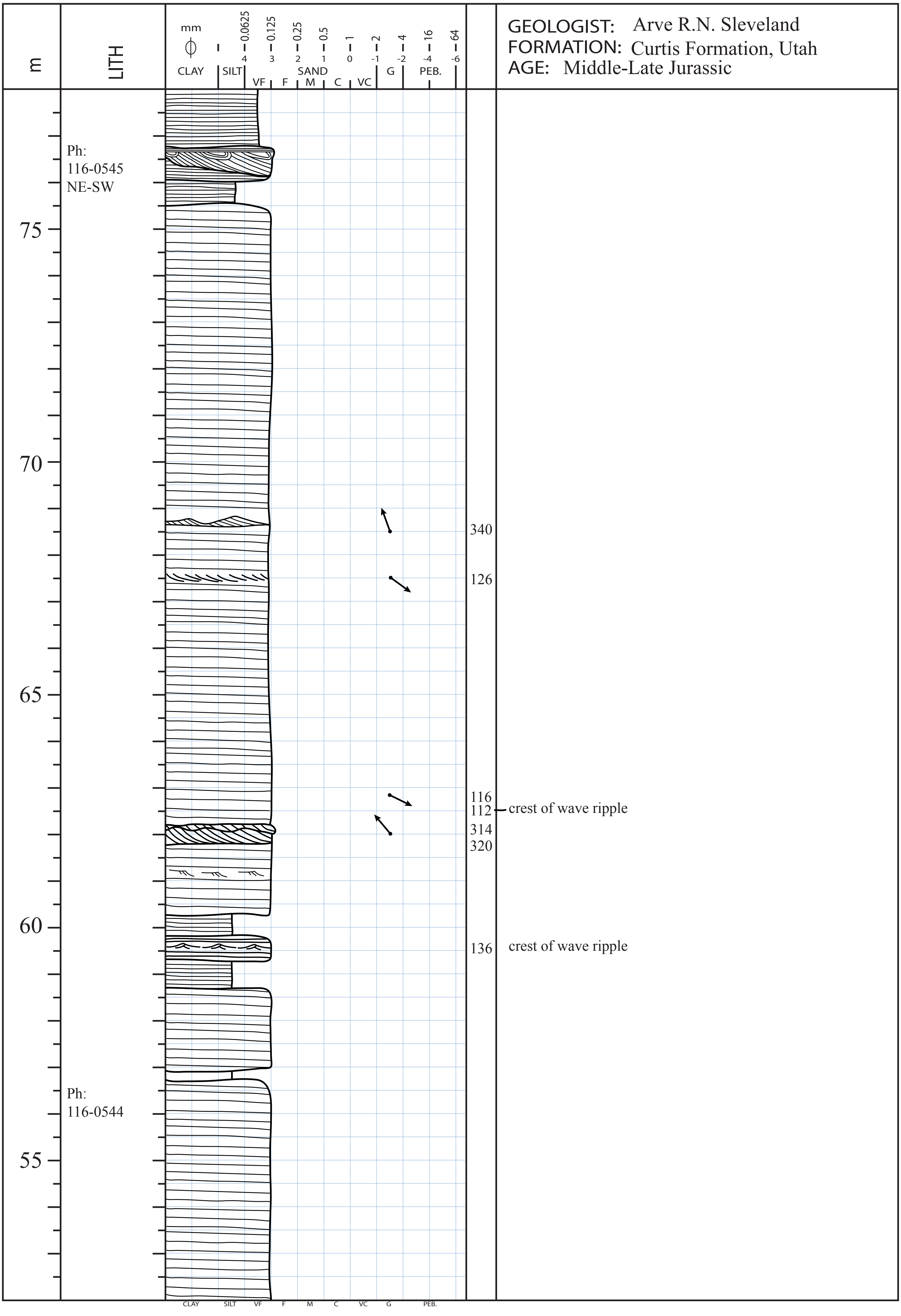
LOCALITY 39°15'43.2"N 110°27'36.0"W SHEET 2 OF 4 DATE: 1.07.15 SCALE: 1:100

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



Log 5 - Neversweat Wash

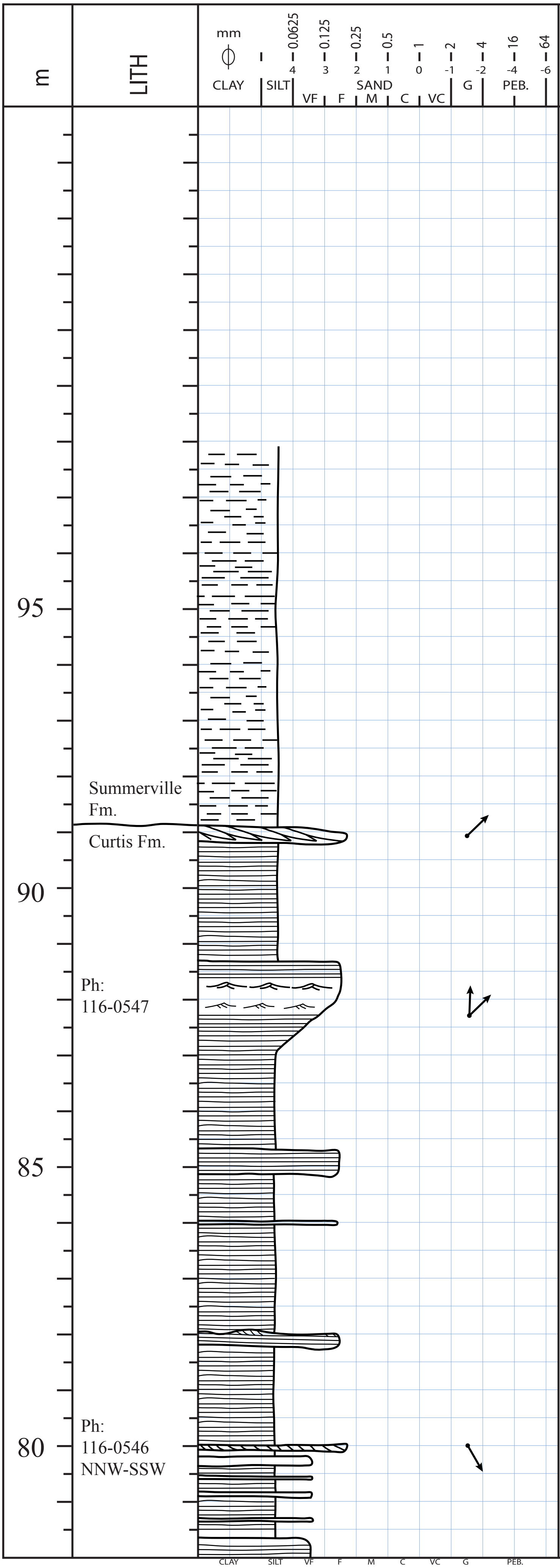
LOCALITY 39°15'43.2"N 110°27'36.0"W SHEET 3 OF 4 DATE: 1.07.15 SCALE: 1:100



Log 5 - Neversweat Wash

LOCALITY 39°15'43.2"N 110°27'36.0"W SHEET 4 OF 4 DATE: 1.07.15 SCALE: 1:100

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



046 Mud-draping in cross-stratification

046
002 Herringbone structure (not measured)

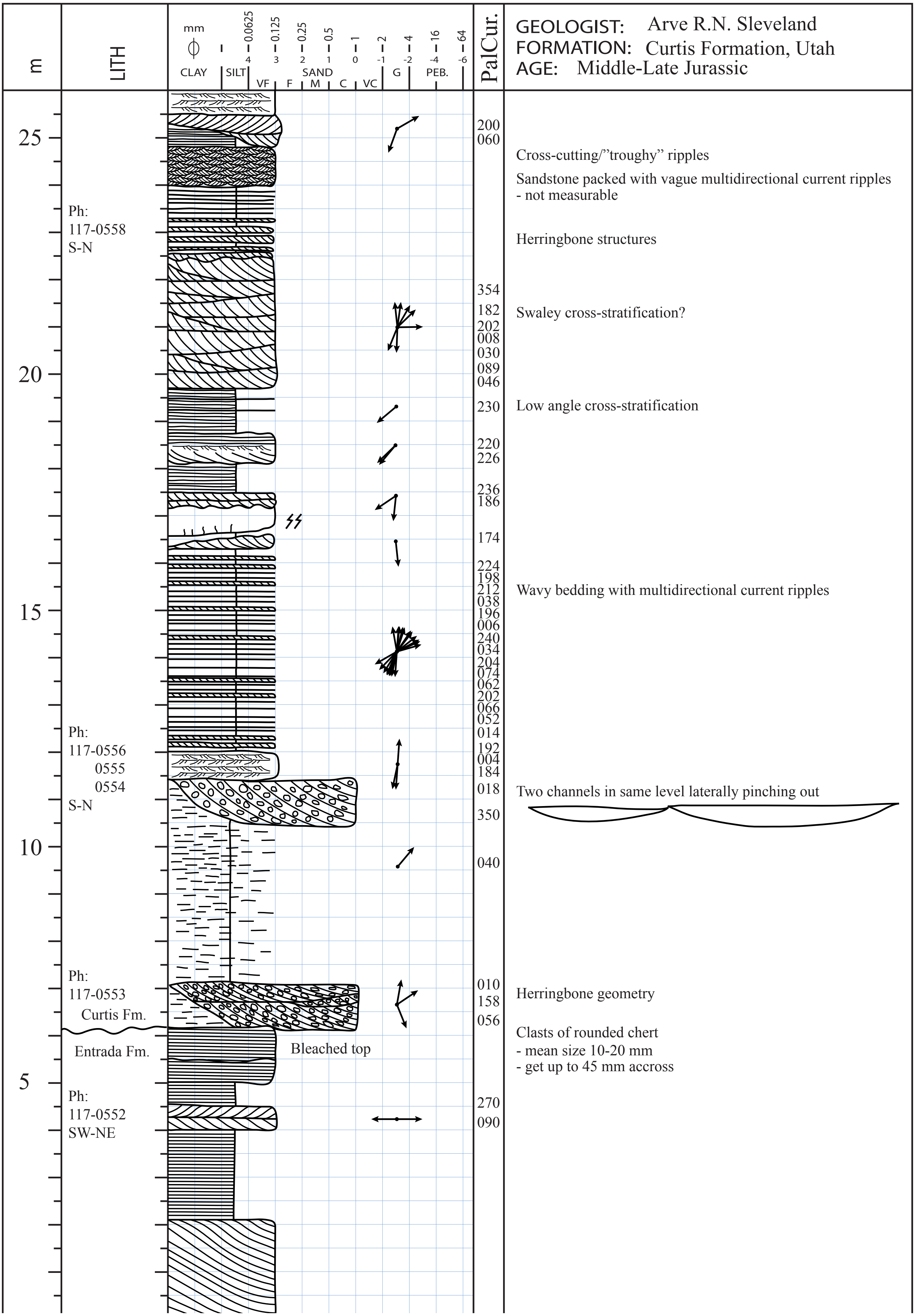
150

Thin layered sandstone with wavy geometry
- secondary diagenetic feature?

