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Karst Subbasins and Their Relation to the Transport of Tertiary Siliciclastic Sediments on the Florida Platform

Running Title: Karst Subbasins on the Florida Platform

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ABSTRACT

Multiple, spatially-restricted, partly-enclosed karst subbasins with as much as 100 m of relief occur on a mid-carbonate platform setting beneath the modern estuaries of Tampa Bay and Charlotte Harbor located along the west-central Florida coastline. A relatively high-amplitude seismic basement consists of the mostly carbonate, upper Oligocene to middle Miocene Arcadia Formation, which has been significantly deformed into folds, sags, warps and sinkholes. Presumably, this deformation was caused during a mid-to-late Miocene sea-level lowstand by deep-seated dissolution of carbonates, evaporates or both, resulting in collapse of the overlying stratigraphy, thus creating paleotopographic depressions.

Seismic sequences containing prograding clinoforms filled approximately 90% of the accommodation space of these western Florida subbasins. Borehole data indicate that sediment fill is mostly siliciclastic deposited within deltaic depositional systems. The sedimentary fill in the Tampa Bay and Charlotte Harbor subbasins is mostly assigned to the upper Peace River Formation of late Miocene to early Pliocene age. This fill is part of a >1,000 km long, Tertiary siliciclastic deposit that stretches north-to-south down peninsular Florida. Sediment fill of these two subbasins is linked to erosion and remobilization of pre-existing, middle Miocene quartz-rich sediments via enhanced sediment transport by local, short-length rivers and discharge into coastal-marine depositional environments. Increased sediment discharge possibly resulted from amplified thunderstorm activity and enhanced runoff during a warm period of the Pliocene.

Rather than incised valley fills or reef-margin, backfilled basins, Tampa Bay and Charlotte Harbor represent spatially-restricted, sediment-filled karst paleotopographic lows. The “dimpling” of a carbonate platform by karst subbasins provides a previously unrecognized mechanism for the creation of accommodation that can result in the “drowning” of a carbonate platform by siliciclastics.

Keywords Karst, carbonate platform, siliciclastics, sediment transport, deltas, sea level, deformation, paleo-fluvial

INTRODUCTION

Tampa Bay and Charlotte Harbor, two major estuaries located along Florida's west-central Gulf of Mexico coastline, seem anomalous in that they do not appear to have formed as drowned, incised river valleys typical of other estuarine systems in dominantly siliciclastic settings such as those along coastal plains (Dalrymple et al., 1994). Indeed, Tampa Bay and Charlotte Harbor reside in the center of the large, dominantly-carbonate Florida Platform and are only fed by a few very small, low-sediment and water discharge streams that are supported by small, local, upland drainage basins. So, estuarine origin appeared to be enigmatic.

Our seismic data, revealed herein, indicate that these shallow (average depth ~2-4 m) estuaries are underlain by karstic, semi-enclosed subbasins that have as much as 100 m of subsurface relief. We define subbasins as distinct basins that are part of a larger sedimentary basin system—in this case, the entire complex of basins containing siliciclastic fill on the Florida Platform. The subbasins (10's km's horizontal scale) beneath Tampa Bay and Charlotte Harbor are really subbasin complexes —subbasins within subbasins (km's horizontal scale). Moreover, at even a higher spatial resolution spatial scale these subbasins reveal significant deformation in the form of folds, warps, and sags in the deeper seismic sequences and the seismic basement (100's m's horizontal scale). Coring indicates that these basins have been filled with mostly siliciclastic sediments. As a result, these subbasins present an unusual relationship between carbonates and siliciclastics that has not been previously described.

Additionally, this evidence indicates that Tampa Bay and Charlotte Harbor are important siliciclastic repositories and represent a type of mid-carbonate platform accommodation not widely recognized for siliciclastic deposition. This stands in stark

contrast to the neighboring Bahama Banks, which do not reveal any mid-platform basins in the shallow subsurface providing accommodation in this manner (Eberli and Ginsburg, 1987; Ginsburg, 2001). These platforms do contain large, buried linear seaways, are much larger scale than these Florida subbasins, do not appear to be karst-related and reveal no deformation. The purpose of this paper is to demonstrate the scale, geometry and infilling facies of these subbasins and to link them to the larger Neogene/Quaternary siliciclastic flux onto the Florida Platform.

GEOLOGIC BACKGROUND

Ever since the first geologist walked Florida's beaches (Vaughan, 1910), it was obvious that the Florida Platform had received substantial quantities of quartz-rich sand in its geologic past. Some of these notable siliciclastic shorelines that have become classic localities in coastal geology (Davis et al., 1992; Davis, 1997) are a trademark of the State's tourist-driven economy, and are world-renown as a result. Additionally, the principal geomorphology of central peninsular Florida consists of paleo-shorelines, terraces and scarps composed of a siliciclastic veneer formed on underlying lower Neogene and older carbonates (White, 1970; Winkler and Howard, 1977). Even early sediment distribution studies of the adjacent seafloor indicate that quartz-rich sediments extend some 40 km out onto the west-central Florida shelf and to the upper slope on the east Florida shelf (Gould and Stewart, 1956; Doyle and Sparks, 1970; Hine, 1997). However, the breadth and extent of these siliciclastic sediments comprising the subsurface of peninsular Florida had not been well mapped.

