FACIES DESCRIPTION AND INTERPRETATION OF THE UPPER LOWER HICKORY SANDSTONE, RILEY FORMATION, CENTRAL TEXAS

A Thesis

by

TIMOTHY DALE COOK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2009

Major Subject: Geology

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Approved by:

Co-Chairs of Committee,	Rick Giardino Arnold Bouma
Committee Member,	Walter Ayers
Head of Department,	Andreas Kronenberg

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ABSTRACT

Facies Description and Interpretation of the Upper Lower Hickory Sandstone, Riley Formation, Central Texas. (May 2009)

Timothy Dale Cook, B.S., Marshall University

Co-Chairs of Advisory Committee: Dr. Rick Giardino
Dr. Arnold Bouma

Present models suggest that fluvial and marine depositional patterns were distinct from modern patterns prior to the appearance of land plants. Although these models are likely correct, problems exist when one attempts to distinguish between fluvial and shallow marine deposits in pre-Silurian strata, making it difficult to accurately determine depositional patterns. The lack of land plants and scarcity of body and trace fossils, especially in Precambrian and early Cambrian strata, make identification difficult. Based on core data and limited outcrops, the Lower Hickory Sandstone, a late Cambrian sandstone, has been interpreted to progress from fluvial to shallow marine. These data have allowed the development of an overall depositional model, but minimal detail of facies changes is available. Based on the limited data, both deltaic and estuarine models have been suggested for the Lower Hickory.

Mining of the Lower Hickory for frac sand has created highwalls in the CarmeuseNA Mine, which provides an opportunity to study facies changes at this site. The CarmeuseNA Mine, located in McCulloch County, Texas, has exposed the formation along ~500 m long and 20 m-high faces, respectively. Because of limited exposure, only the south and west walls, as well as part of the east wall, could be examined. Digital photographs of the faces were mosaiced using standard photogrammetrical practices to produce visual representation of the highwalls. Bedding geometry was then mapped on the digital images to facilitate a detailed interpretation of the depositional process. Core and well data were used to map Hickory thickness to produce an isopach map.

Four primary facies were observed in the quarry, dominated by small-scale and large-scale cross-bedding. Paleocurrents are generally unidirectional to the south-southeast indicating a braided fluvial origin, but rarely opposing directions are seen. Bioturbation is rare low in the section, but increases upwards. Together with the rare herringbone cross-bedding, clay drapes, and bioturbation, a tidal influence is strongly suggested. The model suggested is a braided stream setting influenced and reworked by tides. A braided-delta fed by braided streams guided by a ridge and swale-dominated setting, which served as the sediment supply for the delta, is proposed.

ACKNOWLEDGEMENTS

I would like to thank my committee co-chairs, Dr. Bouma and Dr. Giardino for their work and patience with me. I would also like to thank my other committee member, Dr. Ayers. I have learned a lot from all of you during this project. Also, I am grateful to former committee members Brann Johnson and Brian Willis for their help. Dr. Johnson, thank you for the lessons and the housing those times in the field.

My family has encouraged me and prayed for me, and I am greatly thankful for them. To all my friends at church who have kept me going, thank you as well.

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INTRODUCTION

Interpretation of sedimentary facies formed during the Proterozoic and early Paleozoic periods has proven to be problematic. Proper identification of terrestrial, shoreline and shelf deposits for this time is often confusing. The lack of land plants and the scarcity of bioturbation make a confident diagnosis of the environment of deposition challenging. As a result, there are relatively few reports of obvious facies transitions between terrestrial and marine deposits. Regressions and transgressions of shorelines, therefore, are difficult to identify. In part, this reflects the absence of diagnostic features in terrestrial facies like well-developed paleosols with root casts or coal. More restricted patterns of bioturbation within shoreline and shelf deposits hinder the distinction of deposits formed in brackish and open marine environments. Difficulties in distinguishing different depositional environments may also reflect significant contrasts between depositional processes that characterize these ancient and equivalent more recent Phanerozoic depositional environments (Eriksson et al., 1995).

Processes of flow and sediment transport in river, shoreline and shelf environments should be fundamentally similar through time, because hydrodynamic properties should remain constant. Based on modern arid climates, the lack of land plants most likely influenced rates of river discharge and the distribution of sediment loads (Miall, 1996). Landscape erosion following rains may have been more extensive

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This thesis follows the style of *Sedimentology*.

without the stabilizing influence of vegetation cover. Sediment resulting from this erosion would clog rivers with sediment, adding greatly to their load and causing a tendency towards braided systems. Physical weathering would be expected to predominate over chemical weathering, resulting in increased fluvial bed loads relative to suspended loads. Fluvial discharge may have been more flashy, channel courses less stable, and erosion and deposition within channels more ephemeral, at least at an active margin (MacNaughton et al., 1997; Sonderholm and Tirsgaard, 1998). Differences in water and sediment discharged from rivers may have influenced patterns of deposition along shorelines as well. Laterally unstable channel systems along coastlines and an abundance of shallow epicontinental seaways and epeiric seas during the earliest part of the Paleozoic may have resulted in shoreline successions that differ from those predicted from modern analogs.

This thesis intends to consider two primary points – 1. Previous work on the Lower Hickory has not agreed on an overall environment of deposition, and explanations have ranged from deltaic to estuarine and varying environments. A primary environment of deposition for the Lower Hickory will be a priority of this study. 2. Since pre-Silurian fluvial and marginal marine environments have proven challenging, this thesis will look at Hickory depositional environments in order to add to current knowledge about pre-Silurian sedimentology.

This study examines facies that comprise the upper lower part of the Middle to Upper Cambrian Hickory Sandstone. The Hickory is part of a several hundred meter-thick transgressive succession exposed in several counties (McCulloch, Mason, Llano, etc) in the hill country of central Texas, U.S.A. (Barnes and Bell, 1977; Kim, 1995; Krause, 1996; Wilson, 2001). The particular field site is the CarmeuseNA quarry in McCulloch County. Past studies of the Hickory Sandstone have been based largely on cores and regional studies of isolated outcrops. This study builds on these previous studies by constructing detailed facies maps of the walls of a large quarry. Bedding diagrams document the hierarchy of stratal variations and internal facies trends to interpret processes of deposition and depositional environments. The goal of this thesis is to add to current knowledge about the deposition history of the upper Lower Hickory Sandstone. This knowledge should facilitate a reassessment of the criteria used for recognizing the depositional setting of early Paleozoic sedimentary strata. It may also aid in the testing of ideas that depositional patterns before the emergence of land plants may have been different than those depicted in facies models developed from the study of modern analogs. The Hickory Sandstone is an important regional aquifer and has been the subject of studies defining sedimentological and structural heterogeneities to subsurface fluid flow (Randolph, 1991; Kim, 1995; B. Johnson, 2005, Per. Comm.).

The composition of the thesis is as follows: 1. An introduction to general pre-Silurian sedimentology, 2. Previous work on the Hickory Sandstone, 3. Methodology, 4. Discussion, 5. Results and Conclusion. Works Cited and Appendices follow the main body of the thesis.

OVERVIEW OF WORLDWIDE PRE-SILURIAN SEDIMENTOLOGY

Studies undertaken worldwide show that interpretations of depositional environments from pre-Silurian strata have proven difficult because of the lack of land plants during this time. Erosion rates would probably have been extremely high because roots would not be available to provide stability. This would lead to a high production of coarse-grained sediment available for transport by fluvial systems (Eriksson et al., 1998). Fines may also have been easily removed by winds, further increasing the bedload component of fluvial systems relative to suspended loads (MacNaughton et al., 1997). The lack of plant roots to stabilize landscapes during runoff would have allowed accelerated erosion of sediment. As a result, stream banks would be unstable and could cave in (Eriksson et al., 1998). This resulting erosion-caused channel bank instability would lead to the development of wide channel belts, which may have avulsed frequently across floodplains (Eriksson et al, 1998). Flashy discharge may have been much more common because no plant roots existed to inhibit bank erosion (MacNaughton et al., 1997; Sonderholm and Tirsgaard, 1998). These factors would lead to the formation of fluvial systems with abundant bedload and wide channels (Eriksson et al, 1998).

Based on these ideas about sediment loads and river channel instability, most pre-Silurian streams are inferred to have had braided-patterns. Gray and Boucot (1977) suggested there was an increase in meandering streams during the Silurian. Large braided systems were probably common in continental cratons (Eriksson et al, 1998).

The Dwaalheuwei and Droogedal Formations in South Africa and the Canadian Shield, respectively, were interpreted to be the deposits of large braid-plains, up to 150 km (93 miles) wide, parallel to transport direction (Eriksson et al., 1998). Amireh et al. (1994) interpreted Cambrian deposits in Jordan to be braid-plain deposits with adjacent tidal flat deposits. Bose and Chakraborty (1994) suggested that the wide range of paleocurrent directions within large tabular sandstone bodies of the Paleozoic Rewa Formation in India indicated they formed in braided-river systems. Cotter (1978) suggested that all lower Paleozoic fluvial deposits in Pennsylvania recorded braided river deposits. He considered most of the younger (post-land plant) fluvial deposits to have formed in meandering river systems.

Tirsgaard and Oxnevad (1998) discussed deposits of Precambrian semi-perennial streams that seemed to have a more constant discharge and a higher water table than younger analogs (Eriksson et al., 1998). Although braided streams are normally reported to have irregular discharge, this irregular discharge is has not been observed in all cases (Jackson, 1978; Beukes and Cairncross, 1991). Large-scale trough cross-beds overlain by stacks of large-scale planar cross-beds are typical of sandy braided rivers, representing dune and transverse bar migration (Beukes and Cairncross, 1991). Sheet sands are also often seen as braided-river deposits (MacNaughton et al, 1997).

Although a limited number of investigators have interpreted meandering facies from pre-Silurian deposits (Sweet, 1988), the criteria used to distinguish these facies from braided types are not definitive (Eriksson et al, 1998). Lateral accretion surfaces observed locally in some of these deposits lack mud drapes and do not fine upwards like in deposits observed in modern meandering river systems (Sweet, 1988; MacNaughton et al, 1997).

Precambrian and early Paleozoic deltaic deposits have been recognized, but are more difficult to define than younger examples. The generally coarse grain sizes and a lack of plant debris and diagnostic delta top coals make identification questionable (Eriksson et al., 1998). Quartz arenites and subarkoses comprise delta front and delta plain deposits (Eriksson et al., 1998). Coarsening-upward sequences from fine-grained prodelta to delta front and delta plain deposits have been observed in Precambrian strata (MacNaughton et al., 1997; Eriksson et al., 1998). McNaughton et al. (1997) found that channel sandstone bodies are the primary preserved component of delta plain deposits. Some point bar-like deposits have been suggested to be a result of tidal processes acting at river mouths. Deltas with macrotidal ranges often form “distal, shore-perpendicular sand bars within the delta front” (Eriksson et al., 1998).

Large braided river systems caused by the high erosion rate and large amount of sediment formed large-scale braid-delta deposits where they flowed into standing bodies of water (Els, 1998; Eriksson et al., 1998). Braided-river deltas are expected where braided fluvial systems emptied directly into a basin (Vos and Eriksson, 1977; Schreiber and Eriksson, 1992). Because braided river mouths can easily shift laterally along the coast, well developed delta lobes and bird’s foot type delta depositional patterns are expected to be rare (MacNaughton et al., 1997). Point-source deltas would be expected to predominate in pre-Silurian deltaic environments. To the extent that huge braid-plains characterized early Paleozoic river systems, the river mouths may have constantly shifted so rapidly that there was inadequate time to develop a delta (Beukes and Cairncross, 1991). For this reason, shoreline deposits, including distinct deltas lobes, are not often preserved within these ancient successions. This absence of shoreline deposits can account for fluvial deposits that directly overlie offshore shallow marine shelf deposits. Soft sediment deformational features have been cited as evidence of prodelta deposition rather than more distal shelf deposits (MacNaughton et al., 1997; Eriksson et al., 1998). Eriksson et al. (1998) suggested that Precambrian delta deposits are unusually thick compared with younger examples, often extending vertically for several hundred meters. These unusual thicknesses may be caused partly by large sediment supply. Adequate accommodation space and/or sea level rise would also be necessary.

The problem of accurately identifying and understanding ancient shelf deposits is more difficult than merely distinguishing fluvial, deltaic, and estuarine deposits. The epeiric seas and shallow Phanerozoic seaways that make up much of the record have no adequate modern-day counterparts (Eriksson et al., 1998). Epeiric seas were likely less than 200 m in depth, which would have "dissipated long-period swells at epeiric sea margins" (Friedman et al., 1992; Eriksson et al., 1998). Tides may have played a more important role because the height of tides may increase as they close in on a wide, low-angle shelf setting (Klein, 1982; Pratt and James, 1986; Eriksson et al., 1998).

Distinguishing early Paleozoic terrestrial and shallow marine (especially inner shelf) deposits can be difficult because of the lack of fossils and bioturbation. Shelf deposit processes seem to be similar to those of more recent origin (Eriksson et al., 1998). Thick beds of mature sandstone, especially quartz arenites, are common in Pre-

Silurian deposits and are often difficult to interpret. A dominance of unimodal cross-bedding is cited as the best way to distinguish fluvial from marine deposits (Eriksson et al., 1998). Hummocky cross-bedding also indicates almost exclusively a marine (rarely lacustrine) environment. Bose and Chakraborty (1994) and Banks (1973) found that fluvial deposits were poorly sorted and immature relative to marginal marine sandstones. Trace fossils suggest marine deposits (Banks, 1973). Seilacher (1967) used Skolithos and Cruziana to identify shallow marine deposits (Banks, 1973).

Shallow marine deposits can have wave- or storm-dominated sedimentary structures, as well as coarsening-upward sequences or thick sandstone beds that change very little in vertical succession (Eriksson et al., 1998). Hummocky cross-bedding is normally found in storm-dominated shelf deposits (Beukes and Cairncross, 1991). Large tabular sets of cross-bedding with drapes of shale may indicate a storm-, tide-, and wave-dominated clastic shoreline (Mueller et al., 2002). Shelf deposits seem to be similar to younger analogs (Eriksson et al., 1998). Beukes and Cairncross (1991) looked at a muddy shelf environment with finely laminated muds and lenticular to wavy laminated shale/siltstone. The abundance of Precambrian thick, homogenous sandstone or siltstone beds may indicate more regular storm activity and wider, flatter shelves than in Silurian to recent times (Tirsgaard and Sønderholm, 1997; Eriksson et al., 1998). High erosion rates from a barren landscape would provide copious amounts of sediment and would encourage the formation of wide, low-angle shelf settings (Eriksson et al., 1998).

Shoreface deposits usually consist of highly mature, well sorted sandstones with very little mud. Sedimentary structures are similar to younger deposits, but with less bioturbation. Thick beds of homogenous sandstone interpreted as shoreface deposits have also been found (Eriksson et al., 1998). These are considerably larger than modern equivalents and consist of planar and trough cross-beds (Eriksson et al., 1998). Cant and Hein (1986) and Soegaard and Eriksson (1989) have proposed that shelf circulation patterns may have been more uniform and persistent than on modern shelves (Eriksson et al., 1998). Foreshore deposits reflect high-energy shoaling wave conditions and are often reported as sandstone sequences. These deposits commonly show parallel lamination and locally graded beds with some cross-bedding and ripple marks. Barrier island and related wave-dominated deposits have rarely been identified (Eriksson et al., 1998).

Tide-dominated deposits consist of thick sandstone beds that may have herringbone and planar cross-bedding and bundled foresets (Eriksson et al., 1998). Sandwave deposits are the most common tidal deposit and often show large-scale planar crossbeds up to several meters thick (Eriksson et al., 1998). Within these sandwaves, trough cross-bedding and ripples are usually subordinate to large-scale planar cross-bedding. Numerous erosional surfaces are found within the trough cross-bedding and ripple marks. Herringbone cross-bedding and reactivation surfaces are common tidal signatures and indicate bidirectional flow. Trough cross-beds separated by low-angle planar surfaces have been found in tidal ridges (Johnson, 1977). These trough cross-beds have been interpreted to represent dune migration along the axes of tidal ridges, corresponding to storm and tidal currents (Eriksson et al., 1998).

The above paragraphs give an overview of fluvial, deltaic, and marginal marine environments from pre-land plant (pre-Silurian) times. Environments of deposition can be observed to be different in many ways from more recent analogues, mostly as a result of the absence of land plants, but also from differences in shelf and slope morphology and comparative lack of bioturbation. These differences in environment have made a proper interpretation of the Hickory Sandstone challenging and will be considered in this study.

HICKORY SANDSTONE

The Hickory Sandstone is a Late Middle to Upper Cambrian transgressive sand, primarily quartz arenite with some arkose. It outcrops only in the Llano region of central Texas. Exposures exist in a number of counties in the Hill Country across central Texas, including Llano, Mason, McCulloch, and San Saba counties. The Hickory Sandstone is the lowest member of the Riley Formation, overlying Precambrian basement rock including the Town Mountain Granite and the Spring Valley Gneiss. The Hickory is overlain by the Cap Mountain Limestone and the Lion Mountain Sandstone of the Riley Formation (Cloud et al., 1945; Krause, 1996). Together, the Hickory Sandstone, Cap Mountain Limestone, and Lion Mountain Sandstone make up the Riley Formation. A general stratigraphic column for the Moore Hollow Group is shown in Figure 1 and the stratigraphy for central Texas on a larger scale is shown in Figure 2. Figure 3 shows the general extent of the Hickory.

Krause (1996) considered the Riley Formation to represent one transgressive-regressive sequence. The Riley Formation is a member of the Moore Hollow Group. The Moore Hollow includes all Upper Cambrian and, locally, some Lower Ordovician rocks exposed in central Texas (Barnes and Bell, 1977). Deposition of the Moore Hollow occurred during late Sauk II time, approximately 514-510 Ma (Krause, 1996). Rocks in the Moore Hollow Group are exposed only in the Llano region, because doming has exposed the Precambrian and Cambrian rocks (Barnes and Bell, 1977).

During Hickory deposition, this area of the Texas Platform was located near the western tip of the Laurentian (proto-North American) craton (Krause, 1996). The

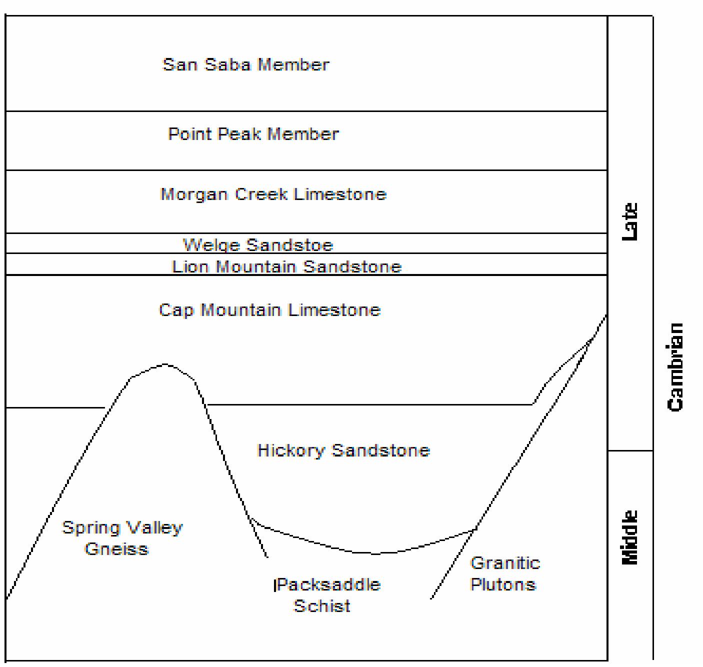
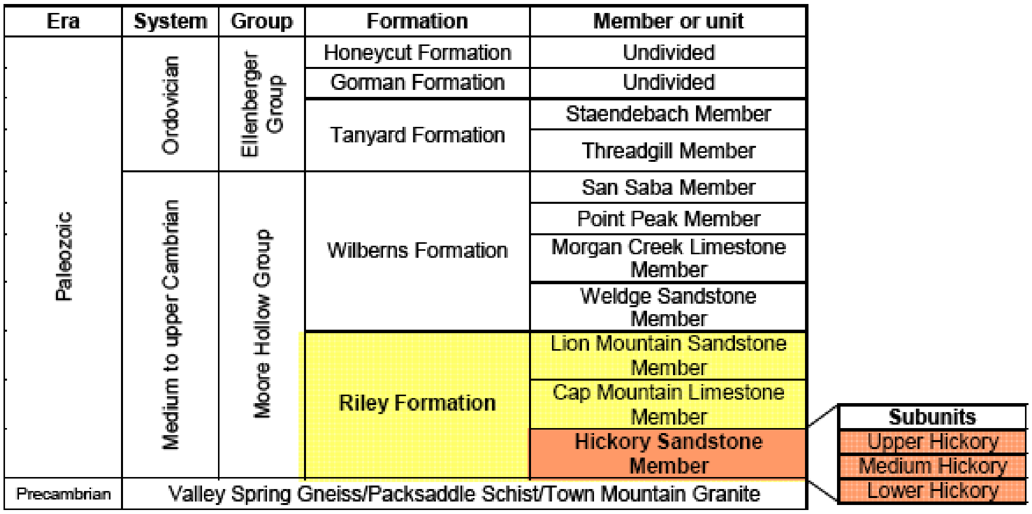


Figure 1. Moore Hollow Group. Modified from Krause (1996).