Appendix G - Log from Dry Mesa

Log 6 - Dry Mesa

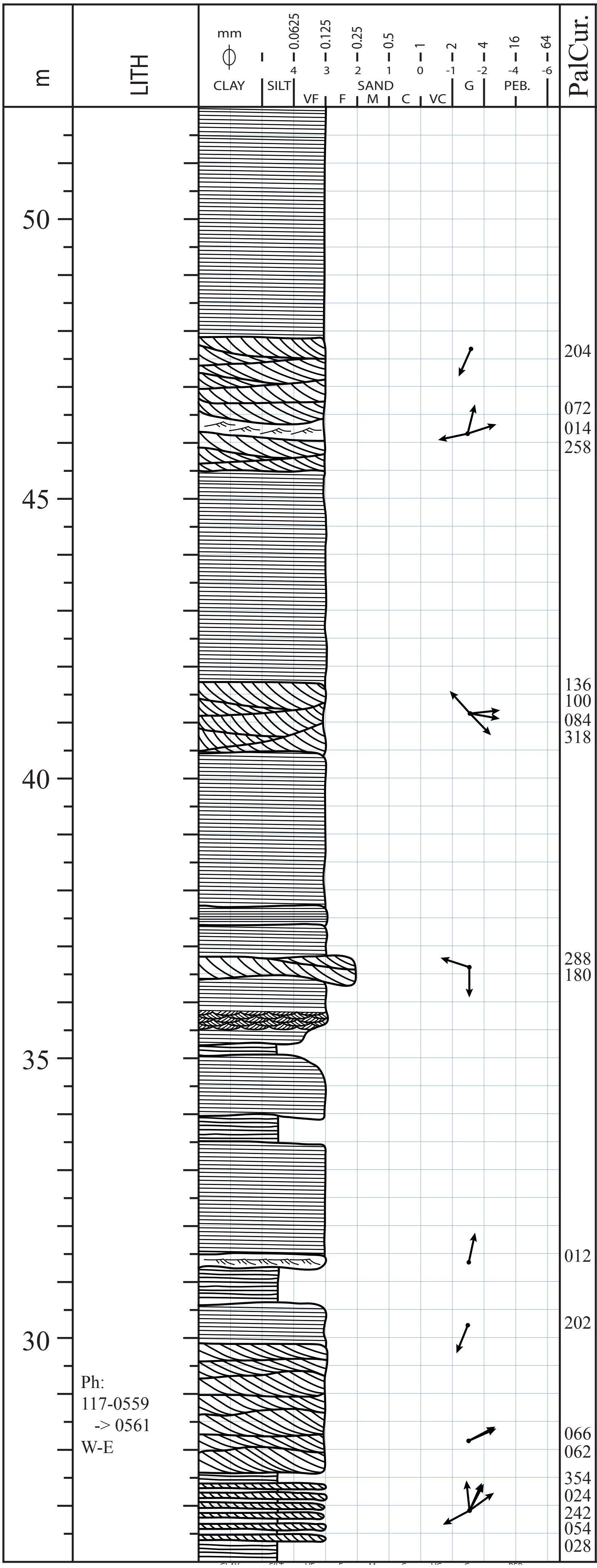
LOCALITY 39°10'28.8"N 110°27'48.2"W SHEET 1 OF 3 DATE: 2.7.15 SCALE: 1:100



Log 6 - Dry Mesa

LOCALITY 39°10'28.8"N 110°27'48.2"W SHEET 2 OF 3 DATE: 2.7.15 SCALE: 1:100

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



Planar- to low angle cross-stratified bedding

Ripples in swaley geometry? Channel deposit?

Low angle cross-stratification

Swaley cross-stratification?

Planar- to low angle cross-stratified bedding
- spacing 20-50 mm

Finely laminated mm scale

Apparently “troughy” multidirectional current ripples

Low angle cross-stratification with some small wave ripples on top of unit
- crest 130°