Strip mining to acquire phosphate-rich sediments as well as borehole geology driven by the search for groundwater and hydrocarbons show that central peninsular Florida is underlain by a complex array of quartz-rich lithostratigraphic units dominated by the Oligocene-to-Pliocene Hawthorn Group (Riggs, 1979; Scott, 1988, 1997). However, the extent of siliciclastic sediments underlying the Pleistocene and modern carbonate-dominated terrain of southernmost peninsular Florida (Enos and Perkins, 1977) remains more enigmatic, perhaps because these units are capped by limestone, mostly

remain unseen at the surface and have been largely unstudied for some time as a result. Missimer and Gardner (1976) and Enos and Perkins (1977), for example, began to recognize the broad extent by which quartz-rich sediments were distributed in the subsurface of southernmost Florida.

This previous work was considerably advanced by the South Florida Drilling Project headed by R.N. Ginsburg. This project was conceptualized in the late 1980's (Ginsburg et al., 1989) and commenced in 1993. Indeed, this scientific effort demonstrated that there had been a significant remobilization of quartz-rich sand and even gravels during the late Miocene through early Pliocene. Missimer and Ginsburg (1998) point out that even during the late Oligocene, the Arcadia Formation in south-central Florida was interbedded and mixed with numerous m-scale units consisting of up to 80% siliciclastic sediments.

However, the late Miocene to early Pliocene remobilization produced a ~150-m thick succession of siliciclastics (Cunningham et al., 1998) that extended from the Lake Okeechobee area in south-central peninsular Florida, running beneath the Florida Everglades and Florida Keys, and terminating by downlap onto the approximately 200 m deep Pourtales Terrace (Missimer, 1992; Warseski et al., 1996; Guertin et al., 1999, 2000; Cunningham et al., 1998, 2001a,b, 2003; McNeill et al., 2004). The partial burial of this deep-marine, erosional Miocene terrace marked the southern end of a >1,000-km long siliciclastic transport system that originated with the weathering of crystalline bedrock of the southern Appalachian Mountains and Piedmont (Figure 1). In general, this siliciclastic transport from the north produced a relatively thin (1-150 m) late Neogene to modern quartz-rich veneer covering a thick (2-6 km) Jurassic-to-Neogene carbonate succession over peninsular Florida (Klitgord et al., 1984).

Results from the South Florida Drilling Project also indicated that there was a late Miocene-to-Pliocene remobilization of siliciclastics in south Florida. Earlier studies had shown that siliciclastics entered the northern Florida peninsula by post mid-Oligocene after the Georgia Channel System (Huddleston, 1993; T.Scott, personal communication)

seaway complex had been filled by prograding deltas probably during a major sea-level lowstand that occurred during the early Oligocene (Hull, 1962; Chen, 1965; McKinney, 1984; Popenoe et al., 1987; Popenoe, 1990; Brewster-Wingard et al., 1997). These sediments made their way to central Florida and formed an important part of the Hawthorn Group, possibly transported by extensive longshore sediment transport during sea-level highstands. However, to the south, carbonate sedimentation persisted ultimately depositing the late Oligocene-to-middle Miocene Acadia Formation and lower Peace River Formation. These lithostratigraphic units are unconformably overlain by the siliciclastic sediments of the upper Peace River Formation, which represents renewed siliciclastic transport in the late Miocene to early Pliocene of the Hawthorn Group quartz-rich sediments lying in central peninsular Florida (Cunningham et al., 2003; McNeill et al., 2004).

TAMPA BAY SUBBASIN

Tampa Bay is a large ($\sim 1,000 \text{ km}^2$), shallow (average depth $\sim 4 \text{ m}$) estuary located along the west-central Florida Gulf of Mexico coastline. Although there has been considerable geologic framework research performed within Tampa Bay in the past, much of this work did not have the benefit of digitally-acquired/processed and GPS-located, high-resolution seismic-reflection profile data gathered in closely-spaced lines allowing for loop-tying and thus 3-D mapping of seismic sequences and bounding surfaces (Stahl, 1970; Willis, 1984; Hebert, 1985; Green et al., 1995; Ferguson and Davis, 2003). Duncan et al. (2003) and Suthard (2005) have provided that data set and correlated their seismic data ($\sim 1,000 \text{ line km}$) to 6 neighboring boreholes on land and numerous short cores within the estuary itself (Figure 2).