Era	System	Group	Formation	Member or unit
Paleozoic	Ordovician	Ellenberger Group	Honeycut Formation	Undivided
			Gorman Formation	Undivided
			Tanyard Formation	Staendebach Member
				Threadgill Member
	Medium to upper Cambrian	Moore Hollow Group	Wilberns Formation	San Saba Member
				Point Peak Member
				Morgan Creek Limestone Member
				Weldge Sandstone Member
			Riley Formation	Lion Mountain Sandstone Member
				Cap Mountain Limestone Member
				Hickory Sandstone Member
Precambrian	Valley Spring Gneiss/Packsaddle Schist/Town Mountain Granite			

Subunits
Upper Hickory
Medium Hickory
Lower Hickory

Figure 2. Stratigraphic Column for Central Texas (modified from Perez, 2007 and Krause, 1996).

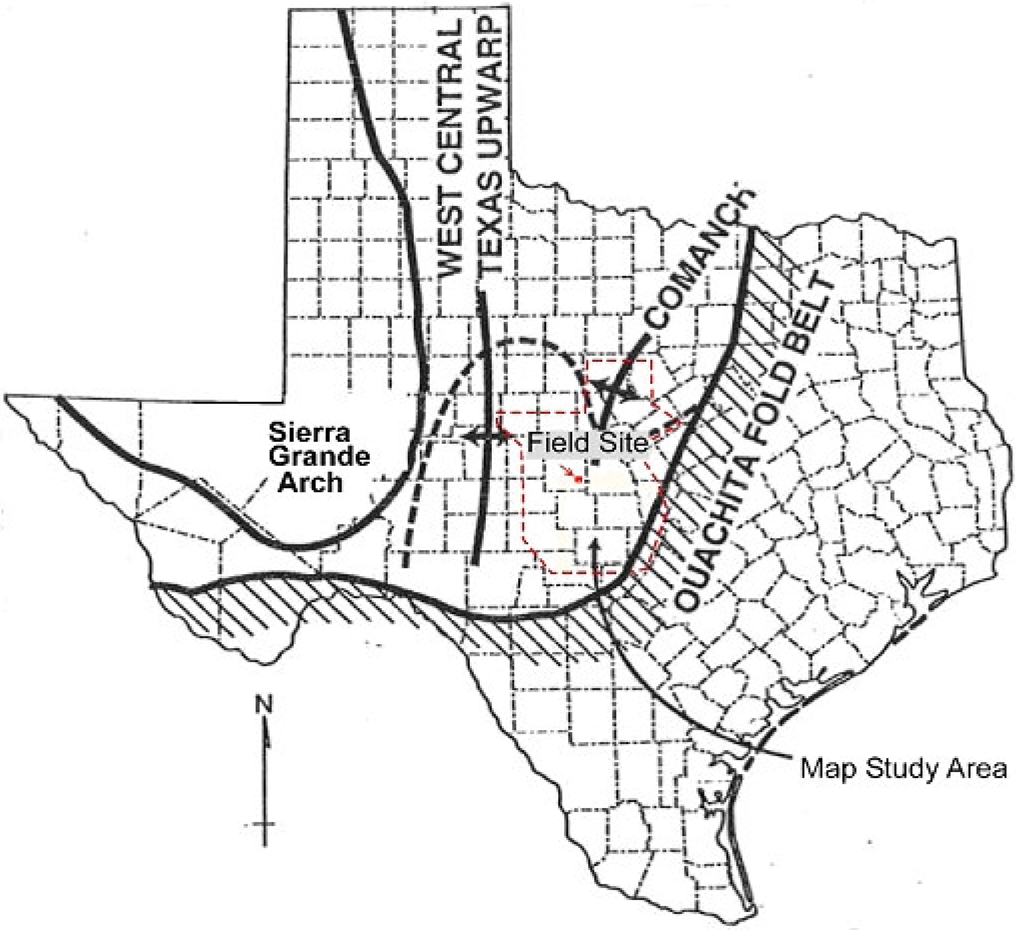


Figure 3. Hickory Formation Deposition in central Texas. The red, dashed line outlines the area of Hickory Sandstone outcrops. The field site for this project is shown as a red block inside the dashed line (modified from Cornish, 1975 and Krause, 1996).

Texas Platform was situated on a passive continental margin (Perez, 2007). Laurentia was located near the equator and rotated to the west, compared to its current orientation. During this time, the Texas Platform was situated near the western tip of the craton (Fig. 4) (Krause, 1996). The Hickory Sandstone was deposited along the margins of a shallow epicratonic embayment on the Texas platform. To the south and southeast, the embayment was bordered by the Western Iapetus Sea. The Sierra Grande Arch and the West Central Texas Upwarp provided western and northwestern boundaries for the Riley Formation (Krause, 1996).

The Texas Platform climate, during Late Sauk II time, appears to have been arid to semiarid. Ventifacts and eolian markings have been found near the base of the lower Hickory just above the Town Mountain Granite suggesting eolian activity (Barnes and Parkinson, 1940; Cornish, 1975; Barnes and Bell, 1977; Krause, 1996). Rainfall is thought to be similar to that of the present (Barnes and Bell, 1977). Alternately, paleosols have been found beneath the Hickory in the Precambrian basement, which could indicate a warm, wet climate (Perez, 2007; Johnson, personal communication 2007). Barnes and Bell (1977) reported possible freezing marks in the Lower Hickory, which would suggest that freezing would possibly have been more likely during the late Cambrian than today. Even so, the overall paleoclimate was probably similar to the modern climate. The Late Cambrian is considered to be a greenhouse period (Berner, 1993; Krause, 1996), when Earth lacked continental-scale glaciers. Thus, climate-forced sea level fluctuations are inferred to have been slower than during the Tertiary.

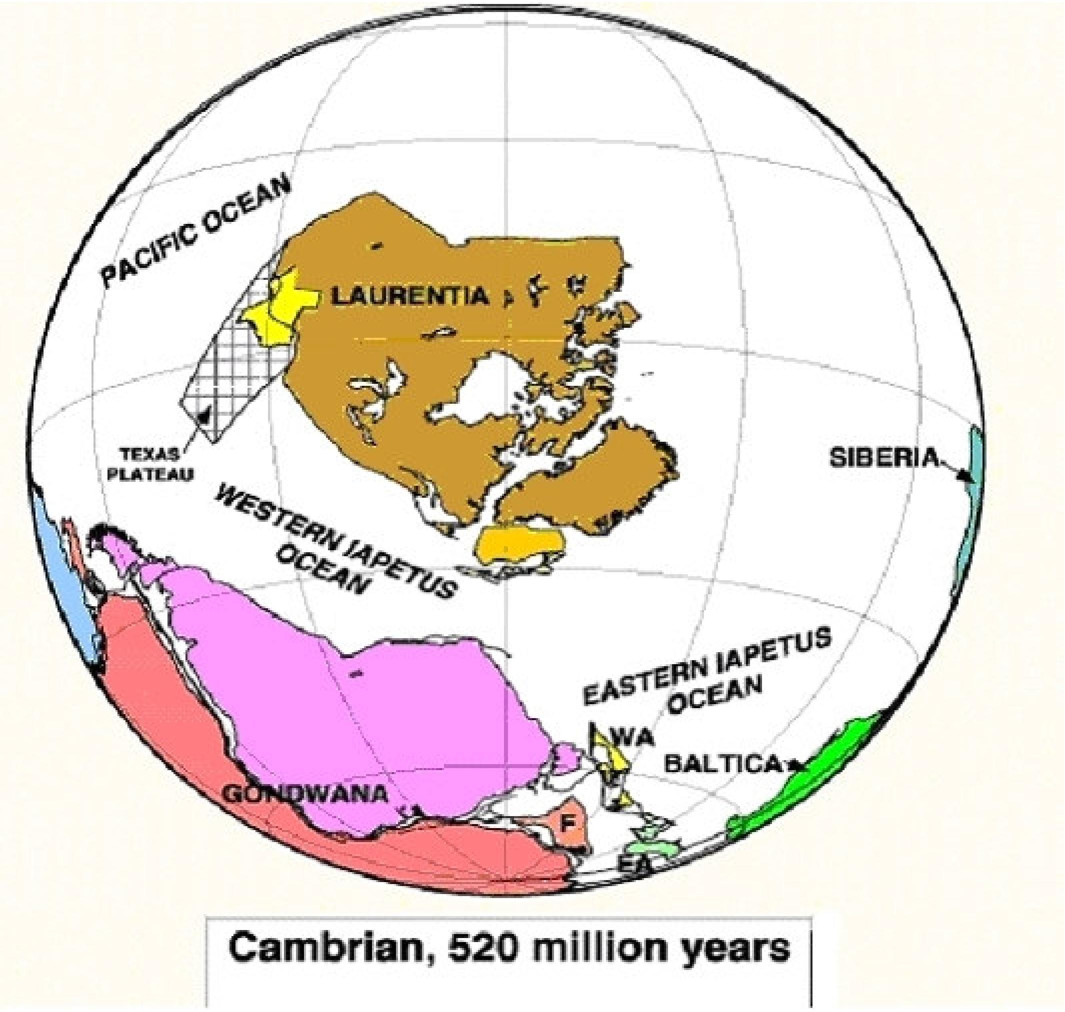


Figure 4. Texas Platform during the Cambrian - Site of Hickory Deposition (Modified from Dalziel and Gahagan, 2006, PLATES Project, http://www.ig.utexas.edu/research/projects/plates/posters/Making_of_Texas_08aug2006.jpg, The University of Texas Austin).

The Llano Orogeny produced doming that was eroded to expose the Precambrian basement before Riley Formation deposition occurred (Muehlberger et al., 1966; Kim, 1995). Folded, northwest-southeast trending Valley Spring Gneiss (1232-1288 Ma) and Packsaddle Schist (1215-1248 Ma) (ages from Mosher, 1996) beds were intruded by granite that is approximately dated at 1116 – 1056 Ma (Garrison et al., 1979; Walker, 1992; Rougvie et al., 1999; Reese et al., 2000; Krause, 1996; Wilson, 2001). A transgression of the Cambrian sea left a bedrock-controlled northwest-southeast trending ridge and swale topography (Barnes and Bell, 1977; Krause, 1996). Differential erosion resulted in a topography of low relief (Wilson, 2001). Generally, mafic-poor gneiss and granite, in local inselbergs, formed the resistant ridges. The Packsaddle schist eroded to form the deeper valleys (Krause, 1996). Ridges of resistant marble also exist, which Barnes and Bell (1977) suggest indicate that the dominant form of weathering was mechanical rather than chemical (Krause, 1977). Early Hickory fluvial deposition was undoubtedly influenced by this irregular topography. Figures 5 and 6 show this ridge and swale structure.

The Hickory lies unconformably upon this surface, which most commonly is the Town Mountain Granite in the study area (Barnes and Bell, 1977; Krause, 1996). As a result of this local control, Hickory thickness varies widely over the region, ranging locally from 0 to ~168 meters (550 feet) (Barnes and Bell, 1977; Wilson, 2001). Thickness tends to increase towards the south, following the prevailing paleocurrent

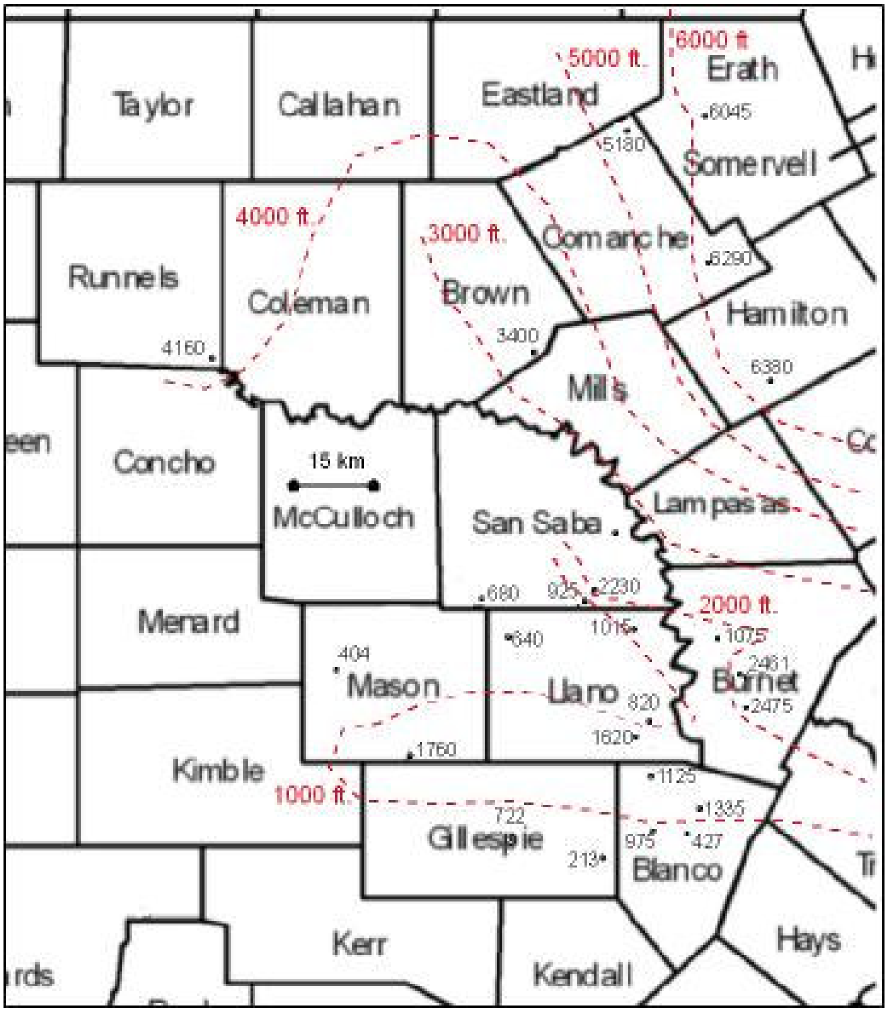


Figure 5. Structural Map Showing Ridge and Swale Structures in Precambrian Strata in Central Texas. Contour Interval = 1000 ft.

flow direction (Krause, 1996). The source area for most of the sediment deposited in the Hickory was from north and northwest. Local granitic and metamorphic paleohighs were additional sources of sediment supply (Barnes, 1956; Wilson, 1962; Cornish, 1975; Krause, 1996; Wilson, 2001).

In accordance with the paleotopographic trends, average paleocurrent directions were generally to the south-southeast for the Lower Hickory and this remained common throughout the Hickory (Wilson, W.F., 1962; Cornish, 1996; Wilson, J.S., 2001). Wilson (1962) observed a mean azimuthal direction of 153°. Cornish (1975) also observed a similar paleocurrent orientation, although the Upper Hickory showed a bimodal nature.

The structural and hydrologic properties of the Hickory Formation have been the focus of study in recent years (Randolph, 1991; Kim, 1995). Faulting is common in the region, with a common fault orientation of northeast-southwest (Cloud and Barnes, 1948; Barnes, 1981; Wilson, 2001). Most faulting consists of high angle normal faults that juxtapose the area (Black, 1988; Kim, 1995). Faulting took place during the Middle Pennsylvanian Quachita orogeny (Cheny and Goss, 1952; Graff, 2006). These normal faults were caused by a regional extension with an NNW-SSE alignment (Becker, 1985; Johnson and Becker, 1986; Johnson, 1990). A geologic map of the area is shown in Figure 7.

The Hickory Sandstone is comprised of Lower, Middle, and Upper Members (Goolsby, 1957). The Lower Hickory averages between 46-69 meters (150-225 ft) thick (Wilson, 2001) and is the subject of this study. Similar strata of approximately the same

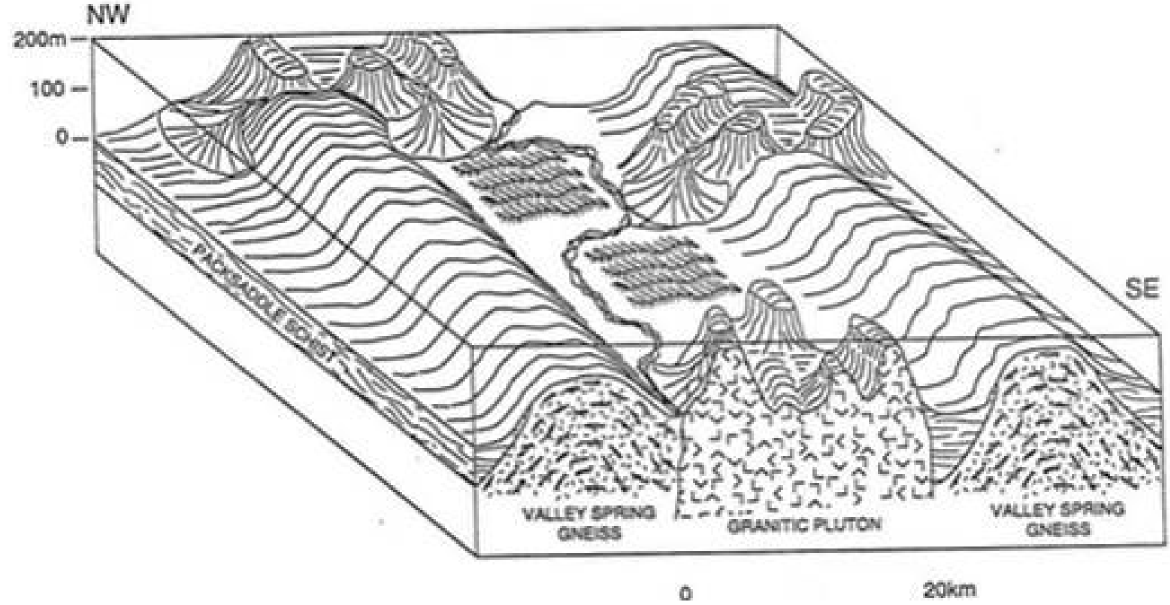


Figure 6. Existing Paleotopography at the Time of Hickory Sandstone Deposition. Showing the Ridge and Swale Topography (modified from Krause, 1996).

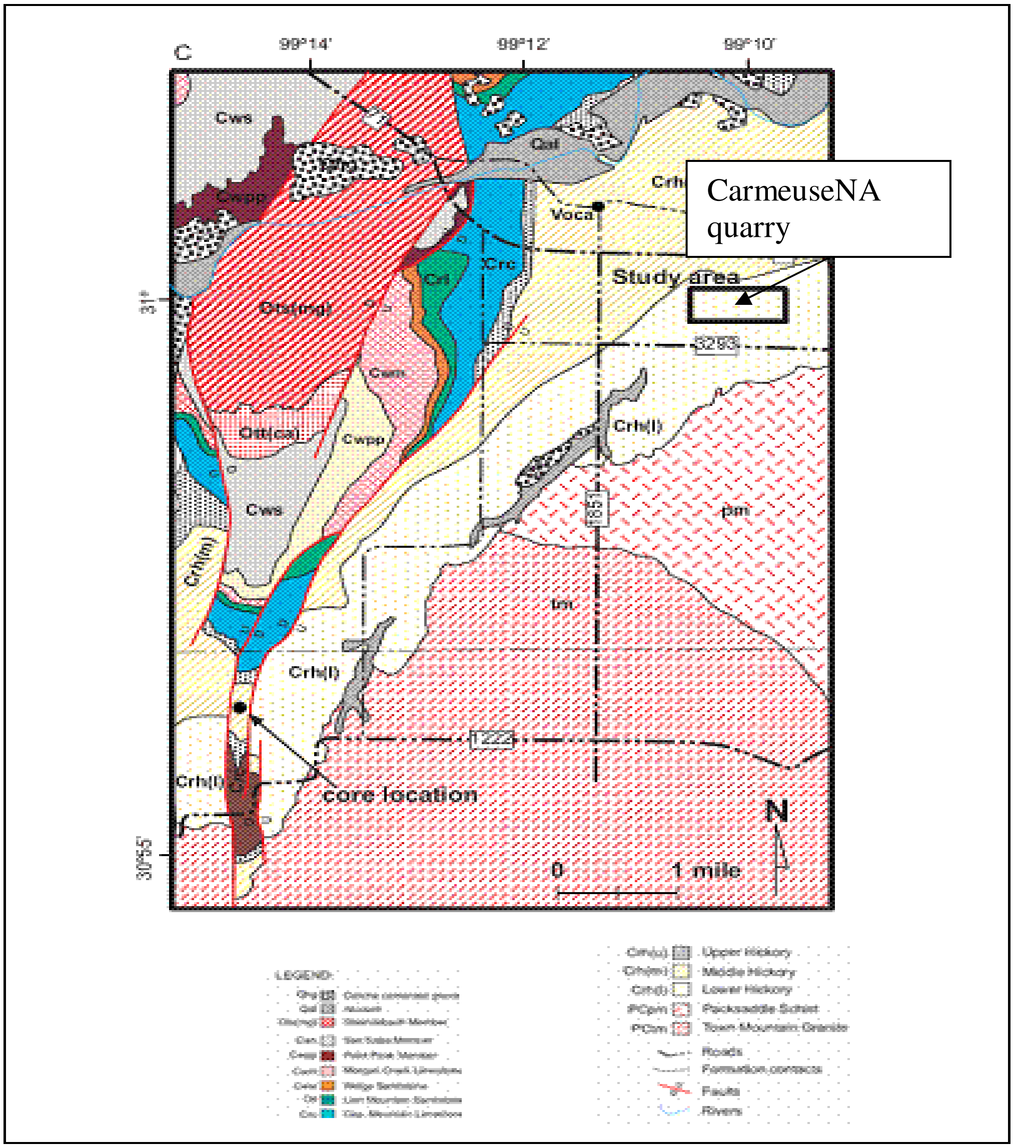
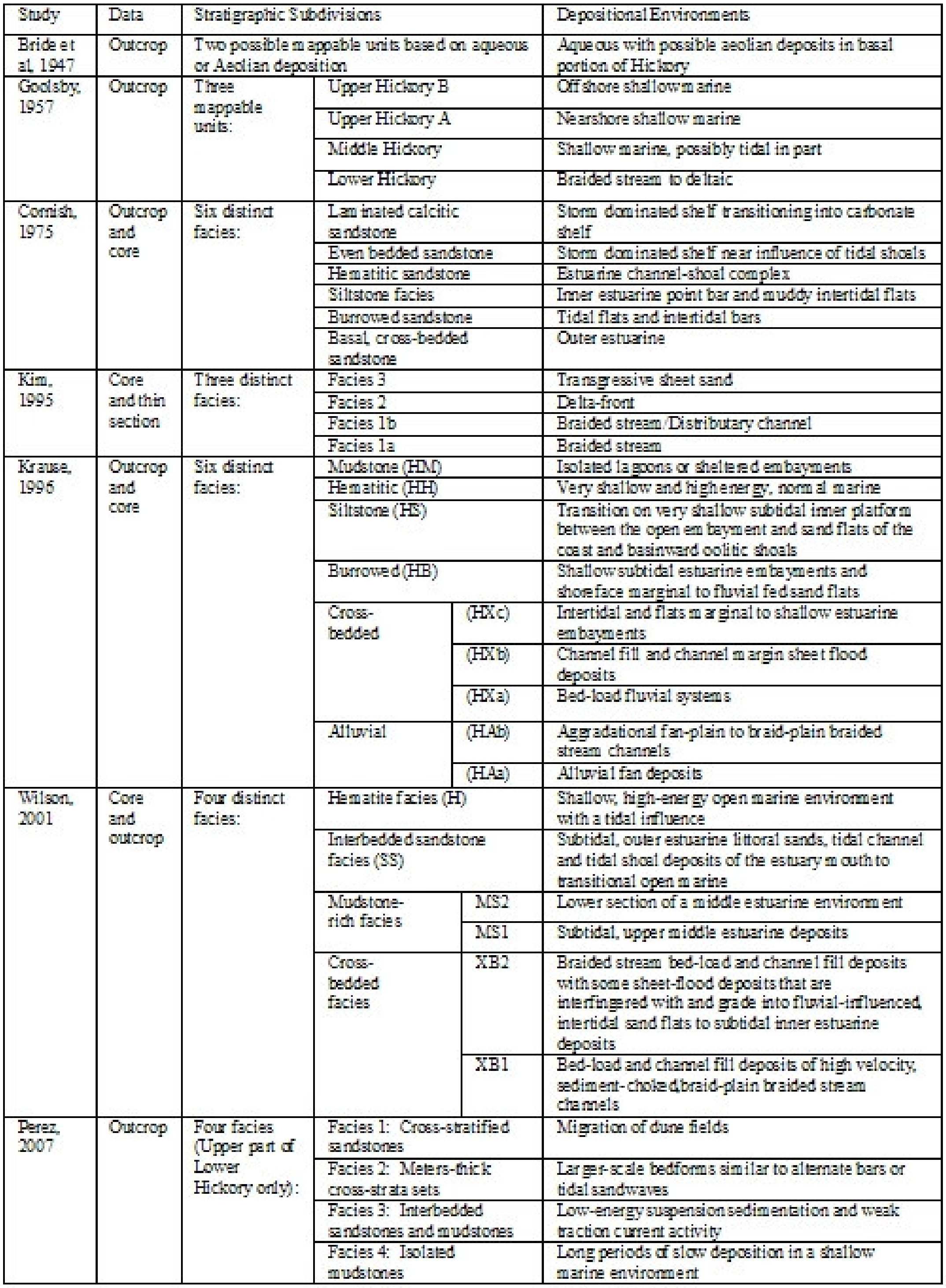