Current ripples

Planar lamination
Vague current ripples
Low angle cross-stratification

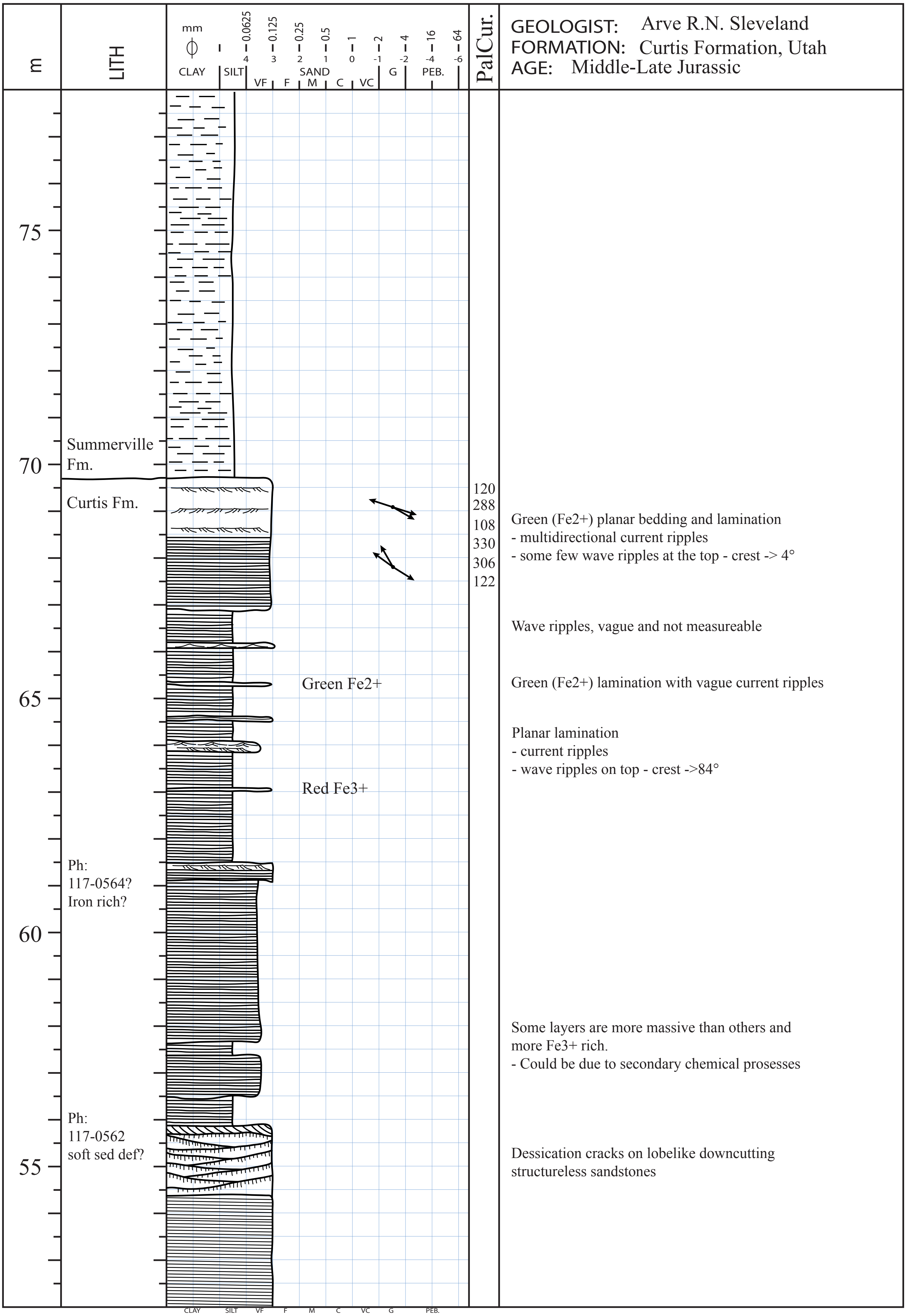
Dunes in tidal reactivation surfaces

Wavy bedding

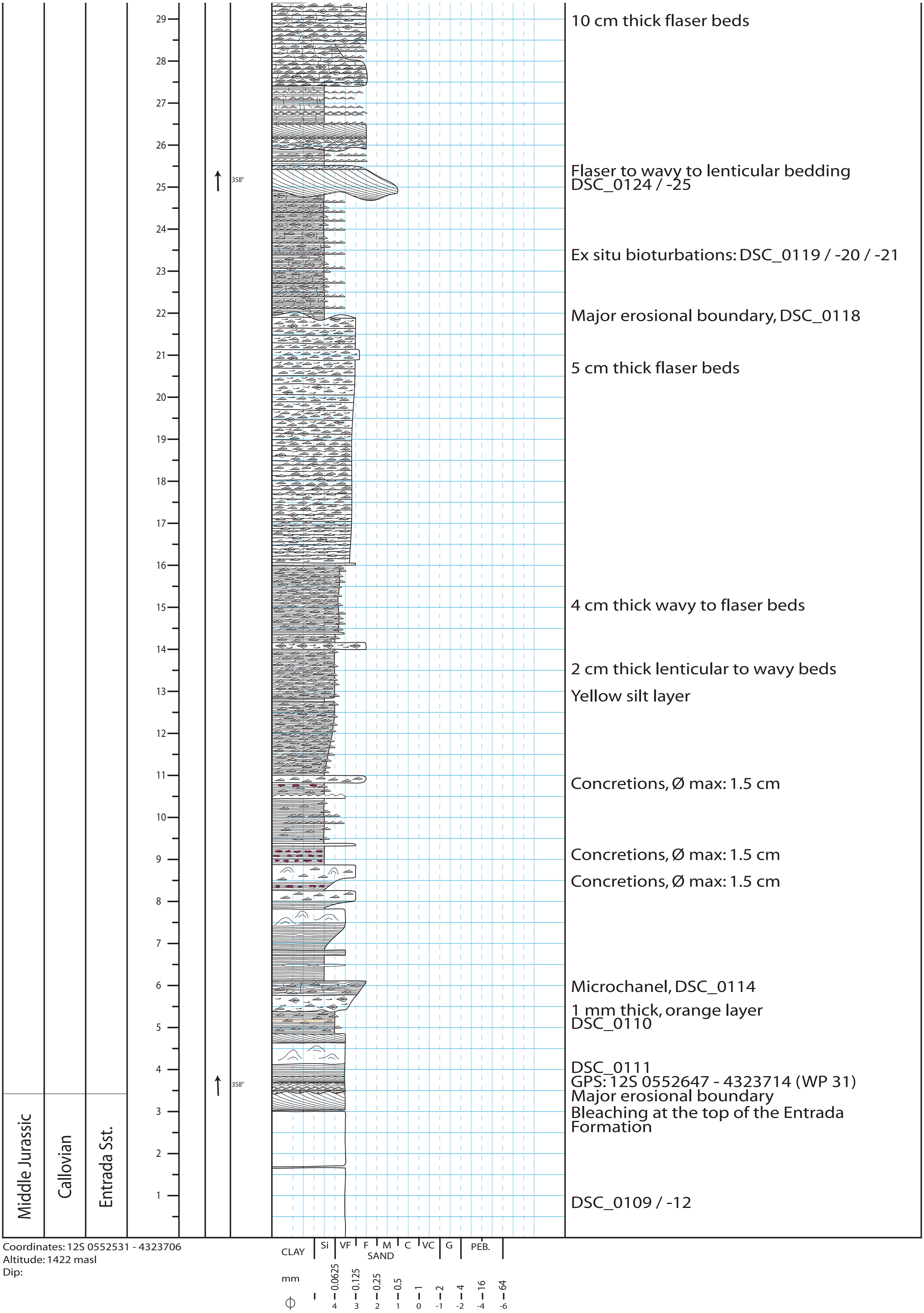
Log 6 - Dry Mesa

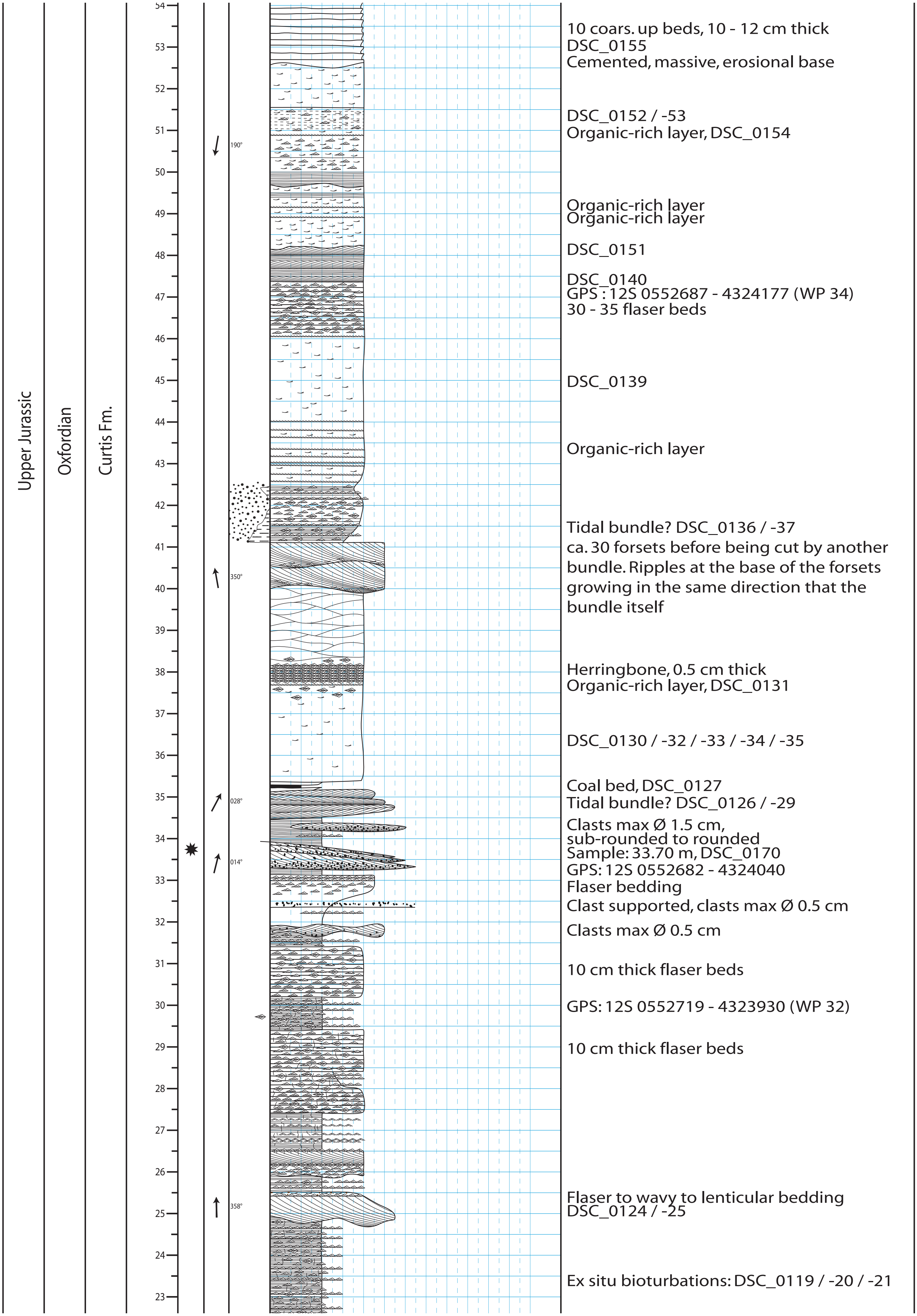
LOCALITY 39°10'28.8"N 110°27'48.2"W SHEET 3 OF 3 DATE: 2.7.15 SCALE: 1:100