The seismic data of Duncan et al. (2003) and Suthard (2005) clearly demonstrate that Tampa Bay is underlain by a sediment-filled subbasin having multiple smaller-scale subbasins each separated by bedrock highs (Figures 3 and 4). Recent data have revealed that “seismic basement” crops out in middle-central Tampa Bay forming hardbottoms supporting appropriate benthic biologic communities. The seismic basement consists of

the Arcadia Formation—an open-marine limestone/dolostone, with occasional thin beds of phosphatic quartz sands (<1.5 m thick) and clays (<1.5 m thick and of limited areal extent) scattered throughout (Scott, 1988; Suthard, 2005). Suthard (2005) jump-correlated his seismic lines to adjacent onshore boreholes (Green et al., 1995) for chronostratigraphic control. Since these basins have 40-60 m of subsurface relief and the average water depth of Tampa Bay is only 4 m, approximately 5-10% of the remaining accommodation space is unfilled.

The seismic data indicate deformation of the Arcadia Formation and some of the immediately overlying seismic sequences forming the subbasin fill. Folds and sags dominate the lower Tampa Bay part of the subbasin (Figure 5). These deformational features are not anticlines and synclines in the classic structural geology sense in that they have very limited lateral continuity (no axial planes)—rather they are small, broad domes (>1 km across) and narrow (< 1 km), circular depressions—some even representing individual sinkholes. This style of deformation is more consistent with deep-seated collapse from below rather than from lateral compression due to tectonic activity.

Finally, seismic reflection and borehole data reveal that the subbasin underlying Tampa Bay is laterally-restricted and does not extend seaward beneath the modern continental shelf more than ~30 km (Figure 4; Hebert, 1985; Duncan, 1993; Duncan et al., 2003). Rather, the seismic basement underlying Tampa Bay rises seaward where it crops out forming hardbottoms, which dominate portions of the west-central Florida shelf (Locker et al., 2003). This lack of cross-shelf continuity indicates that these subbasins are not shelf valleys that been carved by rivers during sea-level lowstands (Dalrymple et al, 1994; Donahue et al, 2003) in contrast to Brooks and Doyle's (1998) contention that the subbasin beneath Tampa Bay was formed by paleo-fluvial incision

Numerous cores from Tampa Bay (U.S. Army Corps of Engineers, 1969) as well as the surrounding on-land boreholes (Green et al., 1995; Florida Geological Survey, 2005) indicate that overlying the Arcadia Formation is the middle Miocene to lower Pliocene Peace River Formation, which constitutes the basin fill. This lithostratigraphic

unit is principally siliciclastic (>66%) with interbedded quartz sands, clays and carbonates. The Peace River Formation is a very complex unit consisting of large amounts of fluvio-deltaic and coastal siliciclastic sediments to minor amounts of restricted and open-marine carbonates (Scott, 1988). The Hawthorn Group, as defined by Scott (1988), is composed of the Arcadia and the Peace River Formations.

Suthard (2005) defined 11 different seismic sequences from two major depositional centers that constitute the Peace River Formation and the overlying Plio-Quaternary siliciclastic units (Figure 3). This seismic sequence mapping reveals dominant north-northwest prograding clinoforms (Figure 3) indicating a source area from the south-southeast—probably from the ancestral Manatee and Little Manatee Rivers (Figure 6). As mentioned above, the lowermost seismic sequences are deformed as well as the seismic basement indicating syn-depositional deformation during the late stage of basin formation and early stage of subbasin filling.

CHARLOTTE HARBOR SUBBASIN

Approximately 150 km to the south of Tampa Bay, located along Florida's Gulf of Mexico coastline, lies Charlotte Harbor having very similar dimensions ($\sim 725 \text{ km}^2$), shape and average depth ($\sim 2.3 \text{ m}$) as Tampa Bay (Figure 1). Evans (1989) and Evans et al. (1989), using a grid of 800 km of analog, high-resolution seismic-reflection data tied to 22 borehole sites around this estuary, found strong similarities to what was later discovered beneath Tampa Bay (Figure 7). Additionally, later work by Cunningham et al. (2003) in the Caloosahatchee River and southern Charlotte Harbor provided chronostratigraphic control through seismic reflection data and borehole analyses.

Charlotte Harbor is underlain by multiple subbasins, some having upwards of 100 m of relief as shown by mapping the seismic basement reflection, which also constitutes the top of the Arcadia Formation (Figure 8.). Evans et al. (1989) and Evans and Hine (1991) concluded that these underlying Tertiary carbonates had undergone extensive dissolution and collapse creating isolated karst depressions that extend seaward beneath

the inner shelf. The same deformational style seen beneath Tampa Bay occurs beneath Charlotte Harbor where broad, high, folded areas are separated by narrow, sinkhole-like sags (Figure 9). One fold in particular, reveals high-angle faulting, fracturing or both indicating some degree of lithologic induration prior to deformation (Figure 10).

Similarly, these smaller subbasins have been filled in with at least six sedimentary sequences that are identified and mapped by their bounding unconformable surfaces seen in seismic data (Evans, 1989). These late Neogene to Quaternary sequences are siliciclastic with three Quaternary seismic sequences, based upon the analysis of 40 short (< 6m long) vibracores, consisting of lithologic units dominated by mud, shelly sand and quartz gravel. These sediments mostly reflect fluvial to upper estuarine, lagoon and tidal-inlet depositional environments (Evans et al., 1989).