Figure 7. Geologic Map of the Study Area Near Voca, TX. The box represents the CarmeuseNA quarry (modified from Randolph, 1991).

age occur in the Sahara and in Arabia (Selley, 1996; Wilson, 2001). Krause (1996) placed the Hickory into the lowstand systems tract of an overall transgressive-regressive depositional sequence. Barnes and Parkinson (1940) thought that the lower part of the Lower Hickory may have been aeolian, but the presence of Cruziana throughout much of the Hickory does not support this conclusion (Barnes and Bell, 1977). It has generally been accepted that the Hickory Sandstone was deposited during an overall marine transgression (Goolsby, 1957; Cornish, 1975; Krause, 1996; and Wilson, 2001). The general interpretation for the Hickory suggested fluvial deposits of the lower Hickory progressing upsection into dominantly tidal flat, intertidal estuarine, and shoreface deposits of the middle Hickory. Details of previous paleo-environmental interpretations do vary widely. Both a single uninterrupted transgression and cycles within a transgression have been suggested as possible explanations (Wilson, 2001). Wilson (2001) maintained that deposition continued with no significant hiatus, whereas Krause (1996) claimed that the Hickory was the first of two basin-filling events in the Riley Formation.

The Hickory has been divided into Upper, Middle, and Lower divisions (Barnes and Bell, 1977; Graff, 2006). The Lower Hickory has usually been interpreted as braided fluvial deposits grading upward into tidal flat and intertidal estuarine deposits (Goolsby, 1957; Cornish, 1975; Krause, 1996; Wilson, 2001). Appearances of continuous, bioturbated mudstones form the boundary between the Lower and Middle Hickory (Perez, 2007). A fluvially-influenced tide-dominated, high microtidal estuarine environment has been suggested for the Middle Hickory (Krause, 1996; Wilson, 2001).



Study	Data	Stratigraphic Subdivisions			Depositional Environments
Bride et al, 1947	Outcrop	Two possible mappable units based on aqueous or Aeolian deposition			Aqueous with possible aeolian deposits in basal portion of Hickory
Goolsby, 1957	Outcrop	Three mappable units:	Upper Hickory B		Offshore shallow marine
			Upper Hickory A		Nearshore shallow marine
			Middle Hickory		Shallow marine, possibly tidal in part
			Lower Hickory		Braided stream to deltaic
Cornish, 1975	Outcrop and core	Six distinct facies:	Laminated calcitic sandstone		Storm dominated shelf transitioning into carbonate shelf
			Even bedded sandstone		Storm dominated shelf near influence of tidal shoals
			Hematitic sandstone		Estuarine channel-shoal complex
			Siltstone facies		Inner estuarine point bar and muddy intertidal flats
			Burrowed sandstone		Tidal flats and intertidal bars
			Basal, cross-bedded sandstone		Outer estuarine
Kim, 1995	Core and thin section	Three distinct facies:	Facies 3		Transgressive sheet sand
			Facies 2		Delta-front
			Facies 1b		Braided stream/Distributary channel
			Facies 1a		Braided stream
Krause, 1996	Outcrop and core	Six distinct facies:	Mudstone (HM)		Isolated lagoons or sheltered embayments
			Hematitic (HH)		Very shallow and high energy, normal marine
			Siltstone (HS)		Transition on very shallow subtidal inner platform between the open embayment and sand flats of the coast and basinward oolitic shoals
			Burrowed (HB)		Shallow subtidal estuarine embayments and shoreface marginal to fluvial fed sand flats
			Cross-bedded	(HXc)	Intertidal and flats marginal to shallow estuarine embayments
				(HXb)	Channel fill and channel margin sheet flood deposits
				(HXa)	Bed-load fluvial systems
			Alluvial	(HAb)	Aggradational fan-plain to braid-plain braided stream channels
				(HAa)	Alluvial fan deposits
Wilson, 2001	Core and outcrop	Four distinct facies:	Hematite facies (H)		Shallow, high-energy open marine environment with a tidal influence
			Interbedded sandstone facies (SS)		Subtidal, outer estuarine littoral sands, tidal channel and tidal shoal deposits of the estuary mouth to transitional open marine
			Mudstone-rich facies	MS2	Lower section of a middle estuarine environment
				MS1	Subtidal, upper middle estuarine deposits
			Cross-bedded facies	XB2	Braided stream bed-load and channel fill deposits with some sheet-flood deposits that are interfingered with and grade into fluvial-influenced, intertidal sand flats to subtidal inner estuarine deposits
				XB1	Bed-load and channel fill deposits of high velocity, sediment-choked,braid-plain braided stream channels
Perez, 2007	Outcrop	Four facies (Upper part of Lower Hickory only):	Facies 1: Cross-stratified sandstones		Migration of dune fields
			Facies 2: Meters-thick cross-strata sets		Larger-scale bedforms similar to alternate bars or tidal sandwaves
			Facies 3: Interbedded sandstones and mudstones		Low-energy suspension sedimentation and weak traction current activity
			Facies 4: Isolated mudstones		Long periods of slow deposition in a shallow marine environment

Figure 8. Prior Work on the Hickory. Modified from Wilson (2001).

The Upper Hickory is interpreted as an estuarine to open marine environment (Wilson, 2001). An increase in hematite cement and the appearance of hematite ooids indicate the Middle and Upper Hickory boundary (Barnes and Schofield, 1964; Barnes and Bell, 1977; Perez, 2007). Previous work and interpretations in the Hickory are summarized in Figure 8.

Goolsby (1957) divided the Hickory into Lower, Middle, and Upper units based on interpreted environments of deposition. He suggested that the Lower Hickory sandstone is composed of ephemeral stream deposits formed in a desert environment. These stream deposits grade upward into marine transgressive nearshore, shallow marine, and deep sea deposits. Cornish (1975), in one of the earliest thorough analyses of the Hickory, found six primary lithofacies: 1) a basal cross-bedded facies, 2) a burrowed sandstone facies, 3) a siltstone facies, 4) a hematitic sandstone facies, 5) an even-bedded facies and 6) a laminated calcitic facies. Cornish (1975) suggested that the Hickory sandstone was deposited by a largely progradational, non-barred estuarine complex.

Krause (1996) also found six facies in the Hickory Sandstone, but his definitions varied somewhat from those of Cornish. These were as follows: 1) Alluvial facies (HA – found in only two cores and not previously identified), 2) Cross-bedded facies (HX), 3) Burrowed lithofacies (HB), 4) Siltstone lithofacies (HS), 5) Hematitic lithofacies (HH), and 6) Mudstone lithofacies (HM). Krause (1996) suggested that the upper two facies described by Cornish were part of the Cap Mountain Limestone. The Cross-bedded facies (HX) is the equivalent of the Lower Hickory and was subdivided into

HXa, HXb, and HXc, respectively. HXa is a basal cobble-pebble matrix-supported conglomeratic lag. Chatter marks, frosting, and ventifacts indicate an aeolian influence. Trough cross-bedding is common, and the unit fines slightly upward. HXa is interpreted as braided stream accretionary lag. HXb is a subarkose to quartz arenite containing both planar and trough cross-bedding. Some channel forms are found throughout HXb. Krause (1996) interprets HXb to show bed channel fill and channel margin sheetflood deposits of braided streams. HXc continues with planar and trough cross-bedded sandstones in a similar fashion to HXb. The primary distinction between HXc and HXb is tidal influence with rare bimodal cross-bedding and mud laminations. Bioturbation increases when compared to HXb and non-channelized units are more common. This bioturbation marks the transition between a fluvial setting and marine-influenced facies of intertidal sand flats marginal to shallow estuarine embayments and a shoreface marginal to a very shallow inner platform. Krause's (1996) overall interpretation of the Hickory Sandstone differed from that proposed by Cornish (1975). Krause (1996) suggested a more complex topography and distribution of paleoenvironments occurring during the northward marine transgression.

Wilson (2001) defined six lithologic types from core description: 1) gravel-rich beds, 2) coarse-grain sandstones, 3) medium grain sandstones, 4) fine to medium grain, feldspar-rich sandstones, 5) interbedded mudstones, siltstones, and sandstones, and 6) mudstones. Like Cornish (1975) and Krause (1996), he described the Lower Hickory as a cross-bedded facies. The Lower Hickory was sub-divided further into five types. These include: 1) buff-yellow to light brown, coarse to very coarse grain, angular to subangular large scale cross-bedded sandstone, 2) buff-yellow to light brown, medium to coarse grain, small-scale cross-bedded sandstone, 3) orange-pink, medium grained, massive to small-scale cross-bedded arkosic sandstone, 4) brown and maroon, massive to horizontal laminated, silty or sandy mudstone, and 5) buff-yellow to light brown, very coarse grained chaotic to crudely cross-bedded sandstone. Types 1-3 are commonly stacked in a fining-upward sequence with thicknesses varying from 25 cm to over 1 m. Several large-scale cross-bed sets are commonly found stacked underlying massively bedded or small-scale cross-bed sets. Type 5 could occur anywhere. The thickness of large-scale cross-beds can extend up to a meter, but thicknesses of 5-30 cm are more common in outcrop. Thickness of the small-scale cross-bedding averaged 3-5 cm. Arkosic sandstones are not common, but when present are usually massively bedded with occasional small-scale cross-bedding. Mudstones most commonly are interbedded with the arkosic sandstones or found as mud drapes ubiquitous to fluvial and tidal environments.

Wilson (2001) divided the Lower Hickory into subfacies XB1 and XB2. Subfacies XB1 is in the lower part of the Lower Hickory and is primarily composed of larger-scale cross-bed sequences. XB1 contains few mudstone intervals, except where found as mud drapes over cross-bed sets or overlying element (3). Lateral continuity of sandstones in XB1 is poor. Wilson interpreted subfacies XB1 to be bed-load and channel-fill deposits resulting from braid-plain braided streams. He compares the strata in XB1 to Miall’s (1988) channel elements, sheet-like elements, and sandstone elements and the coarse sand deposits and rippled sand and silt facies of Smith (1974).

Subfacies XB2 has similar cross-bed sequences to XB1, with some differences: 1) the sands are not as well sorted, 2) thinner large-scale cross-beds, and 3) the coarse, chaotic strata is more common. As a whole, subfacies XB2 tends to fine upwards. Bioturbation can be found (although rarely) in mudstones, which are themselves seen with greater frequency than in subfacies XB1. Wilson (2001) first found bioturbation in XB2. Lateral continuity of bedding increases in subfacies XB2, which continuity marks the boundary between the XB1 and XB2 subfacies. Wilson (2001) interpreted Subfacies XB2 to be braided stream bed-load and channel-fill deposits with some sheet-flood deposits. These fluvial deposits grade into fluvially-influenced, intertidal sand flats to subtidal inner estuarine deposits. The transition for a fluvial-dominant setting to greater marine influence occurs in the lower 6-12 m of XB2, which is where bioturbation is first observed. Wilson's work was primarily based upon core and small road-side outcrops and had limited information concerning details of bedding architecture. Correlation across the Lower Hickory proved difficult between boreholes. Only a few mudstones and stacked cross-bed sets could be correlated, and the whole Lower Hickory is highly discontinuous. Wilson considered the Hickory to fit Reinson's (1992) facies model for a tide-dominated, high microtidal estuary.

To summarize, the Hickory Sandstone has been universally interpreted as a marginal marine environment, although the interpretations have differed as to the estuarine or deltaic nature of the deposits. It is a transgressive sand, representing one transgressive-regressive cycle. With the exception of Cornish (1975), the general interpretation of the overall Hickory include fluvial deposits of the lower Hickory progressing upsection into dominantly tidal flat, intertidal estuarine, and shoreface deposits of the middle Hickory.

METHODOLOGY

The field site is located at the CarmeuseNA (formerly Oglebay-Norton) Mine, Voca, Texas. The location is approximately twelve miles from the town of Brady, in McCulloch County, Texas. The exact location of the site can be seen in Figure 9. This quarry is roughly rectangular in shape (Fig. 10) with walls ~ twenty meters high. The sections of the quarry studied extend ~ 500 meters both parallel and perpendicular to flow direction. Dip of strata exposed in the quarry is at a very low angle northward (~2 degrees). The south wall exposes the lower part of the upper Lower Hickory. The north wall exposes a section slightly higher and, near the top of the wall, may include the transition from the Lower to the Middle Hickory Sandstone. The general paleocurrent direction is to the south-southeast.

The Lower Hickory exposed in CarmeuseNA quarry is a poorly-cemented, poorly sorted quartzitic to subarkosic sandstone with discontinuous mudstone interbeds. Near the base of the Lower Hickory, facies appear to be composed almost entirely of sand. They are composed of coarse to medium- or fine-grained sandstone, with large-scale to smaller-scale cross- bedding predominating. Upward toward the Middle Hickory, fine-grained sediments become more common. Along the strike sections (i.e. north and south walls), beds can be traced for a short distance (normally not more than 40-50m), but are not necessarily continuous. Mud layers perpendicular to flow direction appear to show less continuity than in the east and west walls (parallel to flow direction). In dip sections, beds are more layer cake.

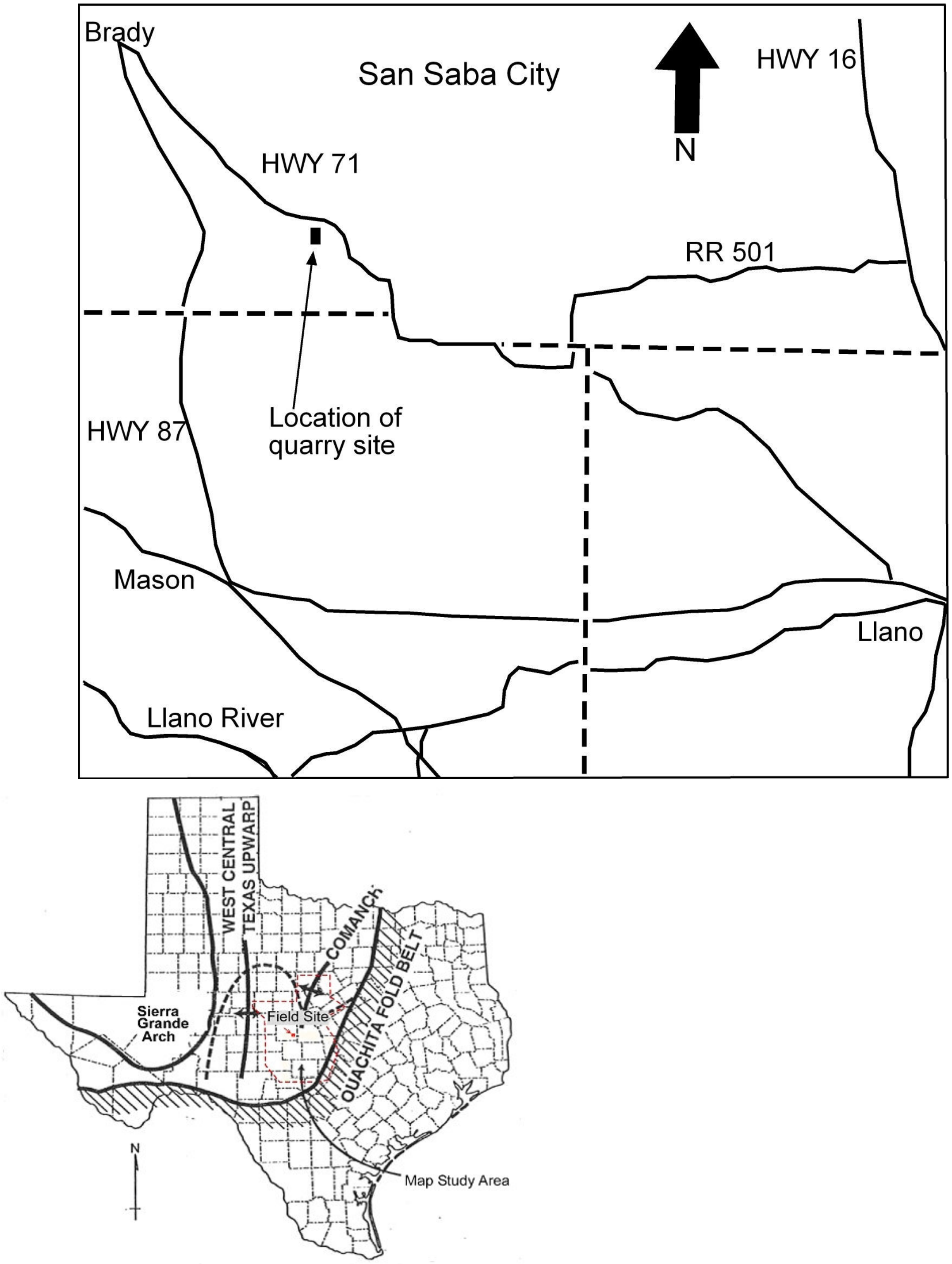


Figure 9. Location of the CarmeuseNA Quarry Site (modified from Krause, 1996).

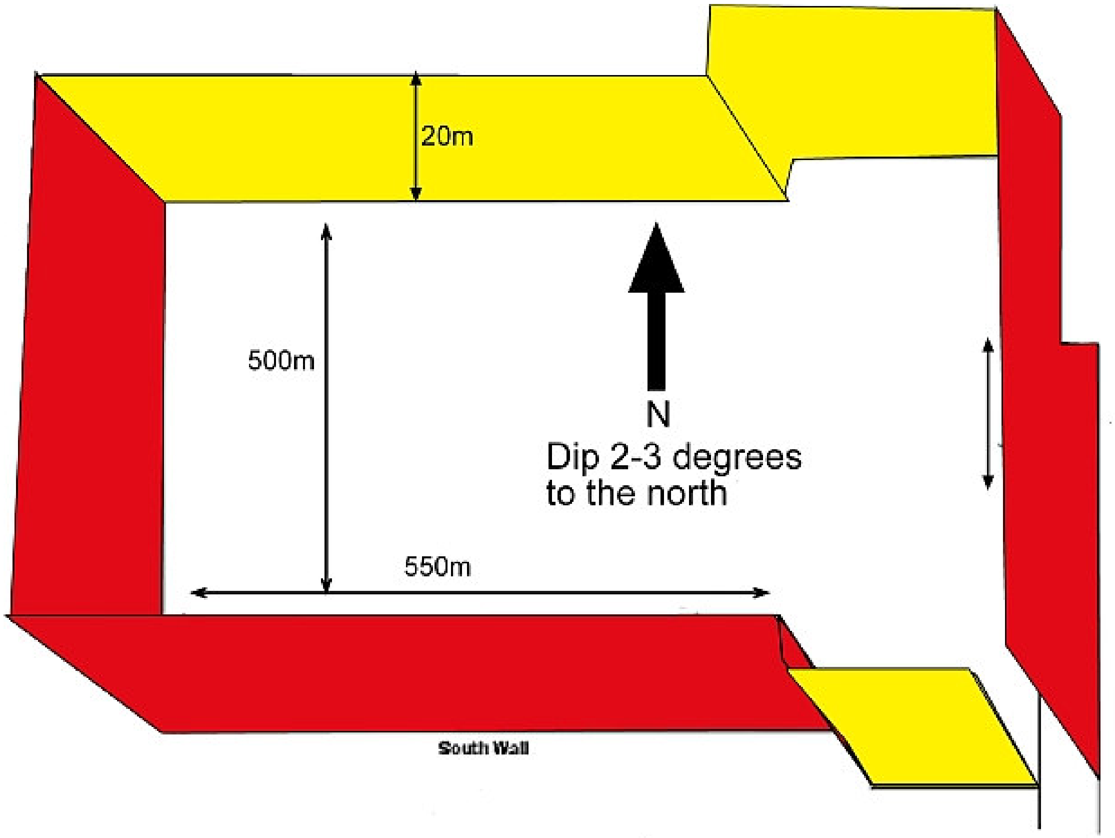


Figure 10. CarmeuseNA (formerly Oglebay-Norton) Quarry. Red-shaded walls and arrows show areas mapped for this study.