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic

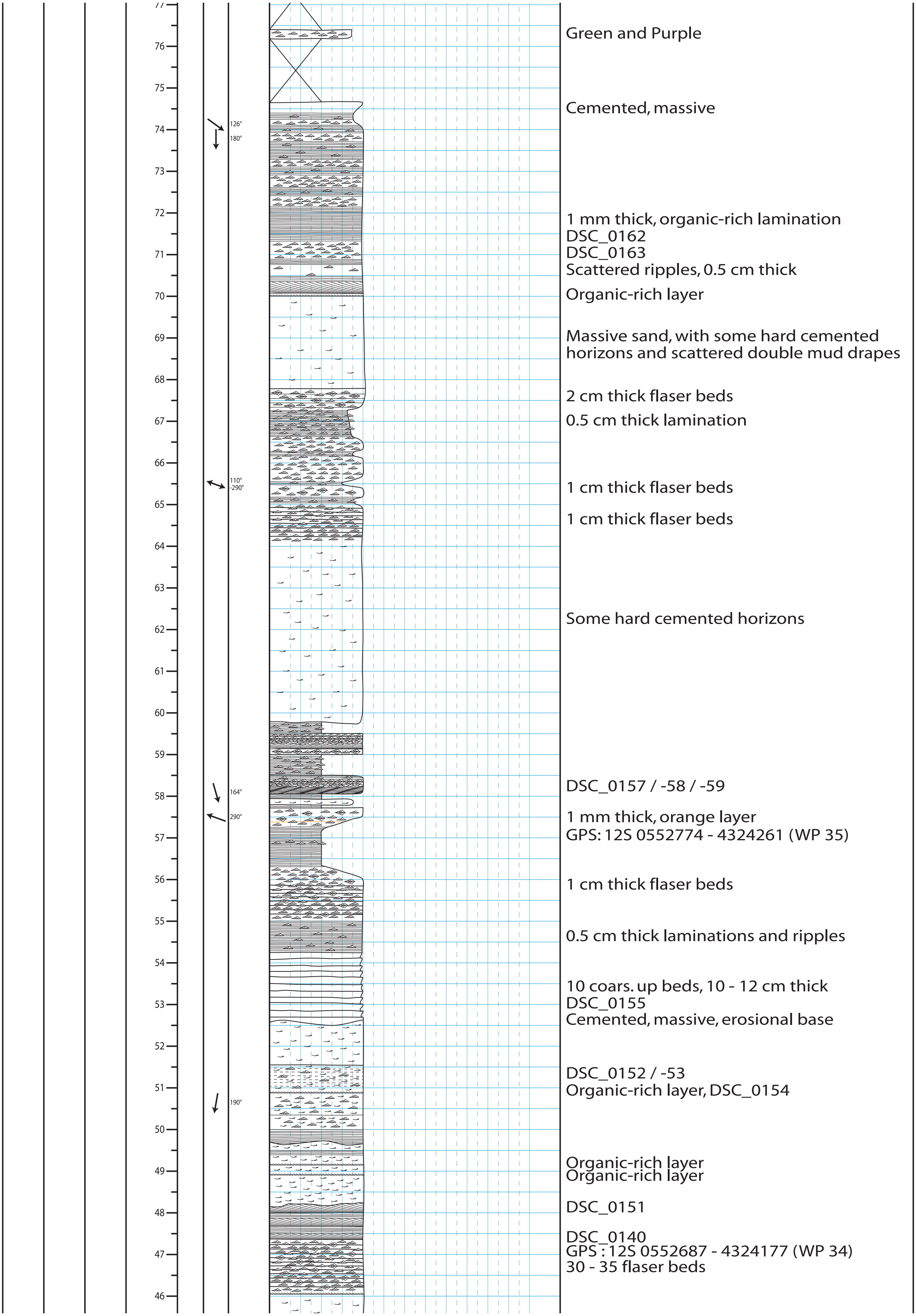


Appendix H - Log from Smith's Cabin North


Middle Jurassic
Callovian
Entrada Sst.
10 cm thick flaser beds
Flaser to wavy to lenticular bedding
DSC_0124 / -25
Ex situ bioturbations: DSC_0119 / -20 / -21
Major erosional boundary, DSC_0118
5 cm thick flaser beds
4 cm thick wavy to flaser beds
2 cm thick lenticular to wavy beds
Yellow silt layer
Concretions, Ø max: 1.5 cm
Concretions, Ø max: 1.5 cm
Concretions, Ø max: 1.5 cm
Microchanel, DSC_0114
1 mm thick, orange layer
DSC_0110
DSC_0111
GPS: 12S 0552647 - 4323714 (WP 31)
Major erosional boundary
Bleaching at the top of the Entrada
Formation
DSC_0109 / -12
358°
358°
Coordinates: 12S 0552531 - 4323706
Altitude: 1422 masl
Dip:
CLAY
Si
VF
F
M
C
VC
G
PEB.
SAND
mm
0.0625
0.125
0.25
0.5
1
2
4
16
64
ϕ
4
3
2
1
0
-1
-2
-4
-6



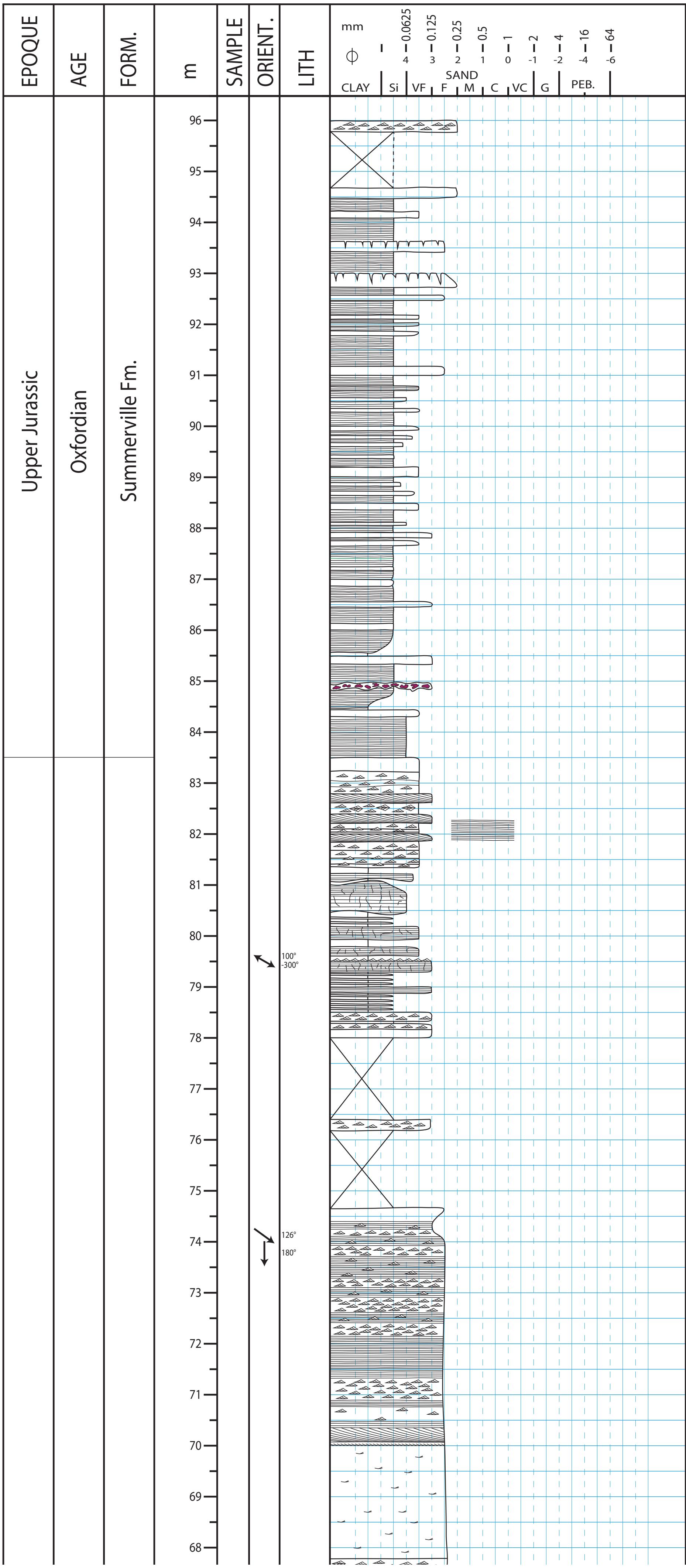
Upper Jurassic
Oxfordian
Curtis Fm.
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
190°
350°
028°
014°
358°
10 coars. up beds, 10 - 12 cm thick
DSC_0155
Cemented, massive, erosional base
DSC_0152 / -53
Organic-rich layer, DSC_0154
Organic-rich layer
Organic-rich layer
DSC_0151
DSC_0140
GPS : 12S 0552687 - 4324177 (WP 34)
30 - 35 flaser beds
DSC_0139
Organic-rich layer
Tidal bundle? DSC_0136 / -37
ca. 30 forsets before being cut by another bundle. Ripples at the base of the forsets growing in the same direction that the bundle itself
Herringbone, 0.5 cm thick
Organic-rich layer, DSC_0131
DSC_0130 / -32 / -33 / -34 / -35
Coal bed, DSC_0127
Tidal bundle? DSC_0126 / -29
Clasts max Ø 1.5 cm,
sub-rounded to rounded
Sample: 33.70 m, DSC_0170
GPS: 12S 0552682 - 4324040
Flaser bedding
Clast supported, clasts max Ø 0.5 cm
Clasts max Ø 0.5 cm
10 cm thick flaser beds
GPS: 12S 0552719 - 4323930 (WP 32)
10 cm thick flaser beds
Flaser to wavy to lenticular bedding
DSC_0124 / -25
Ex situ bioturbations: DSC_0119 / -20 / -21


77
76
75
74
73
72
71
70
69
68
67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
126°
180°
110°
-290°
164°
290°
190°
Green and Purple
Cemented, massive
1 mm thick, organic-rich lamination
DSC_0162
DSC_0163
Scattered ripples, 0.5 cm thick
Organic-rich layer
Massive sand, with some hard cemented horizons and scattered double mud drapes
2 cm thick flaser beds
0.5 cm thick lamination
1 cm thick flaser beds
1 cm thick flaser beds
Some hard cemented horizons
DSC_0157 / -58 / -59
1 mm thick, orange layer
GPS: 12S 0552774 - 4324261 (WP 35)
1 cm thick flaser beds
0.5 cm thick laminations and ripples
10 coars. up beds, 10 - 12 cm thick
DSC_0155
Cemented, massive, erosional base
DSC_0152 / -53
Organic-rich layer, DSC_0154
Organic-rich layer
Organic-rich layer
DSC_0151
DSC_0140
GPS : 12S 0552687 - 4324177 (WP 34)
30 - 35 flaser beds

LOCALITY: SMITH'S CABIN NORTH

DATE: 22nd-23rd Sept 2015

GEOLOGISTS: V. ZUCHUAT
A. SLEVELAND
WEATHER: SUNNY AND DRY



Grey, with 1-2 cm thick ripples
GPS: 12S 0553101 - 4324423 (WP 37)
1433 masl

Mud Crack, DSC_0169

Mud Crack, DSC_0169

All the massive layers are cemented
DSC_0167 / -68

2 cm thick green horizon

Concreation layer

Homogeneous thickness: 1-2 cm
Thickening up, mm to cm thick laminations

Thickening up, mm to cm thick laminations

11 very fine grained sandstone beds,
1-2 cm thick
9 grey siltstone beds, alternating with
purple mudstone
16 grey siltstone beds, alternating with
purple mudstone, DSC_162
Purple Siltstone
Cemented, massive