In the southern portion of the Charlotte Harbor estuary near the Caloosahatchee River, lies a prograding deltaic lobe (Figure 11) interpreted to be part of the Peace River Formation overlying the Arcadia Formation based on seismic data gathered by Missimer and Gardner (1976), Missimer (1999), and Cunningham et al. (2001b, 2003). This information combined with seismic data and borehole chronostratigraphy by Cunningham et al. (2001b, 2003), indicate that much of the late Neogene and early Quaternary seismic sequences mapped by Evans et al. (1989) are the late Miocene to early Pliocene Peace River Formation—same as in the Tampa Bay subbasin. Seismic data indicate a greater presence of Quaternary cut-and-fill paleochannels in the seismic sequences beneath Charlotte Harbor than in their counterparts beneath Tampa Bay, suggesting greater paleo-fluvial activity.

Finally, an interpreted seismic line (Figure 12) extending from the Charlotte Harbor subbasin to Lake Okeechobee run in the Caloosahatchee River illustrates the deformation within the underlying Arcadia Formation that forms a seismic basement high separating two distinct subbasins. Both basins are filled with prograding clinoforms typical of delta lobes. The clinoforms in the eastern subbasin have up to 100 m of relief ,indicating that a delta lobe prograded into water of at least that depth. Borehole data

adjacent to the Caloosahatchee River verify a delta depositional environment (Cunningham et al., 2003). This large delta is the northernmost extent of the paleo-fluvial and deltaic depositional systems that migrated approximately 200 km south to the Florida Keys (Cunningham et al., 2003).

DISCUSSION

Formation and Filling of the Tampa Bay and Charlotte Harbor Subbasins

Since the deformed, underlying limestone is late Oligocene-to-middle Miocene in age and the overlying siliciclastic sediments are late Miocene to early Pliocene, the subbasins probably formed during the middle to late Miocene. The style of deformation indicates that deep-seated dissolution caused overlying stratigraphic collapse producing a complex of sags, warps and folds, which combined to form the Tampa Bay and Charlotte Harbor subbasins. This dissolution and collapse most likely occurred during the extended late Miocene sea-level lowstand shown in Figure 13 (TB3.1 to TB3.3) although dissolution was probably widespread throughout all Cenozoic lowstands as well (Popenoe et al., 1984; Scott, 1990). During lowstands of sea level, these subbasins caused the local-to-regional streams and rivers to flow into them forming lakes or swamps (Edgar et al., 2002). During high stands of sea level, these subbasins became estuaries, open-marine systems, but were filled primarily by prograding deltas.

It is unknown why the subbasins are restricted and located where they are. Their location may be related to selective faulting and fracturing of the Mesozoic and Cenozoic carbonate succession overlying the Paleozoic/PreCambrian basement-- perhaps related to reactivation of regional transform faults (Klitgord et al., 1984; Sheridan et al., 1988). Fracturing and faulting may have been stimulated by the early Cenozoic collision with the Cuban arc system (Bralower and Iturralde-Vinent, 1997; Moretti et al., 2003; Pindell et al., 2006). Or, fracturing may have occurred throughout geologic time resulting from differential subsidence associated with passive margins facing the Atlantic and the Gulf of Mexico (Klitgord et al., 1988; Sawyer et al., 1991). Indeed, relatively minor seismic

activity (earthquake magnitudes < 6.0) is ongoing throughout the eastern Gulf of Mexico/Florida Platform region (<http://earthquake.usgs.gov/eqcenter/eqinthenews/2006/usslav/>). Nevertheless, differential geothermal gradients setting up Kohout-style convection (Tanner, 1976; Fanning et al., 1981; Kohout et al., 1977; 1988; Mitchell-Tapping et al., 1999; Mitchell-Tapping, 2002) mixing ground-waters of different salinities and carbonate saturation states possibly produced selective dissolution of carbonate, evaporite rocks or both.

Much of our own high-resolution seismic reflection profiling on the Little and northern Great Bahama Bank, and Cay Sal Bank reveals no subbasins or subsurface deformation in the shallow stratigraphy (Hine and Neumann, 1977; Hine, 1977; Hine et al., 1981; Hine and Steinmetz, 1984). Admittedly, there are large gaps in our data coverage and most seismic lines were run across the margins of these huge, modern carbonate platforms. However, we see a complete lack of deformation anywhere, even in the interior seismic lines and even in deeper penetrating seismic data (e.g., Eberli and Ginsburg, 1987; Ginsburg, 2001). Perhaps, the fact that the Bahama Banks are isolated and detached as compared to the Florida Platform with its main aquifer system extending into the southeast US presents a fundamental difference (http://capp.water.usgs.gov/gwa/ch_g/G-text7.html)? During lowstands of sea level, the Florida Platform still received groundwater influx from the northern components of the Floridan Aquifer allowing for continued or perhaps even stimulated deep-seated dissolution. Whereas, the Bahama Banks, being physically isolated, cannot receive groundwater influx from some lateral source, but only receives its fresh water from local rainfall perhaps limiting subsurface dissolution.