Because of the active nature of the quarry, the danger of rockfall excluded physical contact with the sandstone wall. This prohibition prevented the collection of physically measured sections and the collection of detailed sedimentological logs of the wall. The prohibition also prevents the collecting of in situ samples from the wall, although fallen rocks were collected and used to describe facies types illustrated in photographs. General paleocurrent direction and patterns based on the dip of the cross-bedding were observed, but detailed paleocurrent data could not be gathered because of the proscription against touching the wall.

Construction of Photomosaics

The research was undertaken in the following steps: a) photographs were taken of the south, east, and west walls, b) photographs were orthorectified for the south wall, c) base maps (photomosaics) were completed from orthorectified photographs of the south wall and from standard photographs of the east and west walls, d) facies, boundaries, and sedimentary structures (as feasible) were traced on the base maps, e) Cores from local sites were logged and facies were located and compared to those inferred from photomosaics.

The south, east, and west walls were photographed with digital cameras, including a Nikon D100 and a Nikon 5600 Coolpix. For the south wall, photographs were taken from three angles, if possible, to produce orthorectified photomosaics. One photo was taken perpendicular to the wall, and the other two were taken at 45^{o} to each side of the first picture. This combination, along with x,y,z coordinates of selected points on the walls, allowed orthorectified photographs to be compiled using Photomodeler®. Orthorectification is performed by inputting x,y,z coordinates on identical points in multiple photographs to reduce camera error. Photomosaics for the south wall were constructed from a series of orthorectified photographs in Photoshop®. For the east and west walls, the photomosaics were composed of standard (non-orthorectified) photographs, also in Photoshop®. These photomosaics were used as the base maps to organize and show information gained from field data and photographs. Field drawings were made of selected areas to aid in the later correlation of points and to add field data.

Facies Mapping

The photographs, photomosaics, field drawings, and observations were used to identify and map the facies architecture (facies types/lithology) of the walls. This architecture was mapped on the photomosaics using Freehand® program. The constructed photomosaics were used as base maps on which the facies mapping was performed. For the south, west, and partial east walls, the architecture was traced on the photographs. All major facies were shown in red, as well as any observed larger packages based on lithofacies or unconformities. Further subdivisions were drawn, showing smaller-scale bedding along stratal divisions or other obvious changes in lithology or structure with differing black line weights (pt size) in order to have as much control over the order and sedimentology as possible. Individual beds based on sedimentary structures were mapped on close-up photographs only. These beds were not visible on the larger base map photomosaics. Sedimentary structures and bioturbation, where visible and identifiable, were used to identify these facies. These data can also be used to define structures using direction of flow, change or continuity of angle of cross-beds, scale of sedimentary structures (especially cross-bedding). Color changes can help to identify boundaries between lithologies; however, color is not a reliable indicator by itself and should be used only in conjunction with other data. Boundaries between lithologies/facies were examined to determine whether they are erosional or depositional in nature. This determination provided a better interpretation of the environment of deposition and how it evolved.

Mapping was based on a hierarchy of bounding surfaces, or surfaces that form upper or lower boundaries of beds or bedsets. Bedset boundaries and erosional surfaces of sufficient length to be mapped across the base map are shown in solid, red lines, corresponding to Perez's (2007) third-order structures. Minor bounding surfaces enclosing individual beds of large-scale cross-bedding, stacked small-scale cross-bedding, mudstone, or interbedded materials are mapped in black, dashed lines. Smaller-scale features such as small-scale cross-bedding and individual mud/silt layers were not mapped except in special close-range examples, because of the overwhelming preponderance of such features. Samples of close-range mapping are shown to illustrate facies types. The method used in mapping stratigraphic hierarchy is similar to that used by Perez (2007). All the photomosaics are shown in Appendices 1, 2, and 3 for the South, West, and East walls, respectively. Areas shaded in red were either covered or too weathered to facilitate an interpretation with any degree of certainty.

Core was logged to examine smaller sedimentological features that could not be seen in the field and to provide a check on interpretation. Comparative grain size from the core, sedimentary structures, and visible trace fossils were examined to provide confidence to the findings. The described cores include the Gene Kidd Research-1, Gene Kidd Research-6 and NNR-4. The resulting core logs were compared with the field maps and the resulting facies maps to provide an independent validation of results.

HICKORY SANDSTONE FACIES DESCRIPTIONS

The upper Lower Hickory is a fine to medium grained sandstone with a large amount of coarse grains. Whereas more complicated than basic layer-cake bedding, beds are arranged in a sheet-like geometry. Occasional channel forms can be seen, but they are not common. Four primary facies types are present in the upper Lower Hickory from the quarry walls and selected cores Gene Kidd Research-1 (GKR-1), Gene Kidd Research-6 (GKR-6), and NNR-4. The facies are as follows: 1) stacked small-scale cross-bedded facies, 2) large-scale cross-bedded facies, 3) interbedded mud/silt/sand facies, and 4) mud facies. A fifth facies type, chaotic sandstone, was observed occasionally in core, but was not observed in outcrop. In core, the fifth facies occurred most commonly, although not exclusively, near the base of large- or small-scale cross-bedding. Rarely, were plane beds or fine-grained sandstone observed, but not commonly enough to classify as a facies type. These facies types correlate mostly with the findings of Perez (2007) albeit in a slightly lower section of the Hickory.

Facies 1 and 2 make up almost the complete exposed section of the upper Lower Hickory, with Facies 1 predominating. The stacked small-scale cross-bedded facies makes up the majority of the highwalls at the CarmeuseNA quarry, as well as being the primary facies found in core extracted a short distance away. The large-scale cross-bedded facies was locally important, but not a major component in comparison to the stacked small-scale cross-bedding. Occurrences of the large-scale cross-bedded facies (Facies 2) are rare in the lower part of the South Wall and greatly increase progressing higher in the section. This leaves Facies 1 as the primary component of the lower section of the upper Lower Hickory at the field site. Mud layers and interbedded mud/silt/sand are comparatively minor components of the formation and rarely occur with any appreciable thickness. Mud layers of noticeable thickness are normally found only at the top of a sandstone sequence, and even then, are not extremely common.

Three cores from the local area were logged – Gene Kidd Research-1, Gene Kidd Research-6, and NNR-4 – to provide an independent evaluation for the data from the highwalls. The same facies are present in the core as in the walls, with the exception of the chaotic facies. The chaotic facies is too thin to be seen in the field and could only be studied in core, as mentioned also by Wilson (2001) and Perez (2007).

Small-scale Cross-bedded Facies (Facies 1)

Facies 1 is composed of stacked small-scale trough cross-bedded sandstone. Facies 1 makes up most of the visible quarry wall and core studied (Fig. 11). The cross-bedded cosets ranged in thickness from 5-20cm and averaged ~ 5-7.5cm thick. Lateral extent of the facies can vary widely. The facies can range from a single set of 4-5cm (although uncommon) to stacks of cosets several meters in thickness. Trough cross-bedding is the principle cross-bed type, especially in the core, but some planar bedding was observed. Grain size is normally fine to medium sand with some coarse sand. Rarely are cosets composed of very fine sand. Cross-strata dip was generally unidirectional within the coset. Dip was primarily to the South or Southeast in the East and West Walls, although cross-strata dipping in the opposite direction also occurred. In several cases, though, dip direction within cosets would be in opposite directions.

Because of the proscription against physical contact with the wall, detailed paleocurrent data in the form of rose diagrams are not available.

The majority of the cross-strata are composed of planar and concave-upward cross-bedding. Planar seemed to be slightly more common. Occasionally, cross-strata geometry changes from planar to concave downdip, and rarely, from concave to planar. Sigmoidal cross-bedding was almost never observed, but does exist in isolated cases. The angle of cross-strata normally increased downdip. Near the end of the cross-bed set, dip angles were near the angle of repose. Cross-strata thickness generally seemed to be constant throughout the cross-bed, although in some samples, the thickness appeared to increase slightly upwards.

Reactivation surfaces, areas where deposition was interrupted by flow variability, are commonly found in this facies. Mud drapes on cross-strata are not common, but do occur, especially higher in the sequence. Very thin mud layers were found several times running through the small-scale cross-beds. Rarely, micaceous layers were seen along cross-strata.

Large-scale Cross-bedded Facies (Facies 2)

Facies 2 consists of fine to coarse grain large-scale cross-bedded sandstone (Figure 12). Grain size is generally coarser than the small-scale cross-bedding (Facies 1) above, and is medium to coarse grained. Normally, this facies is composed of individual sets, unlike Facies 1 which are normally cosets. Rarely, primarily in core but also in outcrop, 2 or 3 sets occur together, but that is very uncommon. When it does occur, an

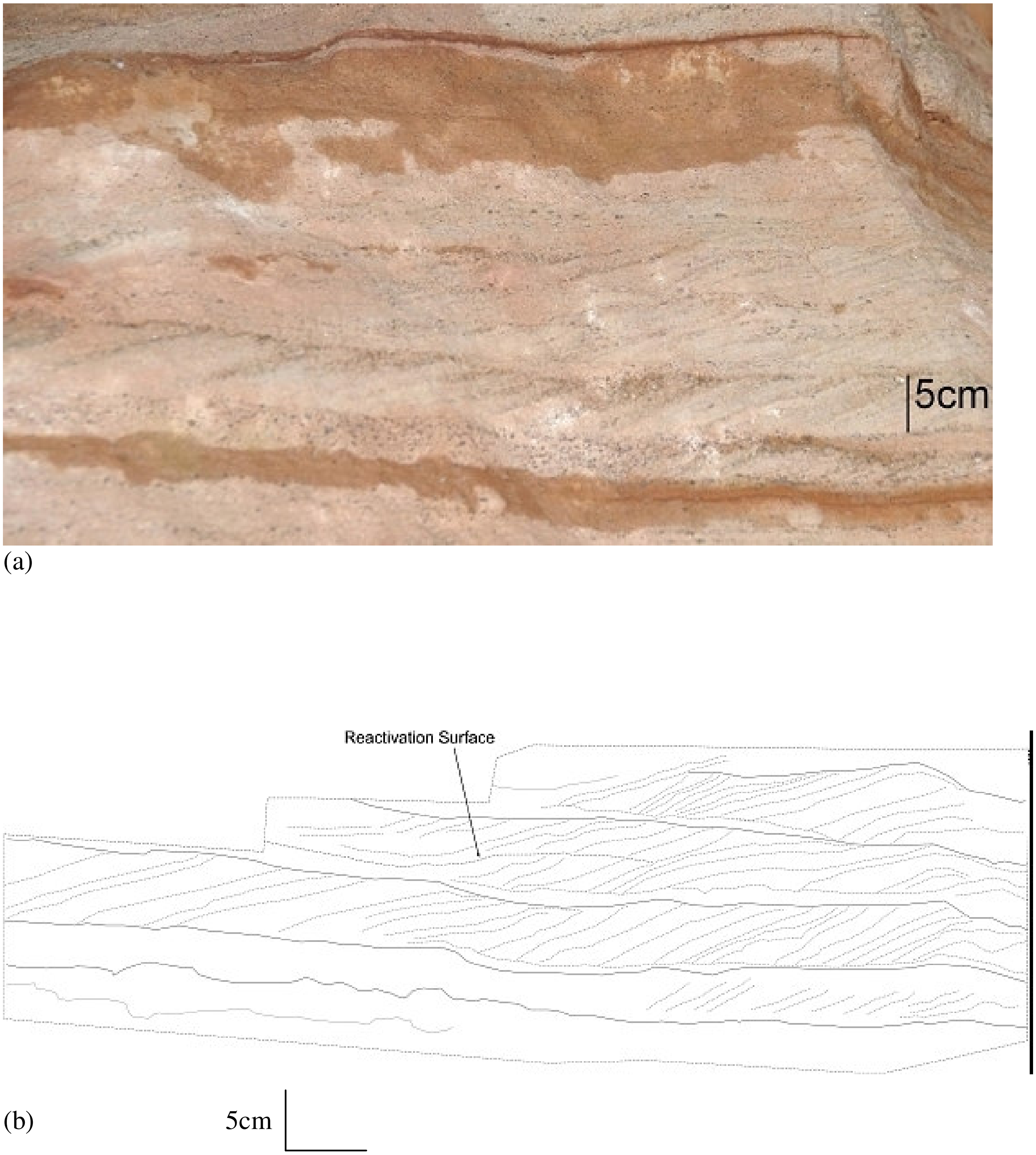


Figure 11. Facies 1. a. Example of Facies 1 (Small-scale cross-bedding) from CarmeuseNA quarry. b. Line sketching from sample above showing reactivation surface.

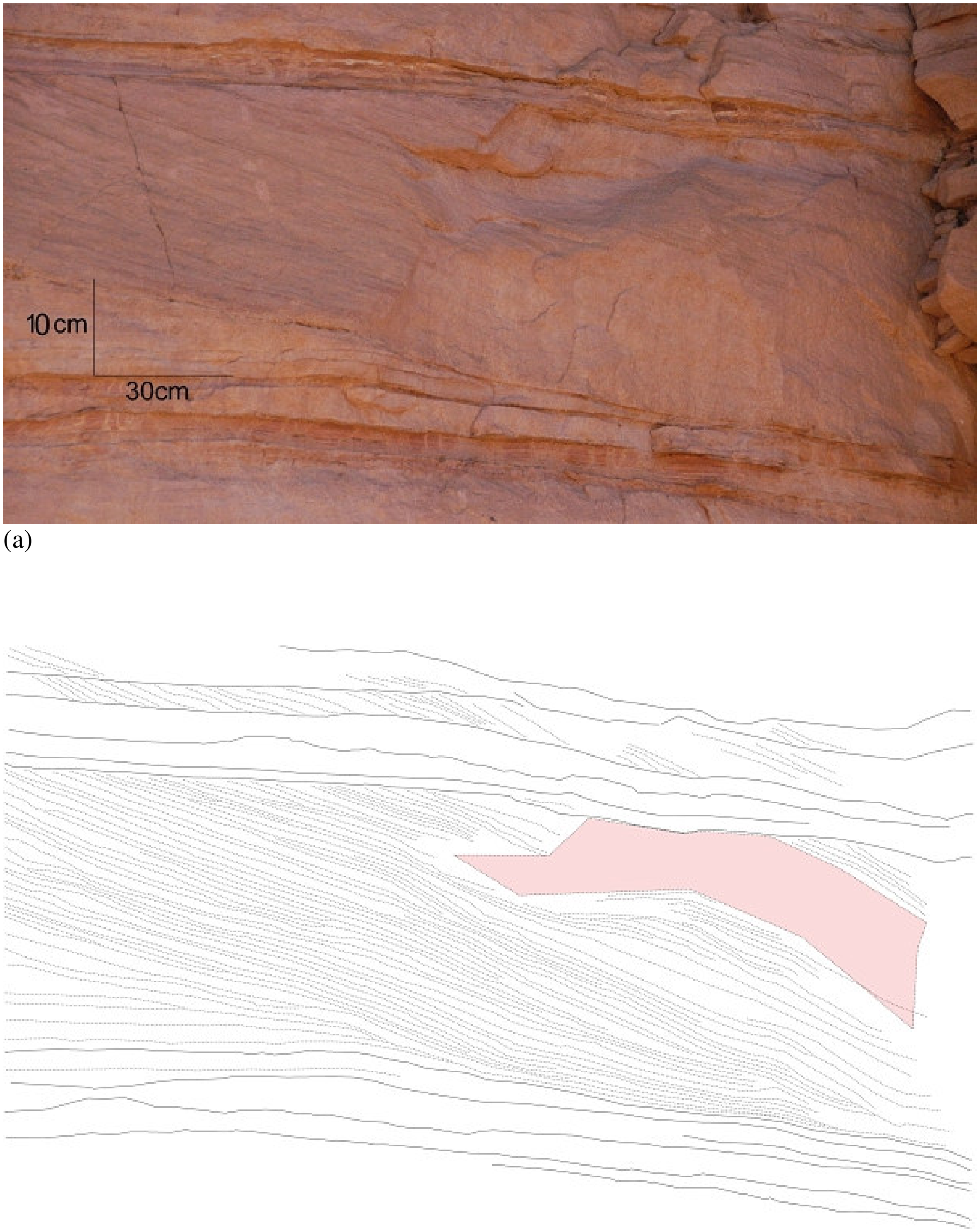


Figure 12. Facies 2. a. Facies 2 (Large-scale cross-bedding) from the CarmeuseNA quarry. b. Line sketch from sample above (pink area represents weathered surface).

erosional surface is usually present between them. Beds appear most commonly to be tabular in shape, but wedge-shaped beds are also present with some frequency, as well as channel cuts. The thickness varies from 0.3m to 1.5 meters, and horizontal measurements vary tremendously from 4-5 meters to greater than 50 meters. Both the basal and upper boundaries of the cross-bed set are usually visibly erosional surfaces, lying unconformably upon the basal surface, in nature. When isolated, Facies 2 is sometimes observed in channel forms with a concave erosive basal surface. The channel cuts through Facies 1 most commonly, but sometimes Facies 3 or 4, also. Although Facies 2 was commonly seen in the upper two-thirds of the South wall, it increased in both amount and lateral persistence parallel to flow in the East wall (Figure 13).

Planar cross-bedding is common, but often approached the basal surface tangentially, as seen in Figure 12. The planar cross-beds are well-sorted. Dip angle was observed to increase downstream within the cross-set, sometimes decreasing again as it graded into another facies farther downstream. Rarely, smaller scale cross-bed sets are seen near the termination of the cross-sets, forming topsets and bottomsets at the basal surface and top surface. Like Facies 1, cross-strata dip usually is toward the South-Southeast. More variability is present in cross-bed dip than in Facies 1, though, especially in the East and West. Cosets normally dip in the same direction, but are rarely observed to dip in opposing directions. This opposing dip is observed most often in walls parallel to flow direction of the paleoflow as seen in Figure 14. Micaceous layers were observed along some cross-strata. Reactivation surfaces are present in some cases, although not noticeably common. Mud drapes are seen along some cross-strata

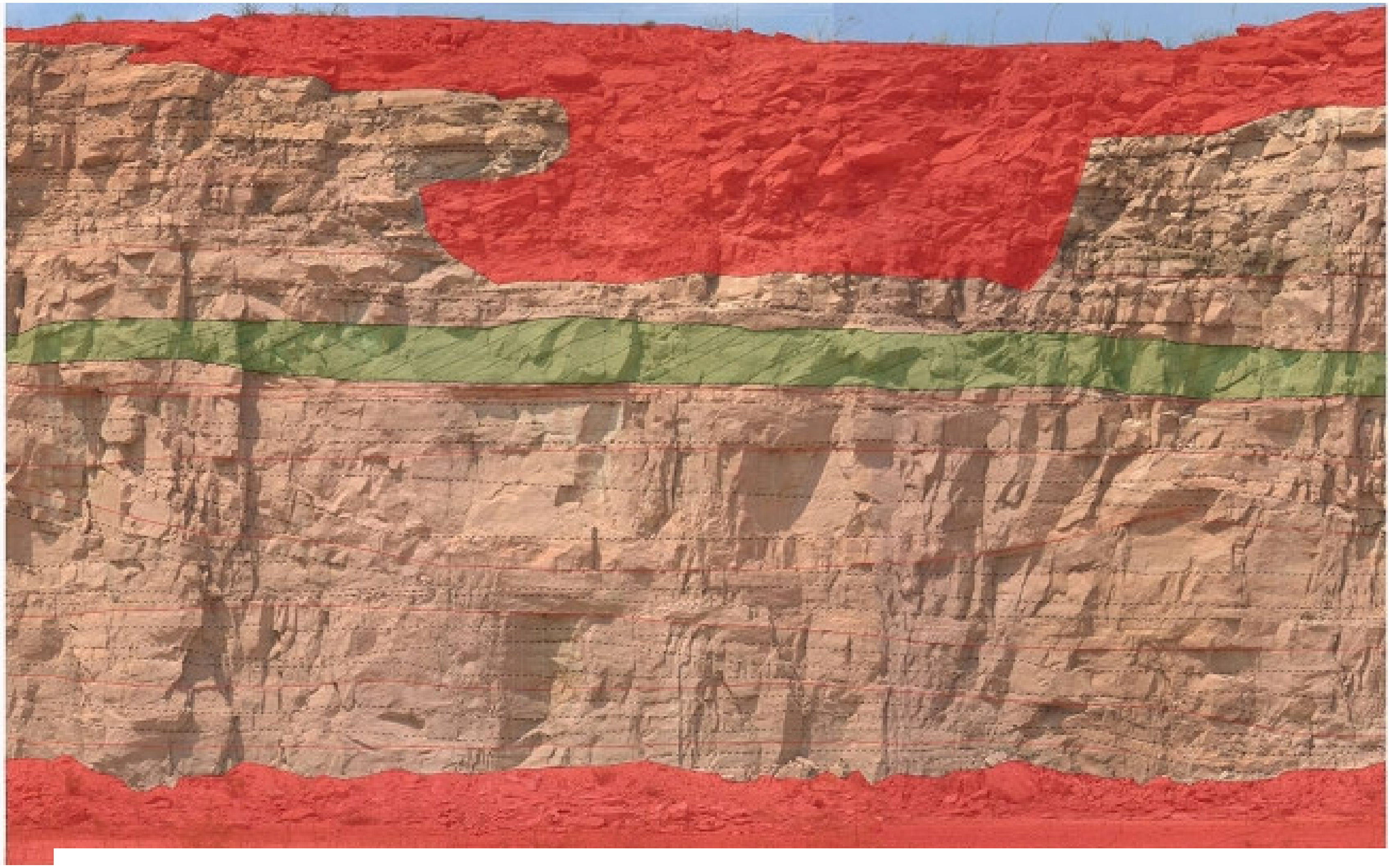


Figure 13. North End of West Wall Showing Lateral Extent of Facies 2 (shown in green). Length of the wall section is ~ 40m.