Green and Purple

Cemented, massive

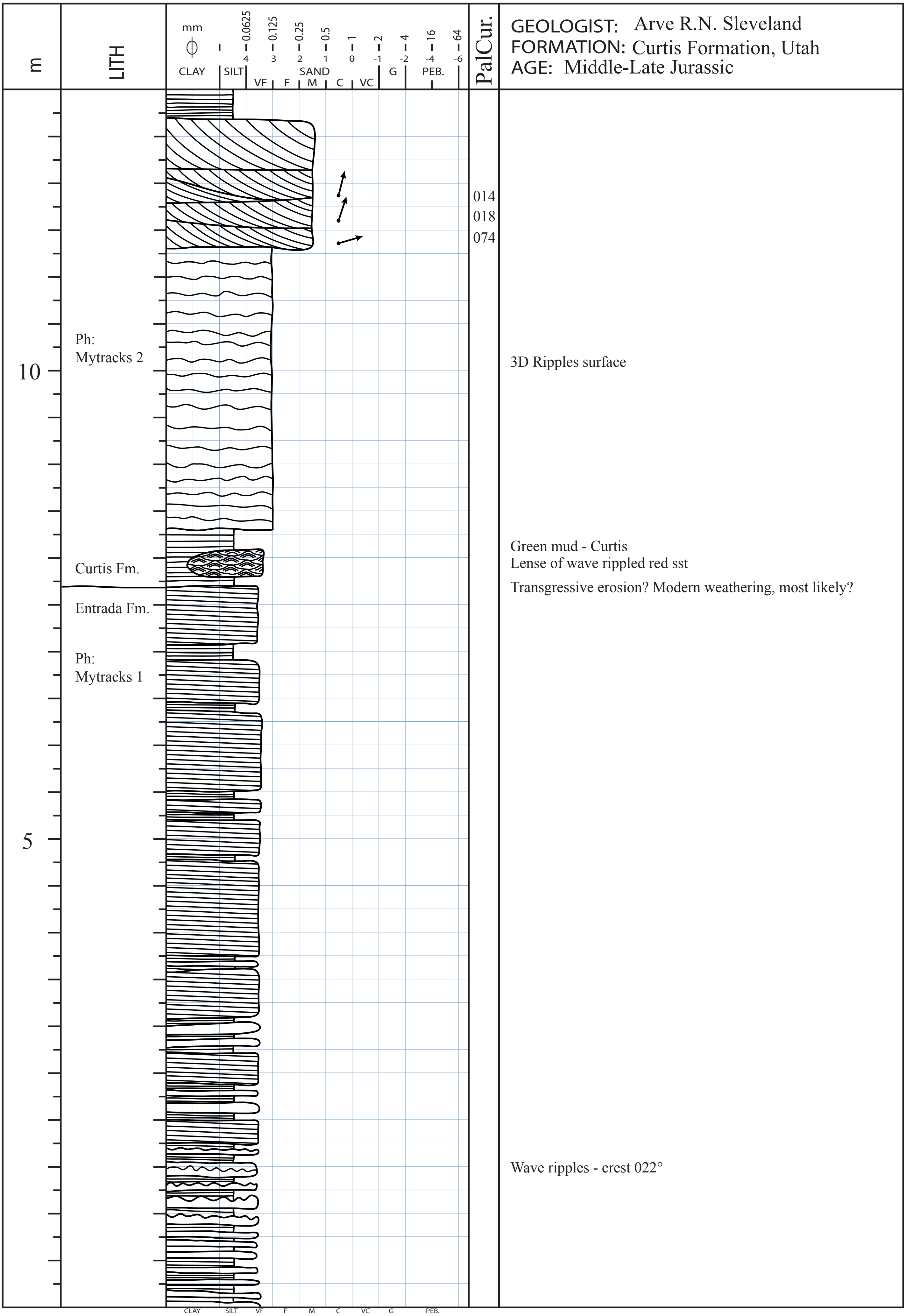
1 mm thick, organic-rich lamination
DSC_0162
DSC_0163
Scattered ripples, 0.5 cm thick
Organic-rich layer

Massive sand, with some hard cemented
horizons and scattered double mud drapes

Appendix I - Log from Smith's Cabin South

Log 8 - Smith's Cabin South

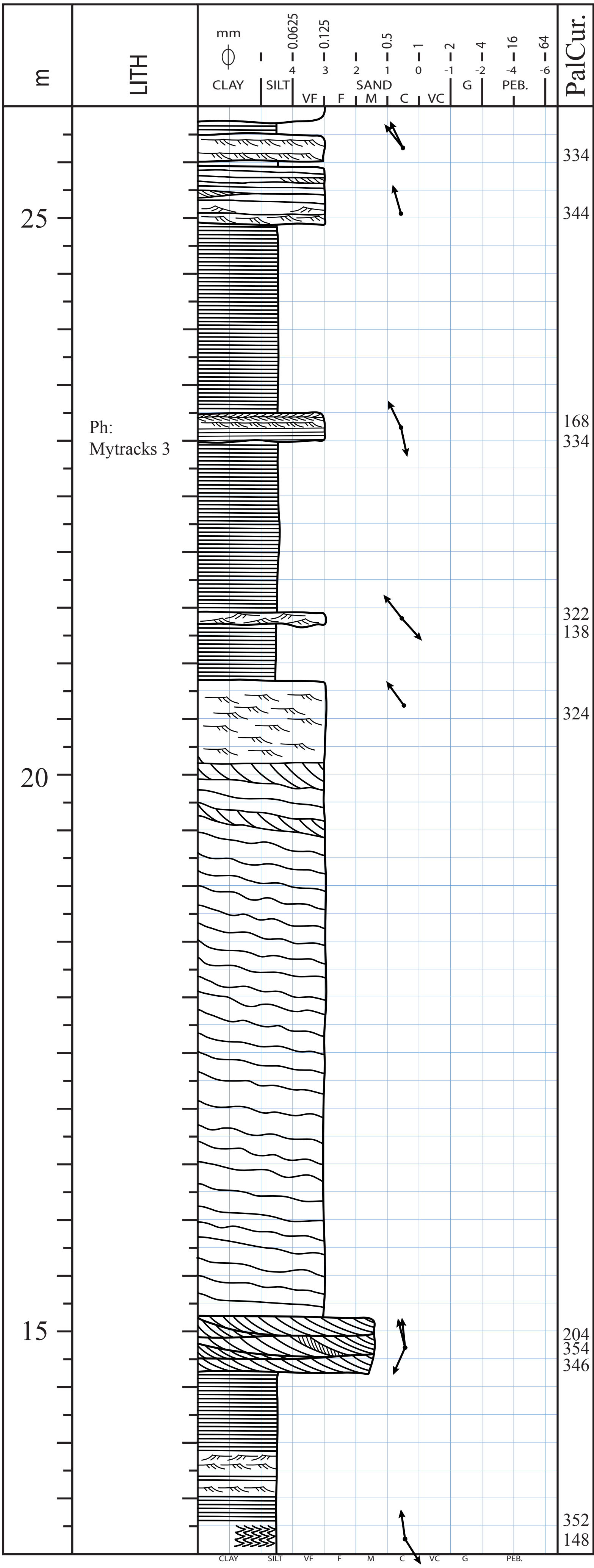
LOCALITY 39°01'24.5"N 110°22'52.4"W SHEET 1 OF 5 DATE: 3.7.15 SCALE: 1:50



Log 8 - Smith’s Cabin South

LOCALITY 39°01'24.5"N 110°22'52.4"W SHEET 2 OF 5 DATE: 3.7.15 SCALE: 1:50

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



Herringbone structures for single erosive current ripples

Herringbone structures and planar parallell lamination

Erosive current ripples - troughy

Layer dip - 12° strike 318°

Planar bedding with current ripples on a weathered surface

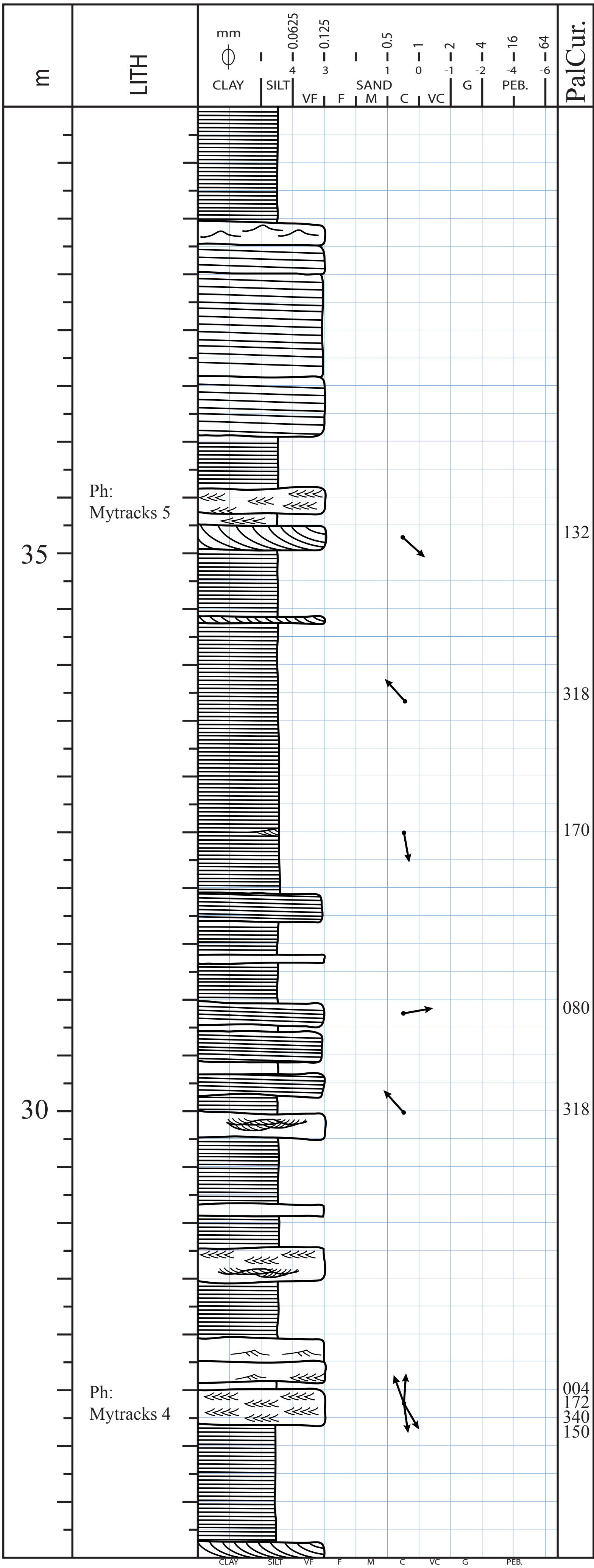
Wavy draped beds, quite massive section, but evidently some mud lenses in wave ripple troughs.