Based upon the lithostratigraphy and chronostratigraphy provided by boreholes adjacent to Tampa Bay, Charlotte Harbor and the Caloosahatchee River, the infilling of the semi-enclosed subbasins beneath these Florida west-coast estuaries occurred during the very late Miocene and Pliocene sea-level highstand (TB3.4, TB3.5; Fig. 13). This was part of the major remobilization and southward transport of siliciclastics in south Florida as pointed out by the various papers associated with the South Florida Drilling Project

(Guertin et al., 2000), and summarized by Cunningham et al. (2003) and McNeill et al., (2004). During the late Miocene and Pliocene, a major fluvial-deltaic depositional system migrated southward approximately 200 km to near the southernmost margin of the Florida Platform.

This scenario poses several related critical questions. (1) Where did the source of quartz sand and gravel come from to fill the Tampa Bay and Charlotte Harbor subbasins and to prograde a deltaic depositional system 200 km south, approaching the margin of the south Florida Platform? (2) What caused the late Miocene-to-Pliocene fluvial-deltaic activity to be significantly enhanced as compared to the present, since today there are no bay-head deltas? (3) What was the nature of the paleo-fluvial network—several large long rivers or a complex network of high-discharge local, short-length streams? (4) What shut down this siliciclastic remobilization event and allowed the return to primarily carbonate deposition in the Pleistocene forming the Florida Keys consisting of the Miami Oolite and the Key Largo Limestone (Enos and Perkins, 1977)? Finally (5) what is the geological significance of these karst subbasins?

The >1000-km Long Siliciclastic Transport Pathway

The primarily chemical weathering of exposed silicate-rich bedrock of the southern Appalachian Mountains and Piedmont provided the ultimate source of quartz sands and gravels to the Florida Platform that eventually reached the Pourtales Terrace lying in 200 m water in the southern Straits of Florida. We provide the following scenario (Figures 1,14) to partially explain this >1,000-km long source-to-sink pathway—a pathway that consisted of multiple sedimentary compartments (coastal plain, river deltas, coastlines, karst entrapment basins and ultimately the open marine shelf/slope) and multiple sedimentary transport processes. Thus, the transport and deposition of siliciclastics probably proceeded as a series of steps modulated by Cenozoic sea-level fluctuations, topographic variations and climate changes.

Streams from the mountains and Piedmont brought sediment to the coastal plain where it was deposited along adjacent floodplains or reached deltas discharging into the marine environment. Through time, river deltas prograded across and filled the Georgia Channel System during sea-level lowstands in the late Eocene and early Oligocene (McKinney, 1984). Probably, during the middle Oligocene major sea-level lowstand (Haq et al., 1988; Popenoe, 1990; Brewster-Wingard et al., 1997), the Georgia Channel System was filled completely and siliciclastic sediments started to cover north-central peninsular Florida. Peninsular Florida, being elevated (Figure 1; St. Johns Platform, Sanford High, Brevard, Platform and Ocala Platform; Popenoe, 1990; Scott, 1997), could not support a long-distance, north-to-south fluvial system. Consequently, primary sediment movement probably occurred in coastal longshore transport systems during higher sea level.

Secondary sediment movement to the east and west occurred by local rivers during lower sea level. The late Miocene to early Pliocene Bone Valley Member of the Peace River Formation represents a paleo-fluvial reworking of older Hawthorn Group siliciclastic and phosphatic rich units (Riggs, 1979). The surficial geomorphology of peninsular Florida, dominated by numerous paleoshoreline features, is best illustrated by the Lake Wales Ridge complex. These extensive north-south trending coastal features have been subsequently incised and eroded by numerous local streams—some of which provided the remobilized siliciclastic sediments that filled in the semi-enclosed, restricted karst subbasins beneath Tampa Bay and Charlotte Harbor.

The Lake Wales Ridge ends in south-central peninsular Florida (Figures 1,14), indicating that extensive north-to-south, coastal longshore transport probably ended there as well. To complete the sediment transport pathway to the southern Straits of Florida, data from Cunningham et al. (2003) and other papers associated with the South Florida Drilling Project (McNeill et al., 2004) indicate that a late Miocene-to-Pliocene prograding deltaic depositional system carried quartz sands and gravels on top of a carbonate ramp that had been exposed for 8 million years thus burying the underlying Arcadia Formation. As this delta complex approached the carbonate margin facing south

into the Straits of Florida, a new siliciclastic shelf and slope system was formed. Fluvial-deltaic sedimentary processes merged into cross-shelf and down-slope sedimentary processes, again all pulsed by variations in sea-level and climate (windiness, storminess, rainfall) as well as oceanographic processes (eg., Florida Current/Loop Current activity).