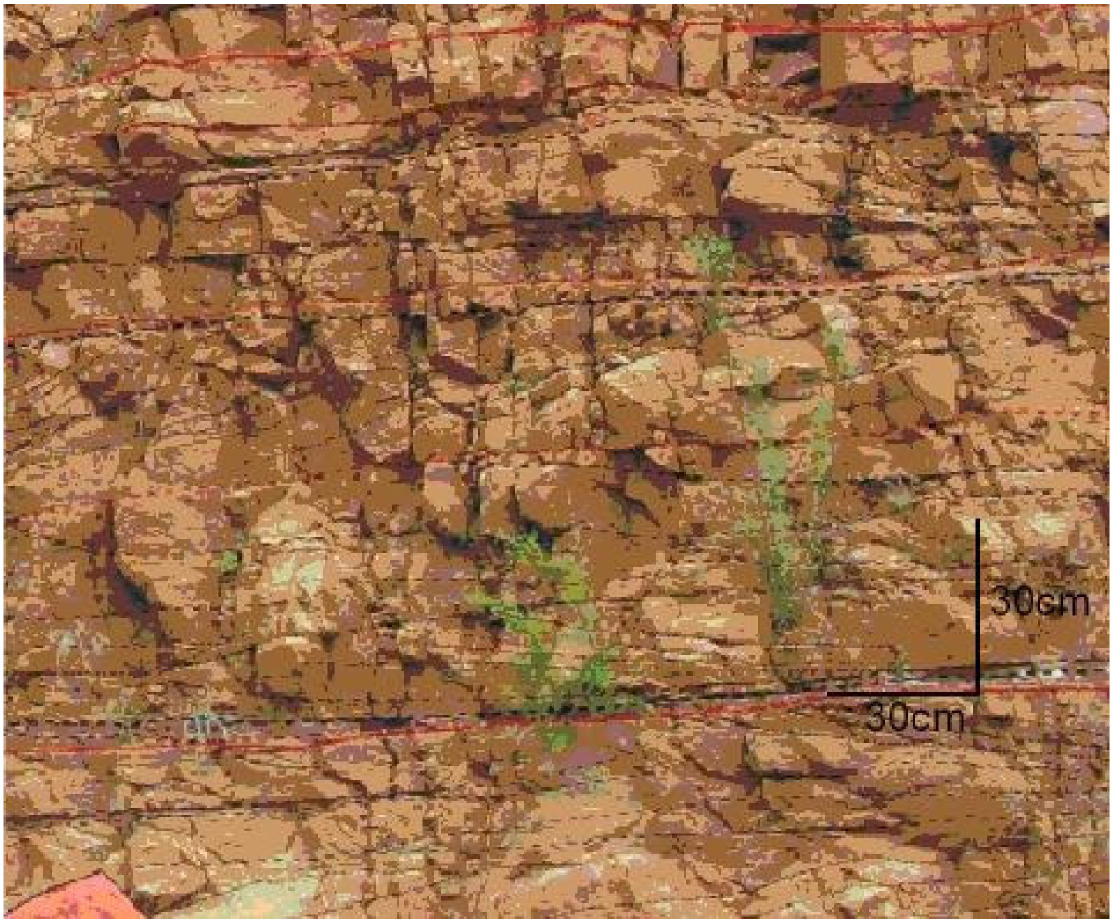


Figure 14. Example of Bi-directional Cross-bedding in Facies 2 in the East wall. Solid red lines show larger-scale facies boundaries.

and are more common than in the small-scale cross-bedded facies. Facies 2 can be observed in isolated beds, but normally is overlain by Facies 1 and either Facies 3 or 4, especially nearer the top of the walls.

Interlayered Mud/Silt/Sand (Facies 3)

This facies consists of interbedded mud, silt, and sand. Usually, the grain size is very fine sand, but occasionally, fine or even medium sand occurred. The sand, silt, and mud layers are mm to cm scale individually. Thickness varied from 5cm to 67cm with an average of approximately 7-13cm. Thicker units (over 20-25cm) appear only rarely in the wall or core. Cycles often thinned upward within a unit (Fig. 15 a & b). Ripples and very small-scale cross-bedding are observed in the sandy and silty parts of the facies. Bioturbation was occasionally observed in the silts and muds. This will be discussed in more detail in the section on bioturbation after the description of Facies 4. Facies 3 is observed in all walls, but appears to be more commonly present in the north end of the West wall than elsewhere at the site. This would be intuitive, because this part of the quarry is closest to the top of the Lower Hickory and the base of the Middle Hickory. Both Facies 3 and Facies 4 are more representative of the Middle Hickory than the Lower Hickory. They are found in increasing abundance in the East and West walls near the north end of the walls, because the dip of the Hickory in the quarry is to the north.

Figure 15. Facies 3 examples. a. Example of Facies 3 (Interbedded Mud/Silt/Sand) from field site. b. Line sketch of Facies 3 form above example. Solid lines show erosional surfaces.

Mud Layers (Facies 4)

This facies consists of layers of mud that are not noticeably interbedded with sand or silt (Figure 16). Facies 4 can be either laminations or beds, as the thickness of these layers is on a similar scale as Facies 3 for the most part. Thickness of Facies 4 averages 10-13cm. Many of the beds have a concave-upward geometry. Mud is not a common component in the lower part of the wall and core, but increases toward the upper part of the upper Lower Hickory as the boundary with the Middle Hickory is approached. As in the description of Facies 3, because the dip in the quarry is to the north, this facies becomes more common along the West wall toward the north. Bioturbation was occasionally observed in the lower part of the walls and core, but became much more common higher in the section. This facies or Facies 3 often cap a sequence of Facies 1 and/or Facies 2.

Bioturbation in the Upper Lower Hickory

Bioturbation was found in Facies 3 and Facies 4 at the quarry (see Figure 17). Especially as seen in core, it is much more common higher in the section, than lower. Wilson (2001) and Krause (1996) also observed this, and found sparse bioturbation in the Lower Hickory. *Planolites* was commonly seen, both in the quarry and in core. *Cruziana* was observed close to middle of the quarry floor between the North and South walls. Since the dip of the strata is toward the north, this represents an area approximately 1/3 of the height of the South Wall. Krause (1996) considered *Diplocraterion* to be the major explanation for bioturbation, whereas Wilson (2001)

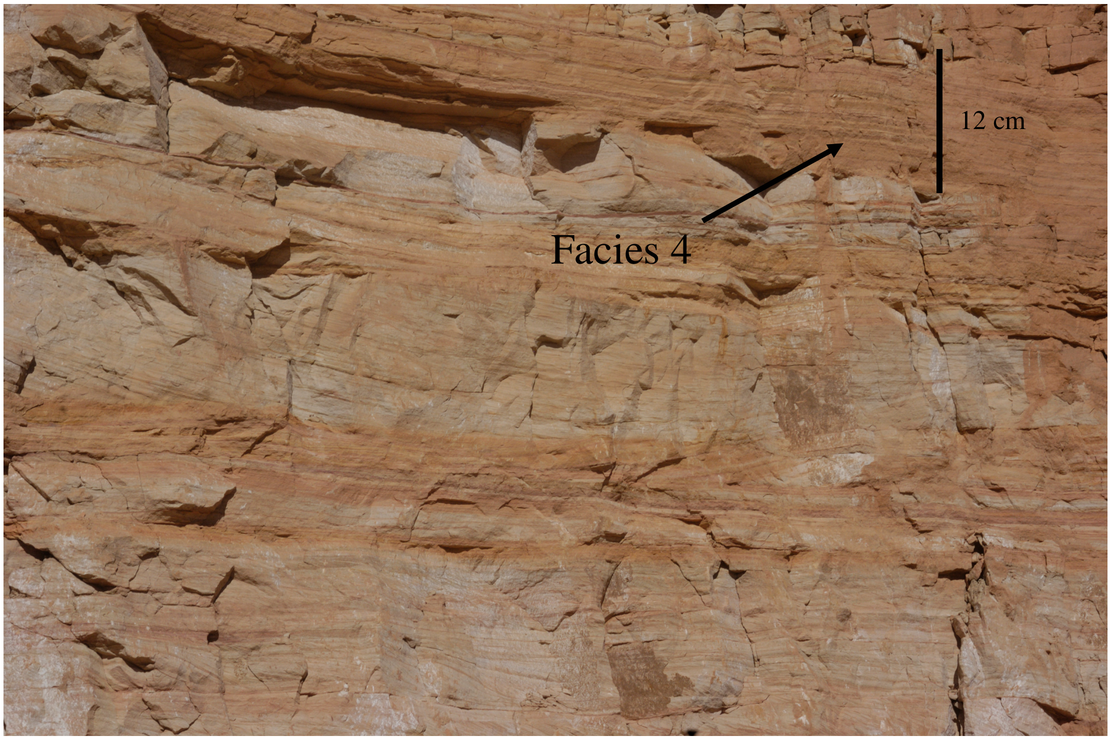


Figure 16. Facies 4 – Mud Layers (upper right).

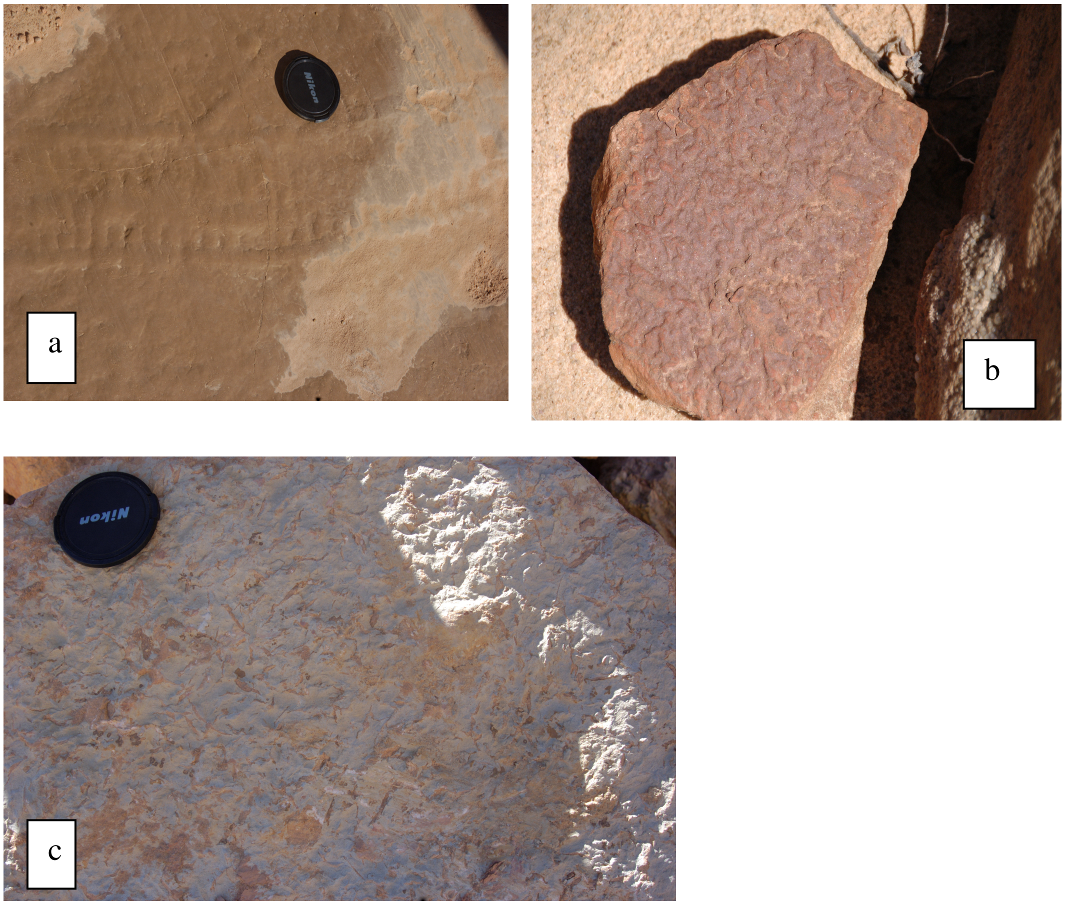


Figure 17. Trace Fossils and Bioturbation in the CarmeuseNA Quarry. a) *Cruziana* exposed in the quarry floor. b) *Planolite*s shown in sample from CarmeuseNA quarry. C) *Planolites*.

reported *Planolites* and *Cosmorhaphe* as sources of bioturbation. Wilson (2001) also observed more rare *Diplocraterion*, *Cruziana*, and *Skolithos*. Perez (2007) found *Skolithos*, *Planolites*, *Rusophycus*, and *Cruziana*. The incidence of bioturbation and trace fossils greatly increases both numerically and in occurrence once the Middle Hickory is reached, because the Middle Hickory is inferred to be a dominant marine-influenced region with minor fluvial input. Since in the Cambrian, all organic activity was limited to marine environments, this indicates that the upper part of the Lower Hickory may have been primarily a fluvial environment but with some definite marine influence to intrusion upsection.

LATERAL AND VERTICAL ARRANGEMENT OF FACIES (BEDSETS)

Although variations exist, facies types generally are grouped together into common arrangements. This vertical and horizontal organization can provide evidence for determining the environment of deposition for the given area and facies arrangement. The ideal vertical bedset would be large-scale cross-bed(s) overlain by small-scale cross-beds. These beds would be followed by either interbedded sand/silt/mud or thicker mud layers to form an overall fining-upward scheme. This pattern does occur occasionally, but can be difficult to accurately identify because of the overall lack of fines. Several basic lateral bedset arrangements were seen in the quarry walls and in core with normal lateral and vertical patterns. Perez (2007) found four end-member bedsets A, B, C, and D in the same area where this project was completed, and the findings of this thesis agree with his results. The listed bedsets correlate with the identically named bedsets of Perez.

Bedset A

This bedset consists of Facies 1 grouped in beds ranging in thickness from 10cm to ~ 2m. Average thickness is ~ 25-50cm. Observed thickness rarely exceeded 1m, but occasionally thicker beds were observed. Lateral extent can vary broadly, but can range from as little as several meters up to hundreds of meters, especially in the South wall perpendicular to flow direction. The cosets are mostly trough cross-beds with occasional plane beds and climbing ripples. Grain size just above the basal surface usually is medium or occasionally coarse sand and either fined upward slightly or continued as medium-size sand. These beds are sometimes underlain by a thin chaotic sandstone with either no visible sedimentary structures or very crude cross-bedding. The chaotic sandstone is very poorly sorted when observed, often dominated by medium grains, but also containing jumbled coarse and very coarse sand. Bedset shape is generally tabular. Dip of cross-sets in the bedset is to the south and southeast as usual, but occasionally sets dip in opposing directions showing what appears to be herringbone cross-bedding. In areas perpendicular to flow, the dip direction appears to be primarily oriented eastward. Bedset A is the most commonly seen bedset at the field site. This bedset corresponds to Bedset A from Perez (2007). Because this bedset consists almost exclusively of Facies 1, this likely represents a migrating dune field through a braided river. The basal erosion surface and internal inclined beds reported by Perez (2007) suggest migration across a bar with a gently sloping front face, such as a braid bar.

Bedset B

This bedset consists of a single bed of Facies 2, which grades into Facies 1 or vice versa. Facies 3 is usually observed to be overlying the cross-bedded part of the bedset, but Facies 1 and 4 are also seen at times. This overlying Facies 3 bed can vary from a few cm to ~35cm in thickness. The overlying bed is often thicker over the Facies 2 part than the Facies 1 part of the bedset. Sometimes, there is only a clay drape present instead of a bed. When Bedset B contains an isolated cross-set of Facies 2, it is sometimes seen in channel forms with a concave erosive basal surface. This erosive basal surface usually is observed cutting through Facies 1, but sometimes Facies 3 or 4. If not observed in channelized form, both the basal and top surfaces are usually planar and the basal surface is erosive. When Facies 2 grades into Facies 1, the dip of the cross-beds decreases downdip. This gradual decrease in cross-bed dip often forms the basal and top surfaces of the cosets of Facies 1, as the dip of Facies 2 is steeper than the dip on the cross-strata in Facies 1. The dip direction of both the Facies 2 solitary set and the Facies 1 cosets are both in the same direction – S-SE parallel to flow and East perpendicular to flow. When Facies 2 grades into Facies 1, the bed thickness sometimes thins downdip. When Facies 1 grades laterally into Facies 2, this may represent flow separation at the downstream face of a bar (Muller and Gyr, 1986; Perez, 2007). High-angle cross-beds were formed in the zone of separation as grainfall from suspended particles. In cases where Facies 2 grades into Facies 1, a reduction in flow velocity and/or flow depth is suggested. This flow variability affects sediment transport and scales the bedforms to the weaker discharge.

Bedset C

Bedset C consists of Facies 1 or 2 grading laterally into Facies 3 or 4. Toward the base of the South wall, almost all examples of Bedset C - with one notable exception - consisted of Facies 1 grading into Facies 3 or 4. Above this in the South wall and in much of the East and West walls, Facies 2 is observed in increasing number of bedsets. The most visible examples of Bedset C are made of Facies 2 grading into Facies 3, or more rarely, 4. In those sets of Bedset C formed by Facies 2, the large-scale cross-bed set thins out as it approaches the mudstone interval. This thinning may be the result of differential compaction of the mudstones. This bedset is interpreted to represent a channel-fill episode. The cross-stratified sandstone in Facies 1 or 2 may be formed during lateral bar migration in the channel, with the mudstone facies forming during channel abandonment.

Bedset D

Bedset D is formed where Facies 2 interfingers with Facies 3 or 4, or grades into one of them. This bedset is much less common than Bedset C. The primary distinction between Bedsets C and D is that in Bedset C, as described by Perez (2007), the cross-bedded facies grades laterally into mudstone. In Bedset D, the cross-bedded facies directly interfingers with the fine-grained layers and does not grade into them. The large-scale cross-bedding dip angle decreases slightly as it interfingers with the mudstone, but the decrease is not as great as that in Bedset C. This bedset represents rapid fluctuations in flow. Bedset D was reported by Perez (2007) and was suggested to record mouth bar deposits at the end of distributary channels.

HICKORY SANDSTONE FACIES INTERPRETATION

Facies 1

Facies A (stacked small-scale cross-bedding) is interpreted to show a field of migrating dunes during a period of net deposition (Bhattacharyya and Chakraborty, 2000) in a braided fluvial environment. Perez (2007) noted that this facies was likely migrating across the face of a bar. Most of the observed cross-stratification was trough cross-bedding, which forms as a result of dune migration. Dune height scales to the turbulent boundary layer of the transporting flow, which is the flow depth at the time of deposition (Willis, personal communication, 2003). This scaling indicates that flow depth would have been shallow during deposition of this facies.

The low variability of paleocurrents indicates an environment of unidirectional flow. This uniformity suggests a fluvial origin, rather than marine, and a braided stream origin rather than meandering. The rare, but observed, reverse dip in the form of herringbone cross-bedding or very rare isolated cross-strata set, though, does suggest some tidal activity interacting with the fluvial channels. The occasional reactivation surfaces represent a time when dune formation was halted temporarily. This temporary cessation of dune formation allows some erosion of the lee face to occur and then restart (McClane, 1995). Reactivation surfaces can occur in fluvial environments, but are much more common in tidal areas (Eriksson et al., 1998).

Common planar cross-strata indicate that grain flow was dominant and argues for a higher flow velocity (Bhattaryya and Chakraborty, 2000). The higher dip angle approaching the angle of repose indicates a flow in the lower flow regime. At times, the cross-strata geometry changes from higher-angle planar cross-strata to a more concave geometry downdip. This variation in cross-strata suggests that flow strength is decreasing. As a result, the dominant form of sediment deposition is changing from grain flow to grain fall in the zone of flow separation on the lee side of the dune (Chakraborty and Bose, 1992; Bhattaryya and Chakraborty, 2000). Sigmoidal cross-bedding was very rarely observed, but did exist. It occurs when stoss-side erosion is inhibited because of high rates of dune aggradation compared to migration, and the topset can be preserved (Chakraborty and Bose, 1992).