Herringbone structures in silty mud - sampled

Log 8 - Smith's Cabin South

LOCALITY 39°01'24.5"N 110°22'52.4"W SHEET 3 OF 5 DATE: 3.7.15 SCALE: 1:50

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic



Wavy ripple shapes - crest 074°

Quite massive sandbeds with vague indication of

low angle cross stratification

Flakey silt with some scattered ripples

More compact but still laminar and breaks easily

Tiny (2-3mm tall) current ripple

Some low angle cross lamination in sand
Easily breakable flakey silt in between

Planar lamination
2D measurement
Troughy erosive current ripples

Herringbone and troughy erosive current ripples

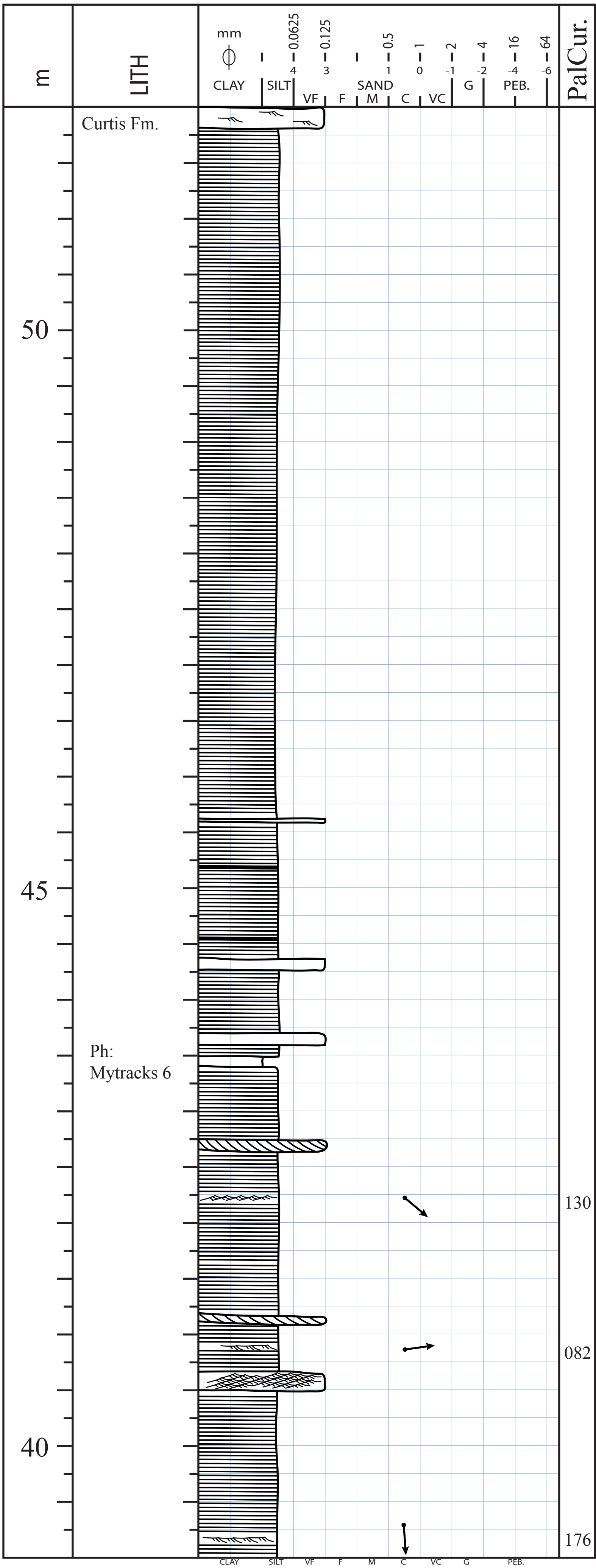
Some vague current ripples

Low angle to planar lamination with some small current ripples

Log 8 - Smith's Cabin South

LOCALITY 39°01'24.5"N 110°22'52.4"W SHEET 4 OF 5 DATE: 3.7.15 SCALE: 1:50

GEOLOGIST: Arve R.N. Sleveland
FORMATION: Curtis Formation, Utah
AGE: Middle-Late Jurassic

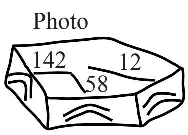


Some vague current ripples

Mostly planar lamination with some rippled rocks - not in situ!

Organic rich layer - paleosoil?

3D Ripples

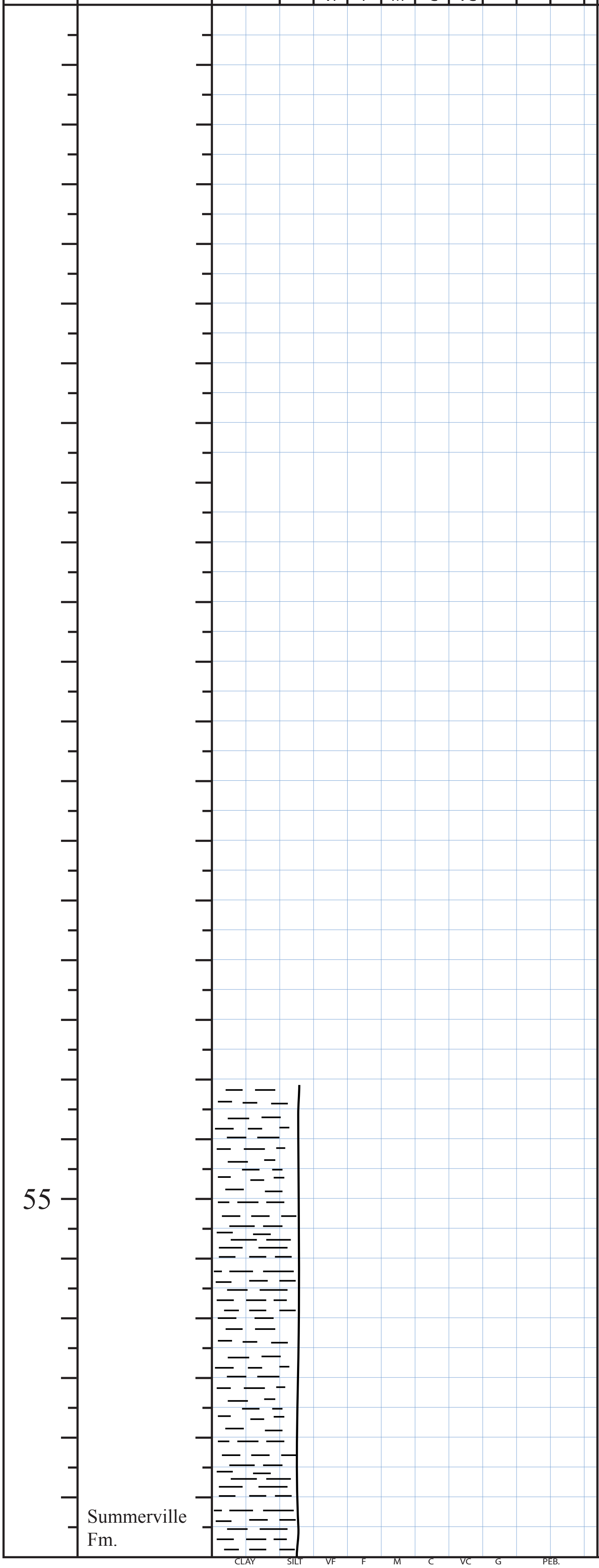


Climbing ripples

Log 8 - Smith's Cabin South

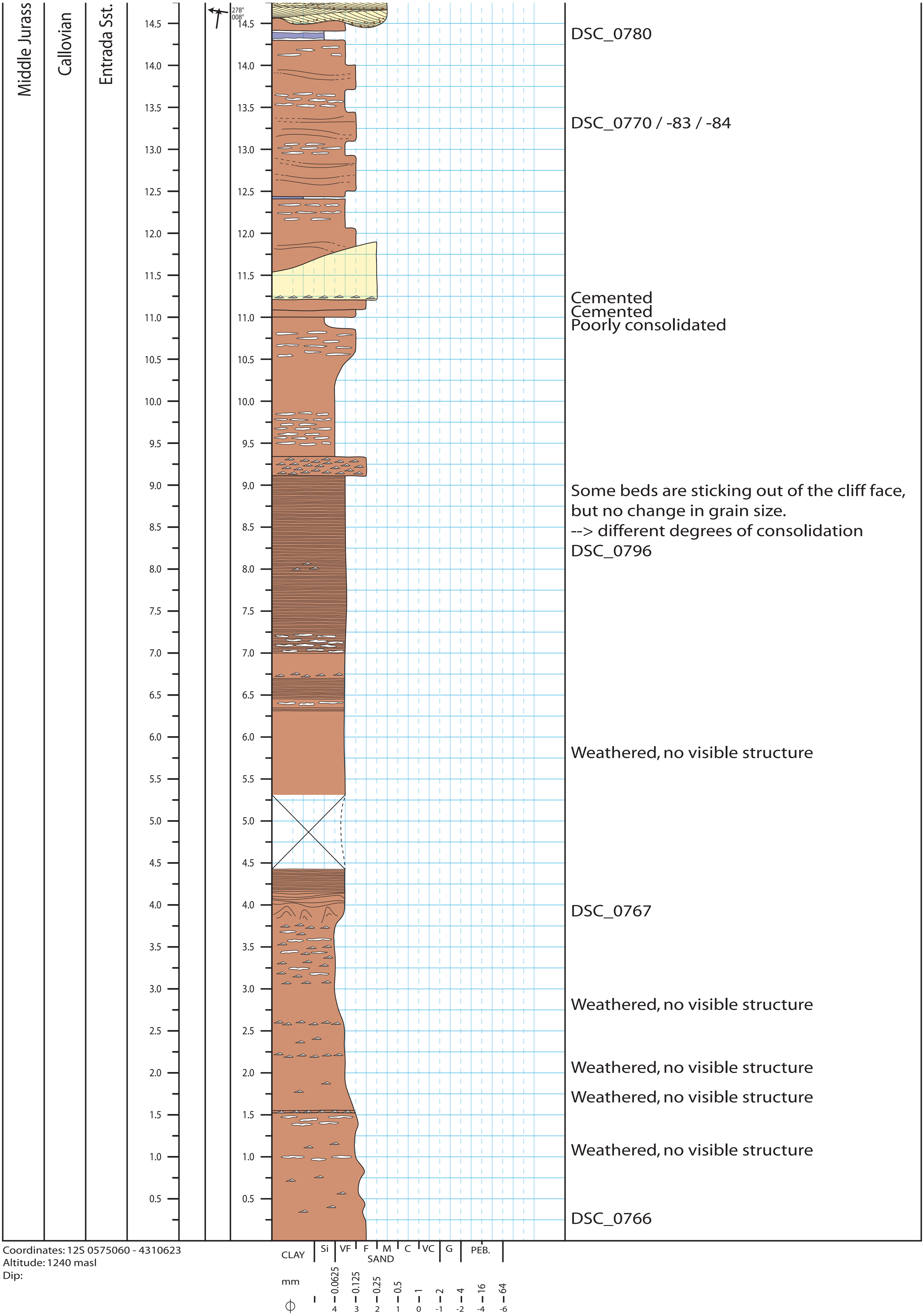
LOCALITY 39°01'24.5"N 110°22'52.4"W SHEET 5 OF 5 DATE: 3.7.15 SCALE: 1:50

m	LITH	mm / ϕ: 0.0625 (4), 0.125 (3), 0.5 (1), 1 (0), 2 (-1), 4 (-2), 16 (-4), 64 (-6) — CLAY, SILT, SAND (VF, F, M, C, VC), G, PEB.	PalCur.	GEOLOGIST: Arve R.N. Sleveland FORMATION: Curtis Formation, Utah AGE: Middle-Late Jurassic