High-Sediment Discharge Local Rivers?

Since there is no evidence for an extensive long-distance paleofluvial transport by a single large river flowing down peninsular Florida from the north, the subbasins beneath Tampa Bay and Charlotte Harbor must have filled in by local, short-length, high-sediment discharge rivers and streams. With no bay-head deltas or sediment-choked areas at the head-of-tides in today's rivers discharging into Tampa Bay or Charlotte Harbor, the rivers of the late Miocene to Pliocene must have had a higher sediment discharge than present. We postulate that the warm period during the Pliocene (Willard et al, 1993; Poore and Sloan, 1996; Dowsett et al., 1996) stimulated local thunderstorm activity over peninsular Florida, thus increasing rainfall, runoff and sediment discharge. Increased sea-surface temperatures in the waters surrounding peninsular Florida ($\sim +2$ – 4 °C; Dowsett et al., 1996, their Figure 1) and increased heating of the land mass would have stimulated the local sea breeze effect, built larger and more vigorous thunderstorms and could have prolonged the thunderstorm season beyond the 4-5 months seen today.

Additionally, the sea-level highstand of the very late Miocene and early-mid Pliocene lasted several million years (~ 5.5 -3 Ma) and may have been as much as +35 m higher than present sea level (PRISM reconstruction of Dowsett and Poore, 1991). So, there was sufficient time for the filling of these peripheral subbasins and for the major fluvial deltaic system to migrate from the southern end of the Lake Wales Ridge complex to the south Florida margin thus covering the pre-existing carbonate ramp. Perhaps, maximum deltaic progradation occurred during multiple, brief intervals or pulses of enhanced sediment discharge during the falling stages of higher-frequency, sea-level events. But, by late Pliocene, the massive siliciclastic influx seems to have slowed or stopped in south Florida (McNeill, personal communication, 2006). In south Florida, this

~150 m thick siliciclastic unit is called the Long Key Formation (Guertin et al., 1999) and is the time-transgressive equivalent of the upper Peace River in the Charlotte Harbor/Caloosahatchee River area.

As Warzeski et al. (1996) and Cunningham et al. (2003) point out, the aggradation of this siliciclastic system provided the substrate for the return of shallow-water carbonates in the Pleistocene. By the late Pliocene/early Pleistocene boundary, a carbonate-dominated depositional environments returned capping the siliciclastics from the Everglades across the Florida Keys to the top of the Pourtales Terrace (Guertin, 1998; Guertin et al., 1999; 2000; Multer et al., 2002; McNeill, personal communication, 2006). These carbonates are overlain by the carbonate Key Largo Formation for which the initiation age is uncertain (McNeill, personal communication, 2006). The aggradation of the siliciclastic system was essential in creating a widespread shallow-water environment to support a vibrant carbonate factory. But, there must have been a concurrent reduction in the siliciclastic transport as well. We can only speculate that rainfall and runoff (and resulting siliciclastic sediment transport in local rivers) must have been reduced during this time allowing the carbonate factory to flourish.

Geologic Significance of Semi-Enclosed Karst Subbasins

The siliciclastic-filled subbasins underlying Tampa Bay and Charlotte Harbor occur in a mid-carbonate platform setting and not along a carbonate margin where siliciclastics have been known to accumulate (e.g. Belize; Ferro et al., 1999; Great Barrier Reef; Dunbar et al., 2000). Rather than incised valley fills or reef-margin, backfilled basins, they represent spatially-restricted, semi-enclosed siliciclastic-filled karst features. Kerans (personal communication, 2005) has indicated that there are large-scale, karst collapse systems with up to 320 m of vertical extent and 100-200 m width in the lower Ordovician El Paso Group of west Texas. Kerans (personal communication, 2005) also points out 35 m vertical relief, 100 m diameter cave collapses of mid-Permian age in the Sierra Diablo Range (Texas). Both of these ancient examples are similar scales to the individual warps, folds and sags seen beneath Tampa Bay and Charlotte Harbor.

However, neither ancient example replicates the spatial scale of these mid Florida Platform semi-enclosed subbasins, and neither are filled in with siliciclastic sediments. As a result, the “dimpling” by coalescing karst basins in the mid Florida Platform setting provides a previously unrecognized mechanism for the creation of accommodation that can result in the apparent “drowning” of a carbonate platform by siliciclastics even though a significant hiatus occurs between the two depositional units.