Facies 2

Large-scale, often solitary, cross-bedding (Facies B) are generally similar in characteristics to Facies 1. Cross-bed sets have a more tabular to wedge-shaped geometry. Dunes would be considered as a possible origin, except that, as mentioned previously, dune height scales to flow depth. Water deep enough to form dunes of this magnitude (up to 1-1.5 m) would have too great a variation to form the cross-strata found in Facies 1. This facies is interpreted to be tidal sandwaves or fluvial or tidal bars. Both sandwaves and bars are most likely represented here. Cross-bedding with tabular bed geometry is usually considered to be derived from sandwaves (Eriksson et al, 1998), which can occur both in fluvial and tidal environments (McClane, 1995). The mud drapes sometimes found in this Facies are a common, although not exclusive, tidal signature. On the South wall, which is the lowest part of the Hickory at the site, Facies 2 does not appear in any significant amount until approximately one-third of the way up the wall. Abundance of Facies 2 increases up the section.

Facies 3

Facies 3 (interbedded sand/silt/mud) is wavy to connected lenticular bedding. This facies would be formed where flow velocity and energy varied quickly. Sand would be deposited in times of higher energy, and silt and mud in quieter waters. During sand deposition, the flow was in the lower low flow regime, because ripples are often seen. Perez (2007) reported occasional small-scale cross-bedding in the sandy strata of this facies, but it was not observed by the author. The sand was likely transported by traction transport and the mud was deposited from suspension (Bhattacharyya and Chakraborty, 2000). This facies could result from flood events in fluvial settings (Bhattacharyya, 1997) or from tidal activity.

Facies 4

Facies 4 is found in both laminations and beds. It would be deposited from suspension in quiet waters. Facies 4 is often seen in isolated beds with a concave-upward geometry, probably resulting from compaction. The thickness of the beds suggests deposition over a longer period of time. In the visible channel forms, it represents the final episode of channel fill from the fine sediments left in suspension. In instances where it can be traced for longer distances, it appears to be more indicative of quiet waters, probably in a marine environment. Facies 4 was the only facies, aside from occasional sightings in Facies 3, where trace fossils were observed. Bioturbation was not observed near the base of the core, but appeared and became more common up the section. *Cruziana* and *Planolites* were observed in the quarry setting and *Planolites* was seen in core. Since during the Cambrian, all known aquatic life was marine, this suggests that this facies was deposited in a marine setting. *Cruziana*, the trailway of trilobites, is thought to occur in a shallow marine setting between the littoral and neritic zones (Seilacher, 1967; Bhattacharyya and Chakraborty, 2000). *Planolites* is found near the shoreline to the shallow shelf (Boggs, 2001; Perez, 2007). The environment of deposition for this facies, especially higher in the section, is interpreted to be nearshore shallow marine.

REGIONAL PALEOTOPOGRAPHIC CONTROL ON HICKORY DEPOSITION

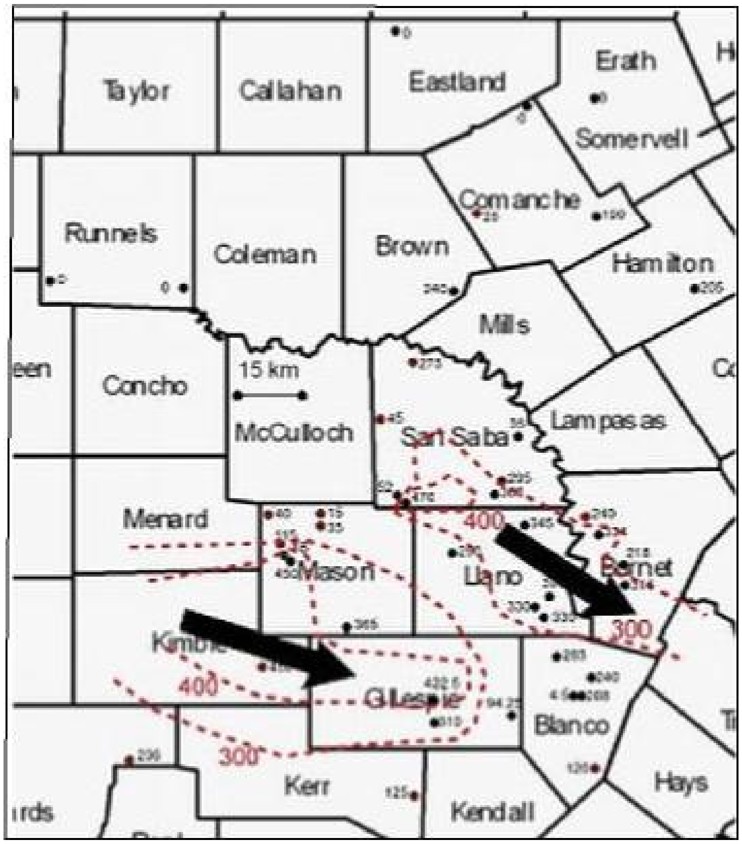
The paleotopography of the area underlying the Hickory has been described as a bedrock-controlled ridge and swale topography oriented northwest to southeast which formed by differential erosion of metamorphic bedrock (Barnes and Bell, 1997; Krause, 1996; Wilson, 2001). The general topography is estimated to be similar to that of the present. Gneissic and granitic ridges alternated with swales formed from comparatively soft schist. If this occurs, Hickory thickness would be expected to vary considerably over central Texas, showing these high and low trends. Thickness should increase over swales and decrease as ridges are approached and accommodation space is reduced. If so, a pattern can be traced showing valleys where fluvial systems could have prevailed, forming the braid deltas discussed by Perez (2007). This mapping would also provide an idea where Lower Hickory deposits should be found, because these fluvial to marine-influenced deposits would be found near the swales. Thinner areas would likely contain strata deposited later in the transgression, when upper Middle and Upper Hickory were deposited.

Hickory thickness measurements were gathered from core and well descriptions throughout a number of counties in central Texas where the Hickory is known to exist. These data were used to determine the thickness of the Hickory at each location. The primary counties where cores and/or wells penetrated the Hickory were Burnet, Llano, San Saba, Mason, Gillespie, and Blanco counties. A listing of the data by name and county is shown in Appendix 4. These thicknesses were then plotted on a map of central

Texas to make an isopach map of the Hickory Sandstone. This map does show the thickness of the entire Hickory at each location, instead of just the Lower Hickory.

Total thickness measurements for the sampled locations spanning 15 counties from Barnes and Bell (1977), Krause (1996), and Graff (2006) were plotted on a map of the previously mentioned central Texas counties. This map was then contoured using one hundred foot intervals for thickness. Figure 18 shows the resulting Hickory isopach map. Thickness trends running in a northwest-southeast direction can be observed readily and traced on a regional scale. Swales are indicated where thickness is greatest, and conversely, ridges are shown as lower values.

The overall result of the isopach mapping is similar to the map of observed granitic bodies in Krause (1996), and it gives further evidence to the idea that the paleotopography acted as a major control on Hickory deposition. The orientation of the trend also correlates to paleocurrent directions seen both in this study and reported in previous studies (Wilson, W.F., 1962; Cornish, 1975; Wilson, J.S., 2001) , where the primary direction of flow reported was to the south and southeast at the time of deposition. Fluvial systems could follow these trunk valleys south to the Western Iapetus Sea. The ridges on each side would prevent a birdsfoot delta from forming, but would allow for the formation of braid-deltas as discussed for the Hickory by Perez (2007) like those in Figure 19. These ridges that form the sides of the enclosed platform would maximize inland tidal range and power into the braided fluvial system. These tides would rework the deposits slightly, causing observed clay drapes, rare bimodal cross-bedding, and bioturbation. Sitting on the edge of a large, gently sloping



Hickory Sandstone Isopach Map

Contour Interval = 100 ft.

Arrows indicate suggested direction of paleoflow.

Figure 18. Isopach Map of the Hickory Sandstone in the Hill Country of Central Texas. Arrows show the direction of flow.

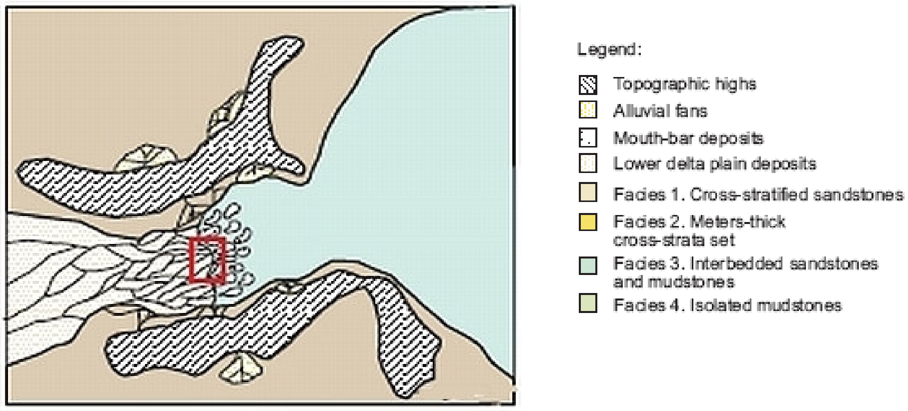


Figure 19. Cartoon Plan View of Braided-river Delta Proposed for This Region by Perez (2007). Red box represents the study area and flow direction follows the arrows in Figure 16.

platform would serve to minimize wave action, preventing wave reworking from occurring. This would explain why oscillation ripples and hummocky cross-bedding have not been found in the Lower Hickory.

During transgression, the sea would have transgressed from southeast to northwest on Figure 16. Fluvial deposits would predominate during the Lower Hickory to be covered as sea level rose. Sediments traveling through the braided fluvial system as shown in Figure 17 would form Facies 1 and 2. Facies 1 would be formed by migrating dunes traveling through the braided stream and into the braided-river delta at the mouth. Facies 2 may be formed in the braided stream as a bar, but also could take the form of mouth bars just at the mouth of the delta. The tidal influences here would rework the sand into tidal or mouth bars at this location. Very similar bars to Facies 2 have been found as tidal bars in a similar environment.

DISCUSSION

The preponderance of unidirectional small-scale cross-bedding, the comparatively large grain size, and an overall scarcity of bioturbation in the field site indicate a primarily fluvially-influenced environment for the upper Lower Hickory. The comparatively large grain size of the sediment deposited suggests a rapid flow (Perez, 2007). Together with the mostly unimodal cross-bedding, this high flow velocity points toward a fluvial setting. Marine influence is noted, however, by occasional herringbone cross-bedding, some bioturbation in the mid to upper part, fairly common reactivation surfaces, and the wavy to connected lenticular bedding in Facies 3. The herringbone cross-bedding indicates a tidally-influenced environment, as the ebb and flood tides produce cross-stratification in opposing directions. None of these signs are exclusively marine, however. Although almost always tidal, herringbone cross-bedding can also be found in fluvial (Bhattacharyya and Chakraborty, 2000; Alam et al, 1985; Allen, 1980) as well as lacustrine environments (Friedman et al, 1992). However, when found in connection with the observed bioturbation, a tidal inference can logically be made. Because bioturbation in the Cambrian is associated exclusively with marine environments, the trace fossils (*Planolites* and *Rusophycus*) that were found indicate a marine influence at some point in the upper Lower Hickory. Reactivation surfaces can be associated with fluvial activity when stage change occurs, but are more often associated with tidal activity on low tidal bars, because during tides, the stages change regularly (Allen, 1980; deMowbray and Visser, 1984; McClane, 1995; Bhattacharyya and Chakraborty, 2000).

The dominant marine influence appears to have been tides, where the interaction between fluvial and tidal forces was the main force controlling the deposition of sediment. Bi-directional oscillatory ripples were not seen in this study, which indicates that waves did not strongly influence sediment deposition patterns. This would seem likely, because the Texas Platform was located along a shallow epicratonic embayment on the Western Iapetus Sea (Krause, 1996). Epicratonic embayments tended to have wide shelves, which would dampen the force of incoming waves, but would serve to strengthen tidal forces. Tidal reworking of the fluvial deposits probably occurred, but the large grain size would have prevented a wholesale reworking, which may explain why tidal features are present but not abundant. Most likely, either tidal forces were not strong enough to thoroughly rework the medium to coarse sand or the sediment was deposited quickly enough that there was no time for tides to rework it. This comparative lack of tidal features suggests that fluvial processes predominated even slightly into the epicontinental sea. A braided river-dominated delta in a tidal environment is interpreted to be the overall environment of deposition, because it would allow for fluvial influence to persist into a marine setting, but would provide a tidal reworking as the sediment was deposited. A delta of this type would not produce lobes such as a modern "bird's foot" river-dominated delta, but would be a line-source of sediment.

The fluvial deposits are interpreted to be from braided stream. Fines are not abundant, and most of the sediment is medium to coarse sand. Sediment of this size would only be transported as bedload in normal flow conditions. Slope and sediment load are generally higher in braided streams than in meandering streams. Braided channels tend to be bedload-dominated, and would be expected in this pre-land plant environment. Overbank deposits were not seen in any significant amount, which would be expected for braided streams, but would be unexpected in meandering fluvial deposits (McClane, 1995). There is a question whether any pre-Silurian meandering stream has ever been properly identified.

Paleocurrents were, with a few exceptions, uniform. This would not be as likely in a stream without comparatively straight channels, as there is no evidence of the flow changing direction near meander bends. Locally, braided streams can have a wide variety of paleocurrent directions, but as a whole, there should be one dominant cross-strata direction (Coleman, 1969; Reinick and Singh, 1975).

Topography at the time of Hickory deposition is believed to be the same as it is now – rolling topography – and the hills of the Town Mountain Granite acted as a sediment source and controlled the deposition of the Hickory. The large grain size of Facies 1 and 2 (largely medium- to coarse-grained with some fine grains) suggest that the site of deposition was close to the source area. Fines were either winnowed out or energy was too high to allow them to be deposited, except during channel abandonment or avulsion or in quieter tidal flats. The Hickory varies in thickness from zero to several hundred feet and this was controlled largely by the Town Mountain Granite and resistant gneiss and marble ridges. Together, a mountainous area with a high sediment supply is the ideal condition for braided streams, because a greater slope and sediment supply select for braided streams over meandering streams.

Past studies of the Lower to lower Middle Hickory have generally interpreted the lower Lower Hickory to indicate alluvial and fluvial facies, which grade into more marine-influenced facies by the upper Lower Hickory and become noticeably marine by the lower Middle Hickory (Goolsby, 1957; Barnes and Bell, 1977; Krause, 1996; Wilson, 2001). With the exception of Cornish (1975), all workers have interpreted the lower Lower Hickory to consist primarily of braided fluvial deposits. The Lower Hickory is mainly bedload, and has nearly unimodal cross-bedding with well-developed large-scale cross-bedding. These correlate with braid characteristics noted by Moody-Stuart (1966) and fit a braided fluvial environment much better than a meandering fluvial setting.

The exact nature of the marine-influenced to marine environment is more questionable. Studies by Goolsby (1957) and Kim (1995) reported deltaic deposits in the Lower Hickory. Cornish (1975), Krause (1996), and Wilson (2001) all preferred an overall estuarine environment, although the details varied greatly. Cornish thought that the sands in the Lower Hickory represented outer estuarine sands with shoaling that grade up into an inner estuarine environment. These then were somehow capped by outer estuarine sands. Krause and Wilson disagreed and both interpreted the sands in the lower Lower Hickory as primarily braided fluvial with some alluvial that become more marine upsection, and then progresses to strictly marine as the Middle Hickory is reached. Krause interpreted the earliest signs of marine transgression to show intertidal sand flats by shallow estuarine embayments and a low-energy shoreface on a shallow, protected inner platform. This was overlain by facies representing subtidal estuarine embayments and fluvially-fed sand flats as the Middle Hickory begins. Krause preferred to explain the Hickory as a continuous transgression over a complex landscape and does not specifically give one overarching environment of deposition, although estuarine references abound. Wilson associated the upper Lower Hickory with Reinson's (1992) tide-dominated, high-microtidal estuarine model.

A point to consider is that all workers have looked at limited exposures or cores. There are no widespread available outcrops than can be followed for a long distance. As noted by Wilson (2001), the Hickory covers a large area that is locally controlled by the Precambrian ridge and swale topography. As such, observations from such limited core or field work cannot be extrapolated to represent the Hickory as a whole with any guarantee of accuracy. The thickness varies enormously in a regional sense, with various facies being in contact with bedrock in different locations. In some areas, the Lower Hickory has not been reported at all, depending on the paleotopography. Interpretations for the Hickory have commonly been either estuarine or deltaic, but both could be correct, at least in a local sense. The primary indisputable point is that a transgression occurred and is recorded by the Hickory.

This present study suggests a general gradation from more fluvially-influenced deposits near the base of the study site toward marine-influenced fluvial deposits. This indicates that an overall transgression took place. It would seem difficult to ascribe Hickory deposition as a whole to a large-scale prograding deltaic environment during a transgressive event. In any case, the ridge and swale paleotopography of the depositional area would make a large-scale fluvial delta unlikely. Perez (2007) described the field site as the result of a line-source braid-delta. Small-scale braid-deltas could be formed anywhere where the existence of eroded swales allowed transport of large amounts of coarse-grained sediment by braided streams from the granitic ridges. This could result in the development of smaller deltaic deposits within an overall transgressive, possibly estuarine, environment.

The deltaic facies reported by Kim (1995) and Goolsby (1957) could easily be deposited in this environment. This present study also reports deposits indicating a small-scale deltaic environment, and a braid-delta explains this well. The ridge and swale topography would almost require such a depositional setting in areas of net accumulation. The ridges would prevent a typical “birdsfoot” delta from forming easily even if a meandering stream existed, instead of a braided stream. The amount of available accommodation space may have influenced the deposition. Some channel forms are observed, but largely the sand appears to have been deposited in non-channelized flows. Amalgamated sandstone bodies are common in areas where accommodation space is low (Sønderholm and Tirsgaard, 1998). Overbank deposits are not commonly preserved in areas with low accommodation space, leaving sand bodies or sheets as the predominant facies. This relatively small amount of fines in areas of low accommodation space seems to correlate with the Hickory. If braid-deltas are building out into a broad, shallow seaway, any fine-grained materials deposited would have been quickly removed.

Grain size is another issue. Comparatively few silt- to clay-size beds are seen, although they do exist. Sand is almost exclusively found in the Hickory, especially coarser grain sizes. Reworking of the original deposits by tide or wave activity could remove fines and leave sand in place. Some reworking probably occurred, but not enough to destroy the unimodal cross-bedding or add abundant clay drapes. Although a tidal signature can be clearly observed, so also can the fluvial imprint of the deposits. On the other hand, the near proximity of the source area and the transport capability of the braided stream flow would carry large amounts of coarse sediment easily.

Correlation with Previous Studies

The Lower Hickory in the study area is considered to correlate primarily to Krause's (1996) HX cross-bedded lithofacies, specifically subfacies HXc which describes a transition from terrestrial fluvial to marine (Perez, 2007). It is suggested, however, that the base of the South wall may be transitional from HXb (Krause's channel fill and channel-margin deposits) to HXc. This statement is suggested because, although mudstone is more abundant than Krause observed, it is limited in lateral extent, and bioturbation and herringbone cross-bedding were not noticed in any abundance in the basal 1/3 to1/4 of the South wall. It also correlates in general to Wilson's (2001) XB2, but again appears to be near the base of XB2, just above the transition zone from XB1 to XB2. The transition to XB2 is complete slightly up the South wall and almost completely over the East and West walls. According to Wilson, XB2 marks the first occurrence of bioturbation in the Lower Hickory. This estimated division of XB1 and XB2 at the field site would make XB2 thinner than was estimated by Wilson, but the thickness of the Hickory varies enormously based on the ridge and swale paleotopography of the Texas Platform.

Pre-Silurian Sedimentology

The major part of the difficulty in distinguishing fluvial from shallow marine environments before the Silurian is the lack of land plants and bioturbation in fresh and possibly brackish water. The lack of land plants allowed for flashy runoff, and higher mechanical weathering rates than would otherwise be expected. A deficiency of bioturbation in strata of this early age prevents the easy distinguishing of cross-bedded sandstones as either shelf or terrestrial. For this thesis research, tidal features and some bioturbation were available to help distinguish fluvial from shallow marine facies. Otherwise, the predominance of unimodal cross-bedding would be the primary method of determination available. Moderate sorting observed in core is also an indication of a fluvial setting (Banks, 1973; Bose and Chakraborty 1994), but neither is completely reliable for this purpose. Together, they would have allowed the recognition of the primary fluvial contribution, but not given an adequate view of the important marine influence that interacted with it in the braid-delta. If bioturbation is found in strata of Cambrian age, however, it is a definite sign of marine activity.

CONCLUSIONS

The upper Lower Hickory Sandstone as seen in the South, West, and partial East walls of the CarmeuseNA sandstone quarry is a transgressive sand with four primary facies, as follows: 1. Stacked, small-scale cross-bedding, 2. Large-scale cross-bedding, 3. Interbedded mud/silt/sand, and 4. Mud facies. Unimodal cross-bedding and a larger grain size point to a fluvial braided stream environment. However, irregular occurrences of herringbone cross-bedding, mud drapes, reactivation surfaces, and occasional wavy to connected lenticular bedding in Facies 3 require a marine influence on the braided streams, which increases higher in the Hickory. Individually, these features could also be formed in a fluvial or lacustrine setting; but taken as a whole, they indicate a shallow-marine to nearshore region. The features are distinctly characteristic of a tidally-influenced setting, and evidence of wave activity was not seen. As well, bioturbation was found in Facies 4 and occasionally in Facies 3, namely Cruziana and Planolites. This bioturbation lends further evidence to the opinion that this was, at least part of the time, a marine setting.

This combination of braided fluvial processes with a high sediment load and a marine influence increasing up the section points to a line source of sediment supply into a nearshore eipiric sea. When looking at larger areas, the Hickory can look estuarine and was classified as such by Cornish (1975) and Wilson (2001). However, the braid-delta suggested by Perez (2007) fits the available field evidence best and the author agrees with that classification. The upper Lower Hickory is best described as an amalgamation of point-source braid-deltas in a ridge and swale topography. Isopach mapping of the

Hickory shows a northwest-southeast trend of thicknesses, forming in the swales and dying on the ridges. These thickness trends follow the paleocurrent direction and show an ideal environment for the braided-river deltas to form during a period of transgression. Sediment was supplied from the surrounding granitic peaks and inselbergs and transported in a braided system funneled through the mostly schistic swales that fed a local tidal shallow-marine setting, primarily intertidal flats and delta plain and front.