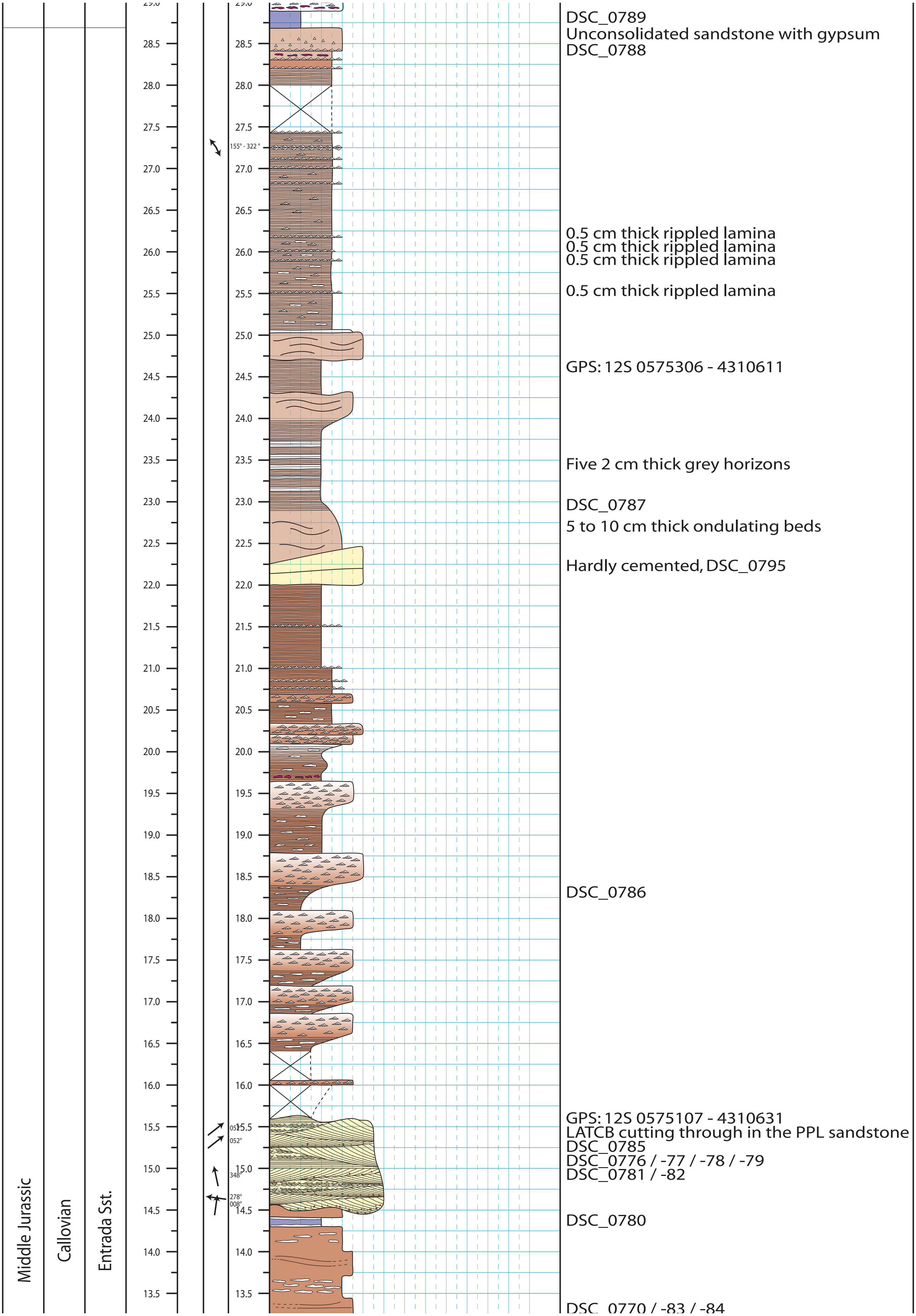


Pink silty mud

Appendix J - Log from Crystal Geyser

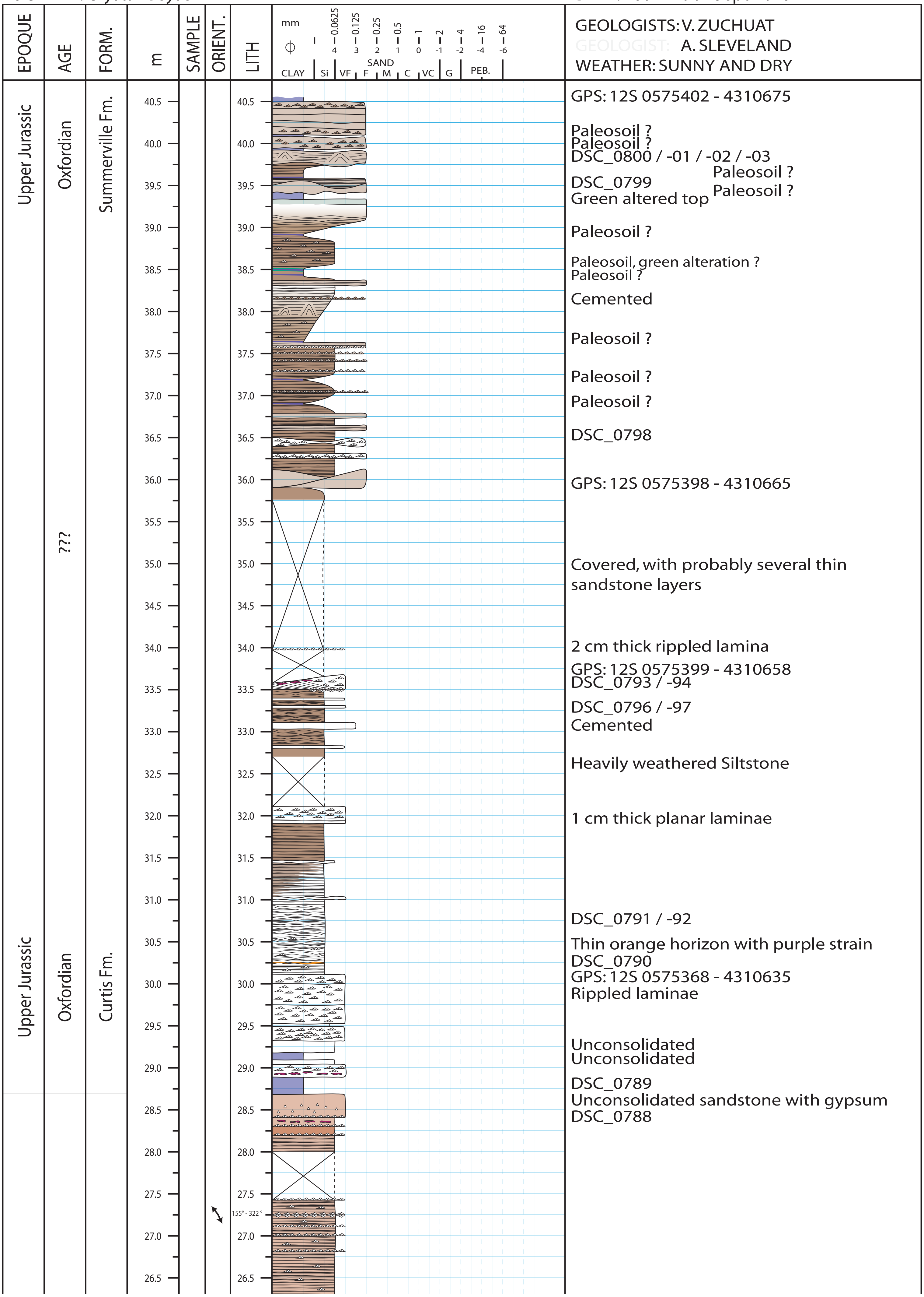


Middle Jurass
Callovian
Entrada Sst.
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
278°
008°
DSC_0780
DSC_0770 / -83 / -84
Cemented
Cemented
Poorly consolidated
Some beds are sticking out of the cliff face, but no change in grain size.
--> different degrees of consolidation
DSC_0796
Weathered, no visible structure
DSC_0767
Weathered, no visible structure
Weathered, no visible structure
Weathered, no visible structure
Weathered, no visible structure
DSC_0766
Coordinates: 12S 0575060 - 4310623
Altitude: 1240 masl
Dip:
CLAY
Si
VF
F
M
C
VC
G
PEB.
SAND
mm
0.0625
0.125
0.25
0.5
1
2
4
16
64
ϕ
4
3
2
1
0
-1
-2
-4
-6


Middle Jurassic
Callovian
Entrada Sst.
155° - 322°
052°
348°
278°
008°
DSC_0789
Unconsolidated sandstone with gypsum
DSC_0788
0.5 cm thick rippled lamina
0.5 cm thick rippled lamina
0.5 cm thick rippled lamina
0.5 cm thick rippled lamina
GPS: 12S 0575306 - 4310611
Five 2 cm thick grey horizons
DSC_0787
5 to 10 cm thick ondulating beds
Hardly cemented, DSC_0795
DSC_0786
GPS: 12S 0575107 - 4310631
LATCB cutting through in the PPL sandstone
DSC_0785
DSC_0776 / -77 / -78 / -79
DSC_0781 / -82
DSC_0780
DSC_0770 / -83 / -84