CONCLUSIONS

1. Multiple, spatially-restricted, partially-enclosed karst subbasins with as much as 100 m of relief in a mid-carbonate platform setting lie beneath the modern estuaries of Tampa Bay and Charlotte Harbor located along the Florida Gulf of Mexico coastline.
2. Seismic basement consists of the carbonate, upper Oligocene-to-middle Miocene Arcadia Formation, which has been significantly deformed into folds, sags, warps and sinkholes. Presumably, this deformation was caused by deep-seated dissolution of carbonates at depth allowing the overlying stratigraphy to collapse thus creating a surficial depression. Subbasin formation occurred during the mid to late Miocene sea-level lowstand.
3. Approximately 90% of the accommodation space of these surficial subbasins has been filled by sequences dominated by prograding clinoforms. Adjacent borehole data indicates that the sediment infill is dominantly siliciclastic deposited in a deltaic depositional setting. The infill of the Tampa Bay and Charlotte Harbor basins consists mostly of the Peace River Formation of very late Miocene to Pliocene age. This sediment fill represents a small component of a large and extensive (>1,000 km long) siliciclastic Cenozoic invasion of peninsular Florida.
4. The sedimentary fill of these subbasins was part of a significant remobilization of quartz-rich sediments through enhanced sediment discharge in local, short-length rivers. Enhanced sediment discharge possibly resulted from increased thunderstorm activity during a warm period of the Pliocene particularly during the late stage of basin fill.

5. Rather than incised valley fills or reef-margin, backfilled basins, Tampa Bay and Charlotte Harbor represent spatially-restricted, mid-platform, filled-in karst features. The “dimpling” of a carbonate platform by coalescing karst subbasins provides a previously unrecognized mechanism for the creation of accommodation that can result in the “drowning” of a carbonate platform by siliciclastics.

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LIST OF FIGURES

Figure Captions

- Figure 1. Satellite image (<http://earthobservatory.nasa.gov/Newsroom/BlueMarble/>) of the southeast US showing (1) a portion of the southern Appalachian Mountains and Piedmont—the siliciclastic source area for the sediments that have been transported to Florida, (2) the transport pathway and (3) the terminus at the Pourtales Terrace. Key paleotopographic areas that played a role in guiding these sediments southward, such as the Ocala Platform and Sandford High, are shown as well as other relevant geographic locations. Note the location of the terminus of the Lake Wales Ridge. Note also that Tampa Bay and Charlotte Harbor are located peripherally off to the side of the main north-south sediment transport pathway.
- Figure 2. Seismic data and borehole locations in Tampa Bay. Adjacent boreholes on land provided lithologic and chronostratigraphic control for the seismic data. Bathymetry revealed in Tampa Bay roughly coincides with subsurface seismic basement topography (see Figure 4).
- Figure 3. Selected seismic lines in Tampa Bay revealing multiple, vertically stacked seismic sequences lying unconformably on top of the seismic basement identified as Arcadia Formation. The sequences form part of the Peace River Formation. Note deformed strata as well as the prograding clinoforms indicating deltaic migration.
- Figure 4. Depth-to-seismic basement map beneath Tampa Bay. Note multiple smaller subbasins separated by basement highs. Also note the extensive karst deformation particularly beneath lower Tampa Bay.
- Figure 5. Detailed seismic line illustrating deformation beneath lower Tampa Bay. Style of deformation indicates collapse from below due to deep-seated dissolution of older carbonate or evaporates (modified Figure 16, Berman et al., 2005).
- Figure 6. Terrain model map showing rivers and point sources of prograding sequences in Tampa Bay aligned with the modern drainage system. The ancestral counterparts provided the source of siliciclastic sediment that filled in the Tampa Bay subbasin.
- Figure 7. Seismic data, track-line location in Charlotte Harbor and the Caloosahatchee River. Note location of cross-sections shown in Figure 9.
- Figure 8. Depth to basement map of Charlotte Harbor revealing the multiple smaller subbasins lying beneath this modern estuary. Maximum relief of subbasins (to Arcadia Formation) is ~100m .

- Figure 9. Interpreted cross-sections from seismic data collected in Charlotte Harbor—see Figure 7 for location. Cross-sections reveal significant deformation in form of warps, sags and folds. Also shown are prograding clinoforms, numerous, small paleo-fluvial cut-and-fill structures and small, buried sinkholes. Seismic sequences are identified as A-F.
- Figure 10. Detail of fold in seismic data from southern Charlotte Harbor. This fold or warp reveals high-angle faulting indicating lithification prior to deformation. This structure is a dome-like fold in that it has limited lateral extent and is not anticlinal in 3D geometry. See Figure 8 for location.
- Figure 11. Seismic line from lower Charlotte Harbor at the west end of the Caloosahatchee River reveals prograding clinoforms from a deltaic lobe as part of the Peace River Formation. This is the lithostratigraphic unit that fills in most of Charlotte Harbor (from Missimer and Gardner, 1976; Missimer, 1999)
- Figure 12. Interpreted seismic line from Charlotte Harbor to Lake Okeechobee extending west-to-east approximately 50% across the State of Florida. This line reveals two subbasins separated by an elevated area of the Arcadia Formation. The western, smaller subbasin is Charlotte Harbor and illustrates the deltaic lobe shown in Figure 11. The much broader and deeper eastern subbasin also reveals much higher relief deltaic prograding clinoforms of the upper Peace River Formation. This is the start point of the 200 km long southward delta migration as described by Cunningham et al. (2003).
- Figure 13. Relationship between lithostratigraphic units, chronostratigraphy and sea level showing timing of subbasin formation, deformation and infilling (modified from Figure 2, Cunningham et al., 2003; eustatic curve from Haq et al, 1988).
- Figure 14. Map (adapted from Fernald, 1981; p. 16) illustrating the transport pathway and suggested modes of transport of Cenozoic siliciclastic sediment: (1) across the Georgia Channel System from the southeast coastal plain via deltaic progradation infilling this seaway, (2) onlap onto the Florida Platform and transport down north and central peninsular Florida to the southern terminus of the Lake Wales Ridge, primarily by longshore transport during high stands of sea-level, (3) paleofluvial infilling of mid-platform subbasins such as Tampa Bay and Charlotte Harbor during lower stands of and/or falling sea level, (4) continued southward paleofluvial progradation covering an exposed carbonate ramp in south-central peninsular Florida, (5) introduced to the marine environment beneath and seaward of the present Florida Keys forming a shelf/slope system influenced by cross-shelf and downslope currents and (6) eventually downlapping onto the 200 m deep Pourtales Terrace.