There are two primary questions addressed in this study. The thesis addressed whether pre-Silurian environments could be distinguished with more certainty, especially relation to marginal marine and fluvial environments. Data available such as paleocurrent direction, bioturbation, and common tidal markers allowed a more reliable environmental interpretation. This study also attempted to identify a primary environment of deposition for the Lower Hickory Sandstone. A braided-river delta in a ridge and swale setting fits all available data for the local setting and appears to be the primary depositional environment. This is limited in this study to a local area. The Lower Hickory appears to vary little over its extent, though, so it is likely that a braided-river delta would largely explain its deposition. However, more work in other areas of the Lower Hickory could be correlated to this study and may result in refinement or re-examination of this conclusion. Isopach mapping of more Hickory thicknesses in the Llano region would also provide additional data for the deposition of the Hickory.

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APPENDIX 1: MAPPED PHOTOMOSAICS OF THE CARMEUSENA QUARRY SOUTH WALL

Figure 1-1: CarmeuseNA quarry South wall part 1 – Eastern edge of studied outcrop on left. Red lines indicate major surfaces that could be traced for long distances. Vertical exaggeration for all South Wall mosaics = 2x.

Figure 1-2: CarmeuseNA quarry South wall part 2

Figure 1-3: CarmeuseNA quarry South wall part 3

Figure 1-4: CarmeuseNA quarry South wall part 4

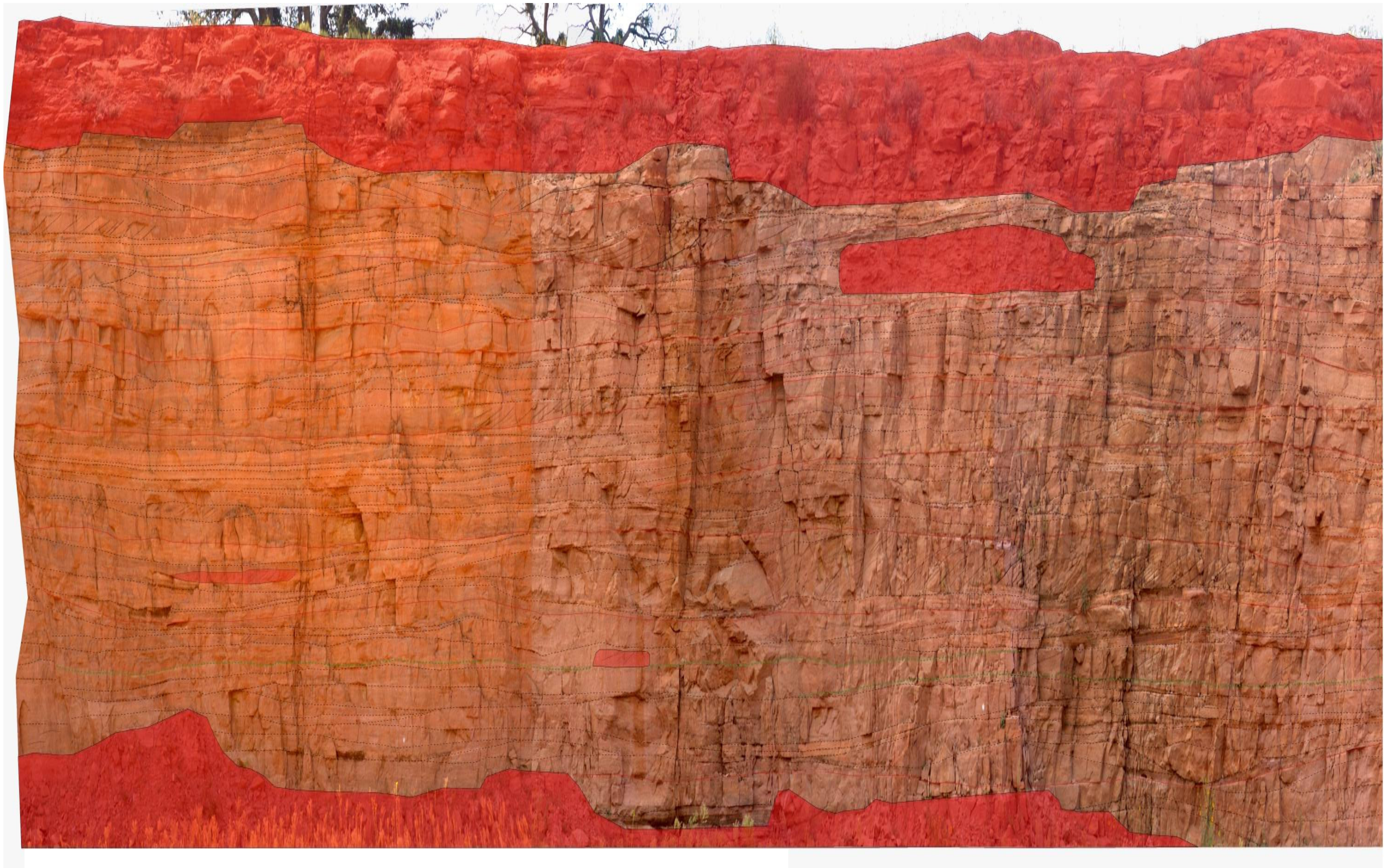

Figure 1-5: CarmeuseNA quarry South wall part 5

Figure 1-6: CarmeuseNA quarry South wall part 6

Figure 1-7: CarmeuseNA quarry South wall part 7

Figure 1-8: CarmeuseNA quarry South wall part 8. Far western side of South wall.

APPENDIX 2: MAPPED PHOTOMOSAICS OF THE CARMEUSENA QUARRY WEST WALL

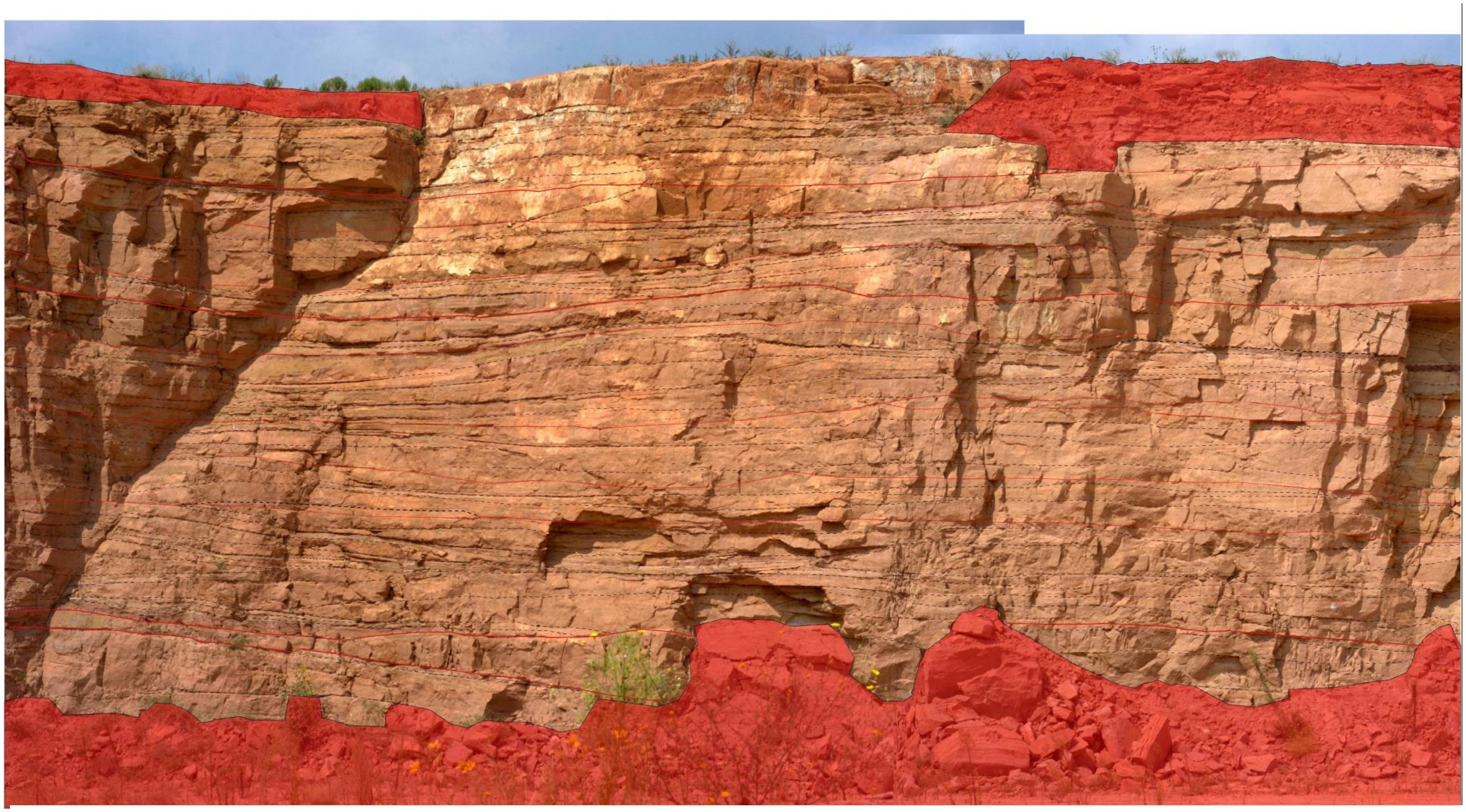

Figure 2-1: CarmeuseNA quarry West wall part 1. Far southern side of West wall.   No vertical exaggeration.

Figure 2-2: CarmeuseNA quarry West wall part 2. No vertical exaggeration.

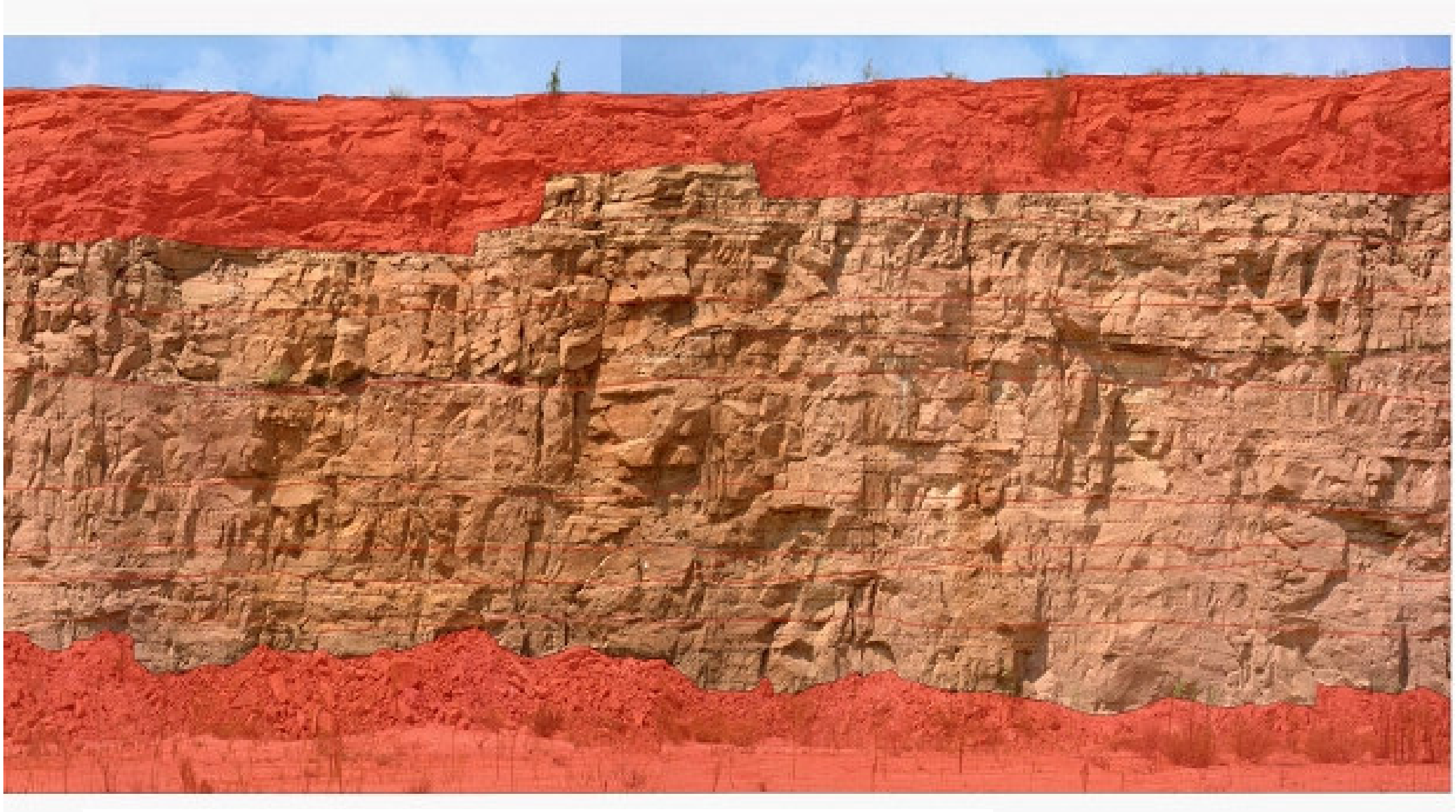

Figure 2-3: CarmeuseNA quarry West wall part 3. VE=1.5x.

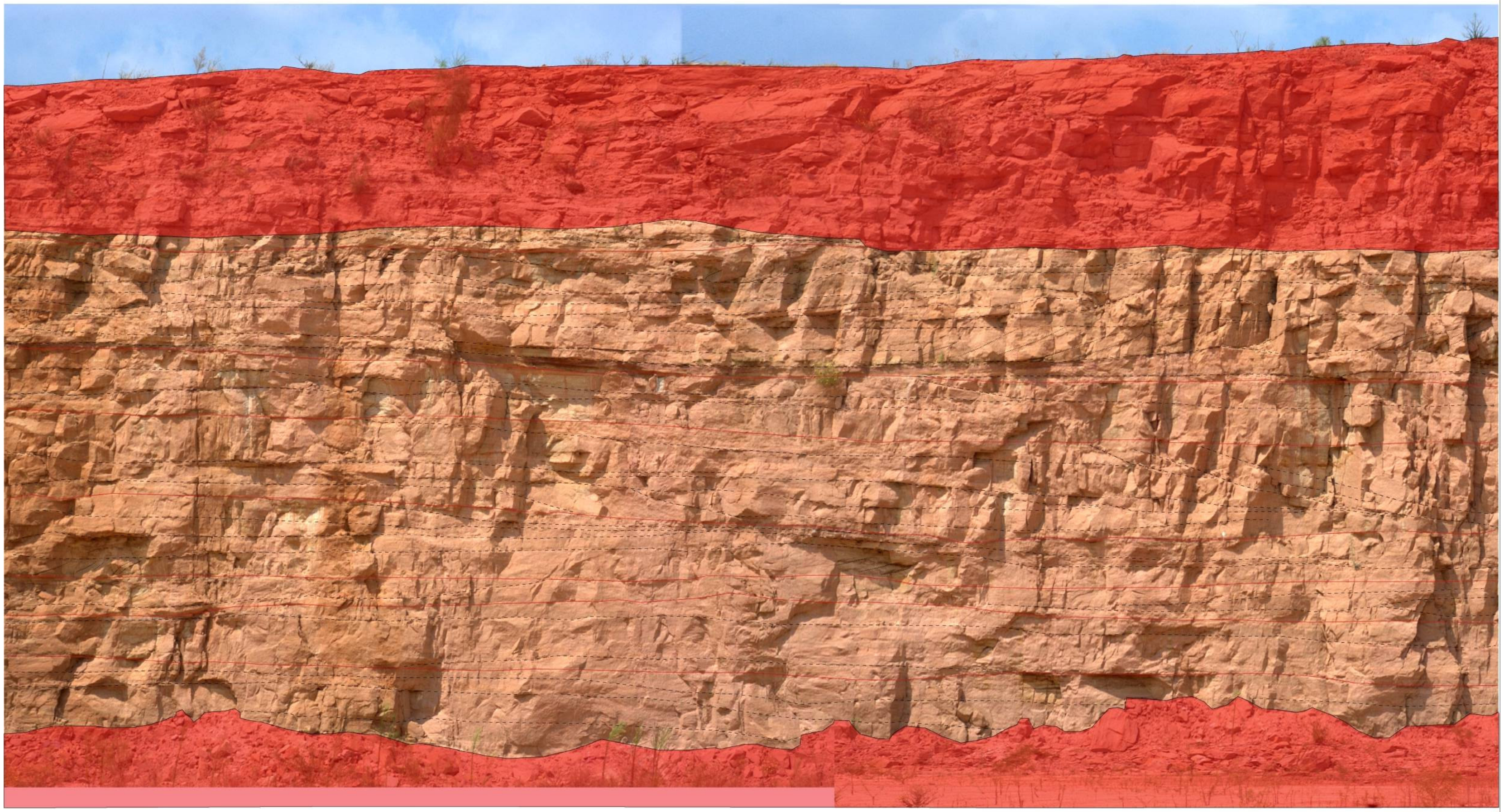

Figure 2-4: CarmeuseNA quarry West wall part 4. No vertical exaggeration.

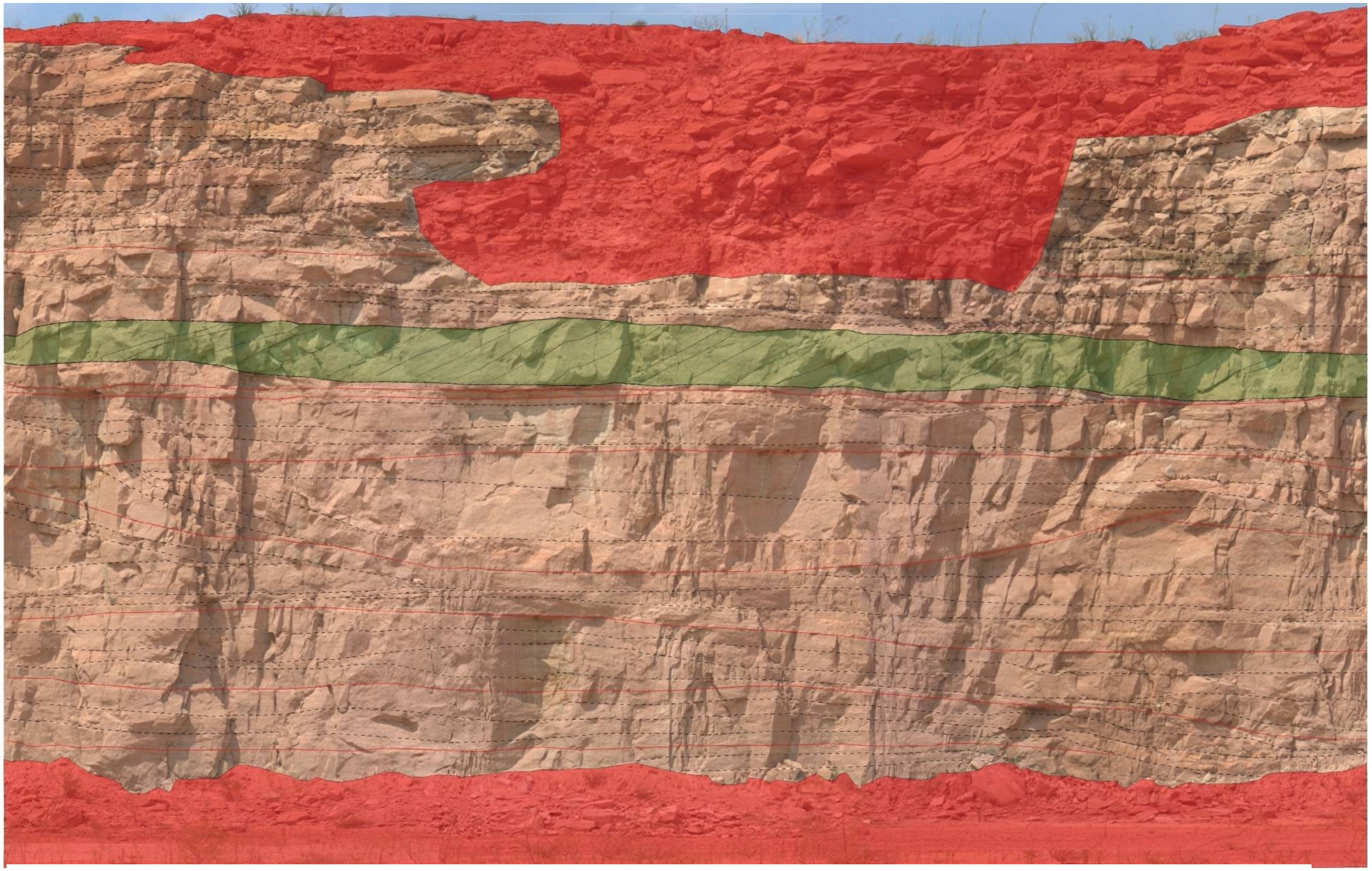

Figure 2-5: CarmeuseNA quarry West wall part 5. No vertical exaggeration. Green area shows extent of Facies 2.