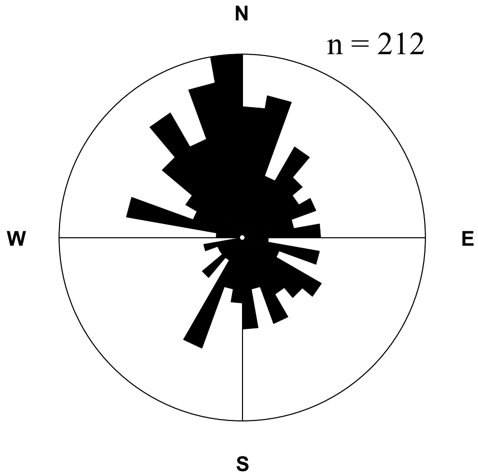
LOCALITY: Crystal Geyser

DATE: 18th - 19th Sept 2015

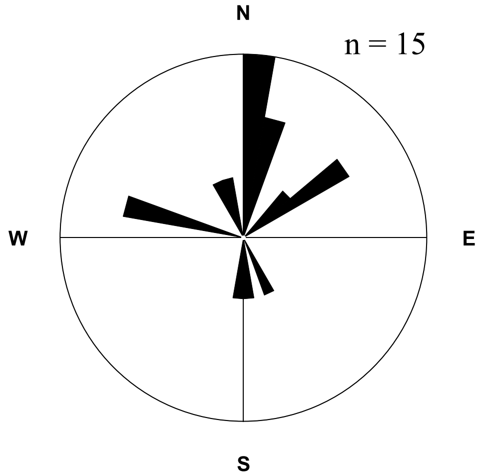


Appendix K - Paleocurrent rose plot diagrams

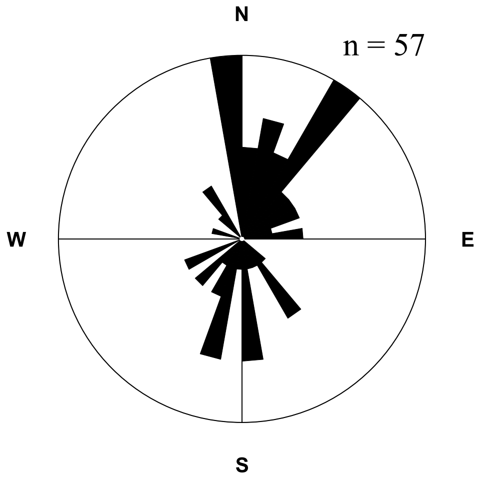
Bulk



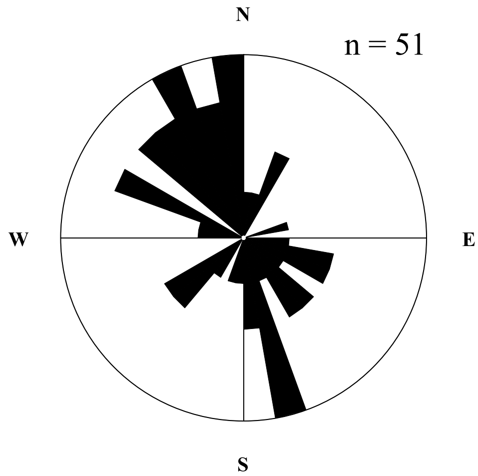
FA 2 bulk



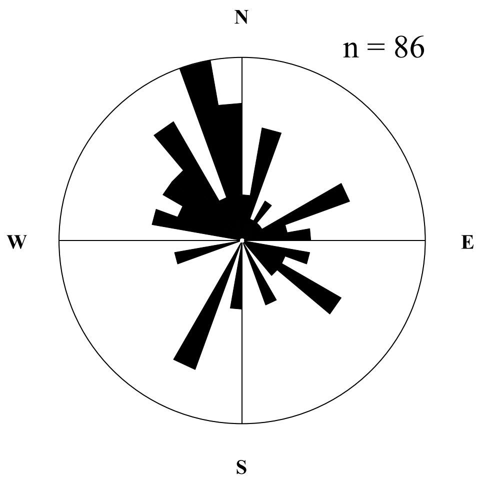
FA 3 bulk



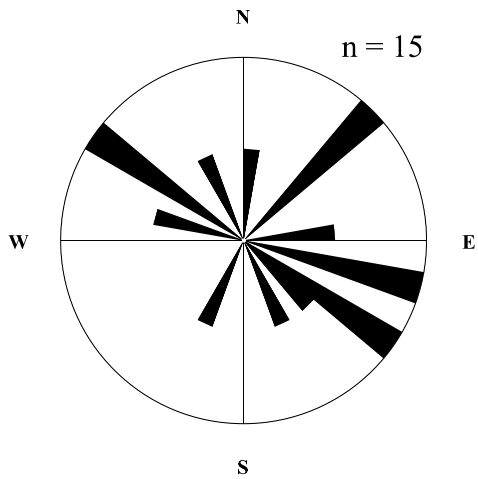
FA 4a bulk



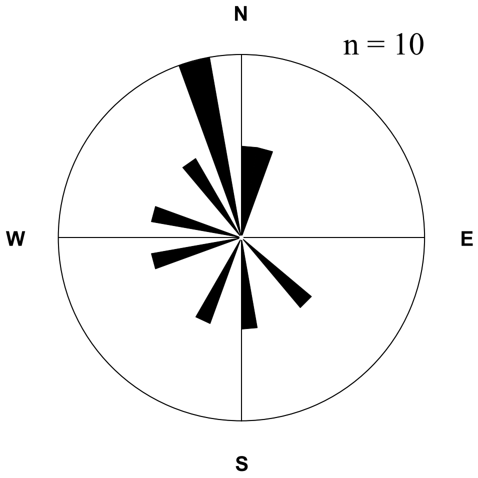
FA 4b bulk



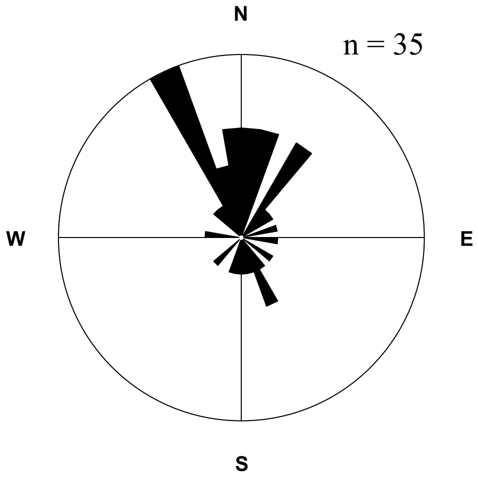
FA 5 bulk



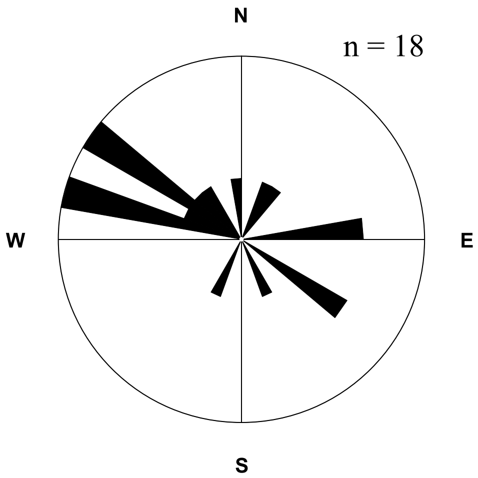
Log 1 - Stove Gulch East



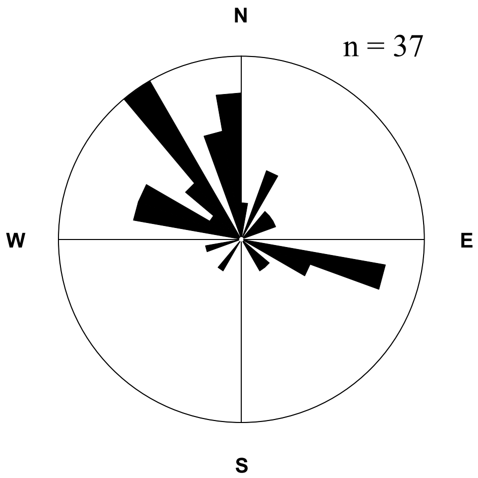
Log 2 - Stove Gulch West



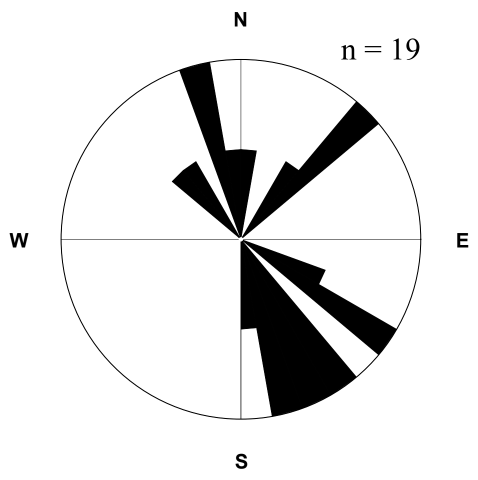
Log 3 - Sulphur Canyon



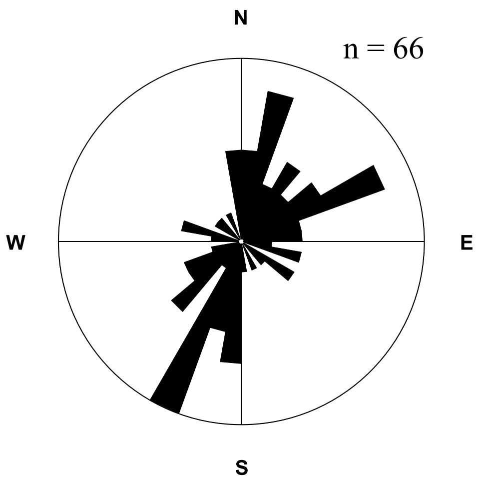
Log 4 - Humbug Flats East



Log 5 - Neversweat wash



Log 6 - Dry Mesa



Log 8 - Smith's Cabin South