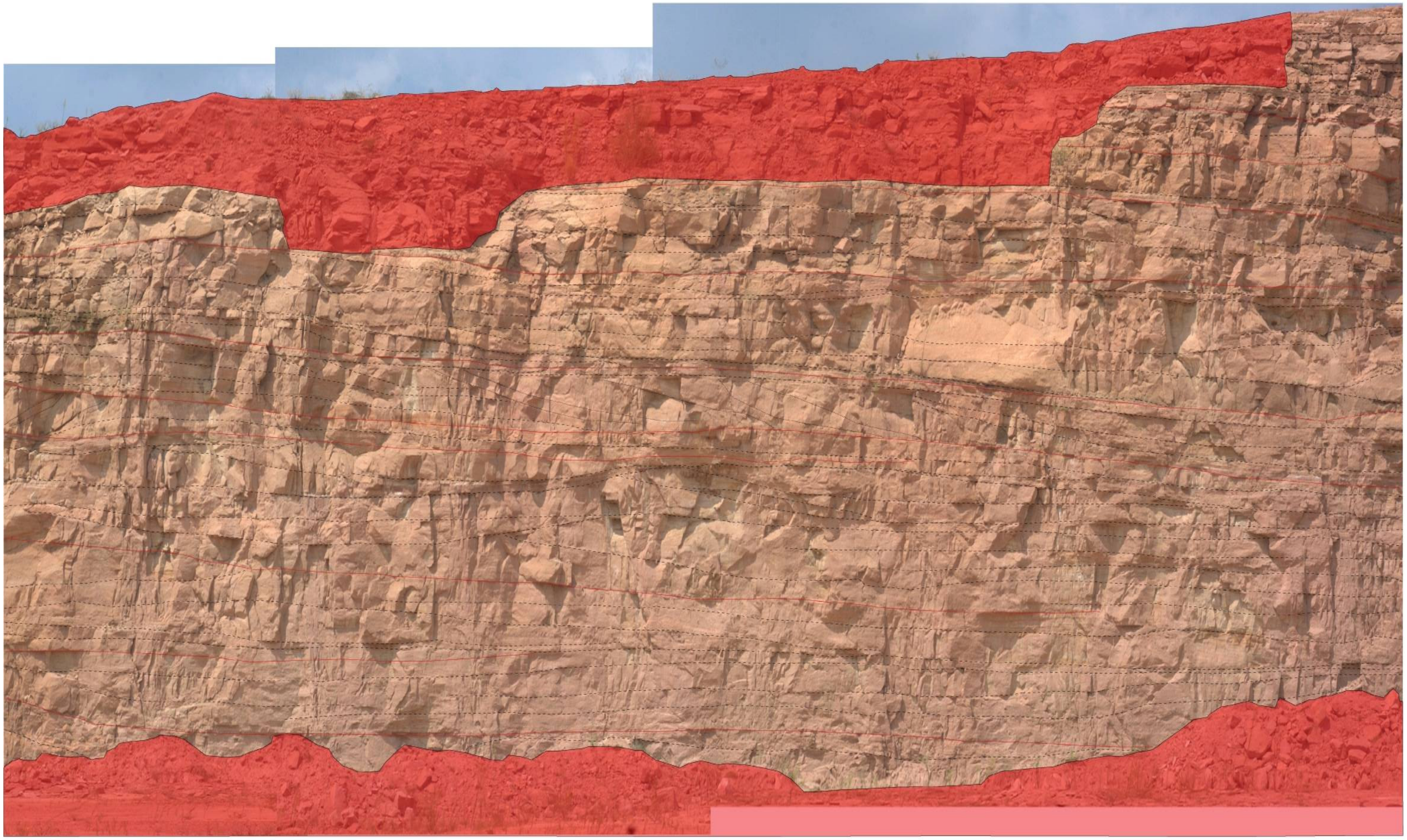

Figure 2-6: CarmeuseNA quarry West wall part 6. VE=1.5x.

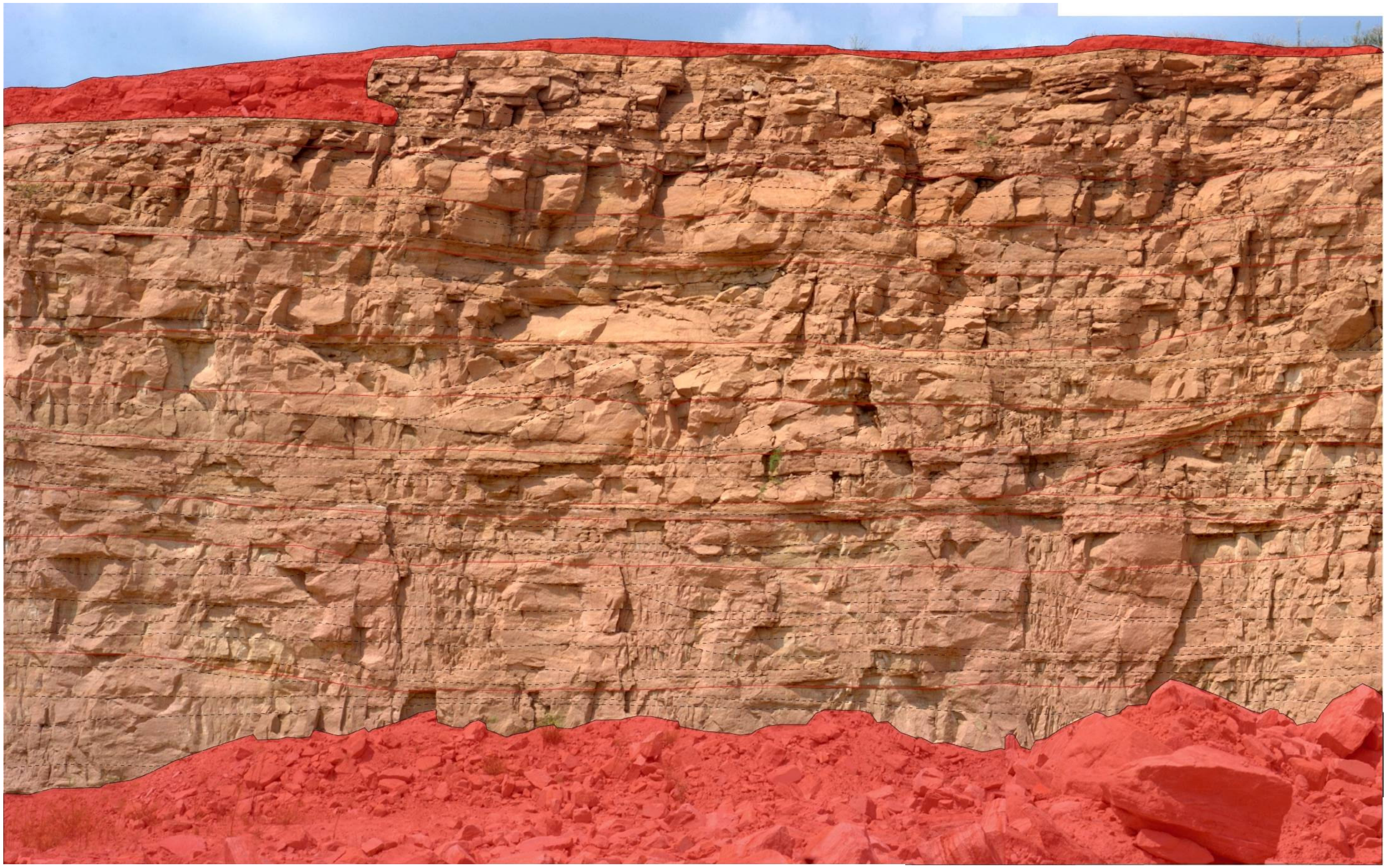

Figure 2-7: CarmeuseNA quarry West wall part 7. No vertical exaggeration.

APPENDIX 3: MAPPED PHOTOMOSAICS OF THE CARMEUSENA QUARRY EAST WALL

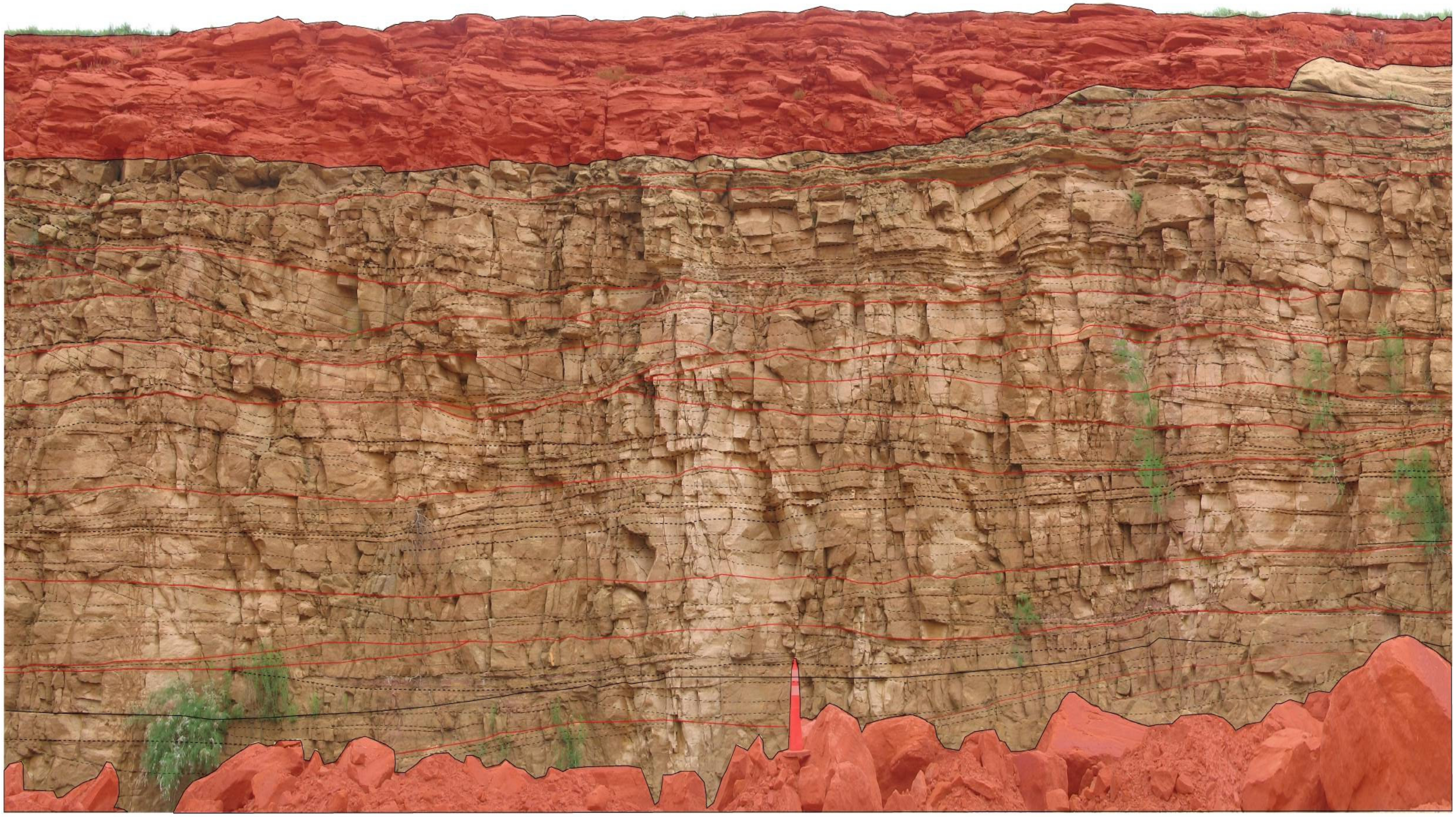

Figure 3-1: CarmeuseNA quarry East wall part 1. VE=1.5x

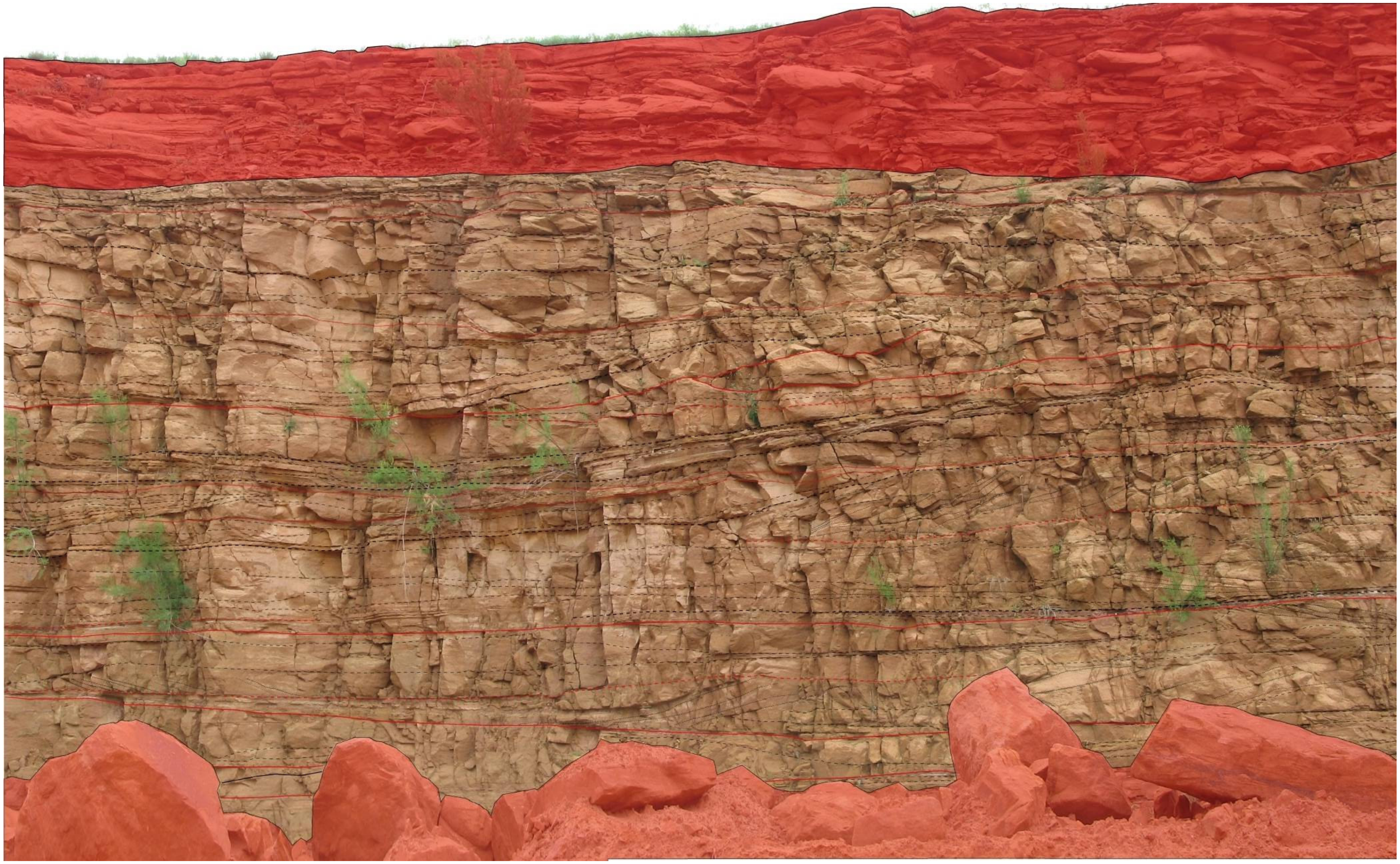

Figure 3-2: CarmeuseNA quarry East wall part 2. No vertical exaggeration.

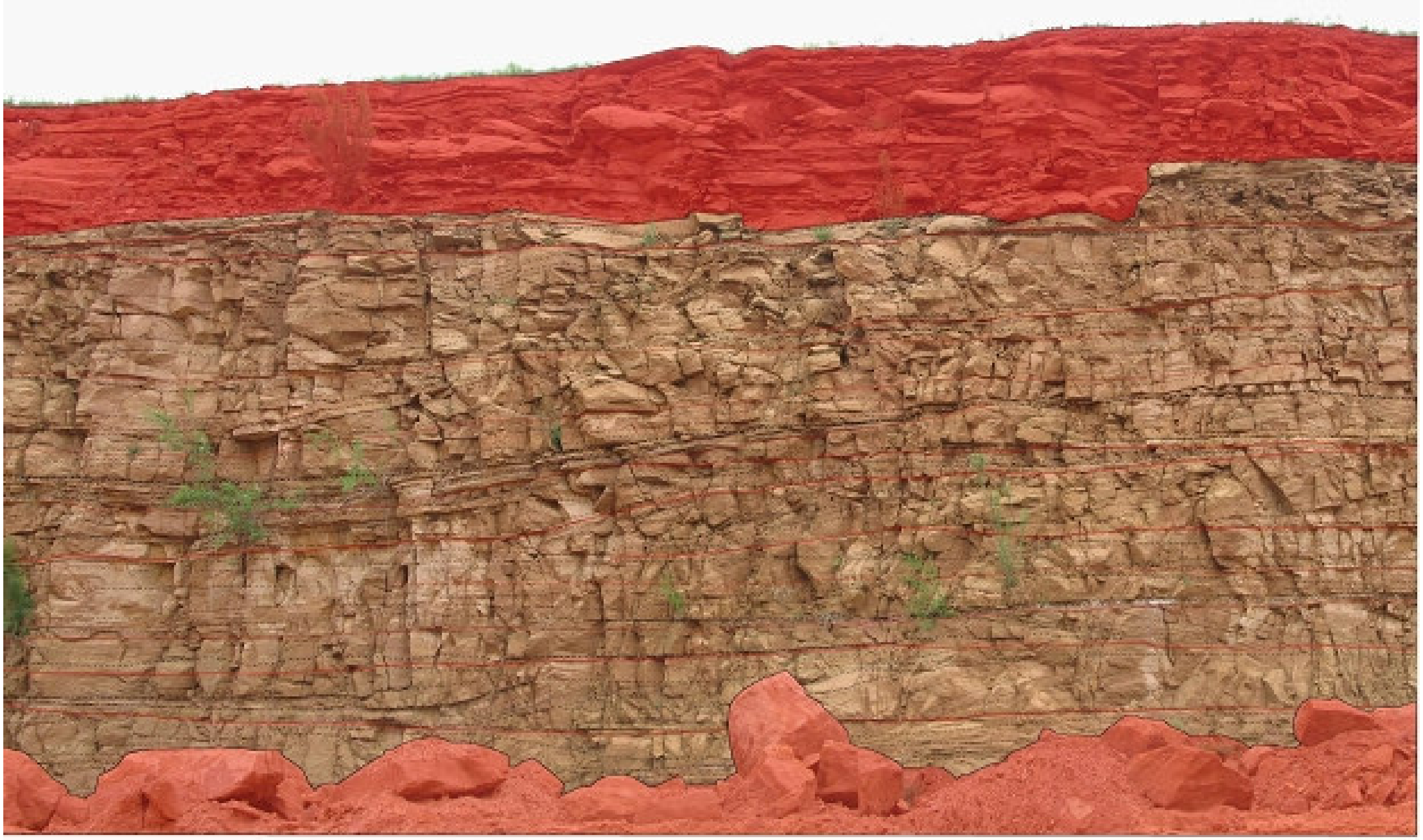

Figure 3-3: CarmeuseNA quarry East wall part 3. No vertical exaggeration.

APPENDIX 4: CORE AND WELL NAMES AND LOCATIONS FOR THE HICKORY SANDSTONE ISOPACH MAP

Map #	Name	County	Thickness (ft)	Precambrian Bedrock Present
1	Threadgill Creek	Mason	365	yes
2	Pontotoc	San Saba	470	yes
3	Slick Mountain	Llano	290	yes
4	Little Llano River	San Saba	360	yes
5	Montgomery No. 1 Yates	San Saba	295	yes
6	Carter Ranch	Llano	345	yes
7	Packsaddle Mountain	Llano	390	yes
8	Moore Hollow and East Canyon	Llano	330	yes
9	White Creek	Blanco	285	yes
10	City of Fredericksburg No. 9	Gillespie	310	yes
11	Humble No. 1 Millican	San Saba	35	yes
12	Morgan Creek	Burnet	334	yes
13	T. F. Murchison Ranch Well	Burnet	315	yes
14	Stratoray No.1 Stribling	Blanco	240	yes
15	Riley Mountain Composite Section	Llano	330	yes
16	Danewood No. 1 Smith	Brown	240	yes
17	Phillips No. 1-A Towson	Hamilton	205	yes
18	NNR-4	Mason	450	yes
19	Klett-Walker	Blanco	4.5	yes
20	Hog Thief Bend #74-1 Core	Blanco	208	yes
21	Slaughter Gap #1 Core	Burnet	218	yes
22	Detmer Property #1 Core	Gillespie	422.5	yes
23	Iron Rock Creek #5 Core	Gillespie	94.25	yes

Map #	Name	County	Thickness (ft)	Precambrian Bedrock Present
25	Harvey No. 1 Giesecke	Runnels	0	yes
26	Humble No. 1 Autry	Comanche	190	Yes
27	Gallagher & Lawson No. 1 Bobby Terry	Comanche	0	Yes
28	Continental No. 1 Wiley	Erath	0	Yes
29	Bilsky No. 1 D. P. Mitcham	Eastland	0	Yes
30	Superior No. 1 McDowell	Runnels	0	Yes
31	Shaw No. 1 Jordan	San Saba	275	No
32	Blumberg No. 1 Wagner	Blanco	126	No
33	Naylor No. 1 Lloyd Mitchell	Edwards	236	No
34	Forest No. 1 Stapp	Kimble	450	No
35	Streeter	Mason	115	No
36	No. 1 Bradshaw	Mason	40	No
37	Humble No. 1 White	San Saba	45	No
38	Gilcrease No. 1 Feril	Comanche	28	No
39	Tucker No. 1 Perkins	Kerr	125	No
40	Sell Highway Material Pit	Mason	35	No
41	Brook's Katemcy Ranch	Mason	15	No
42	Goodrich Ranch Composite	Burnet	240	No

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