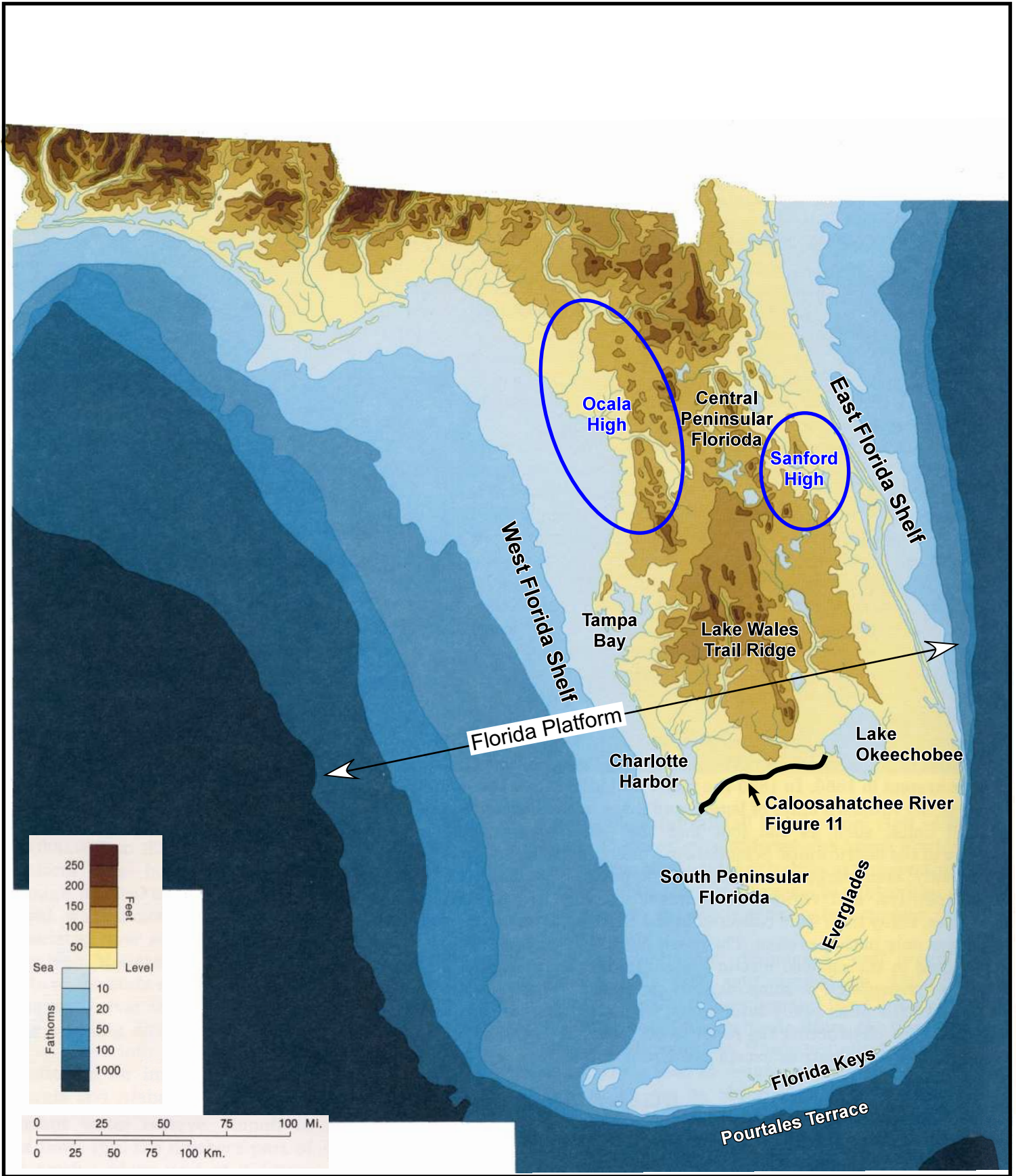
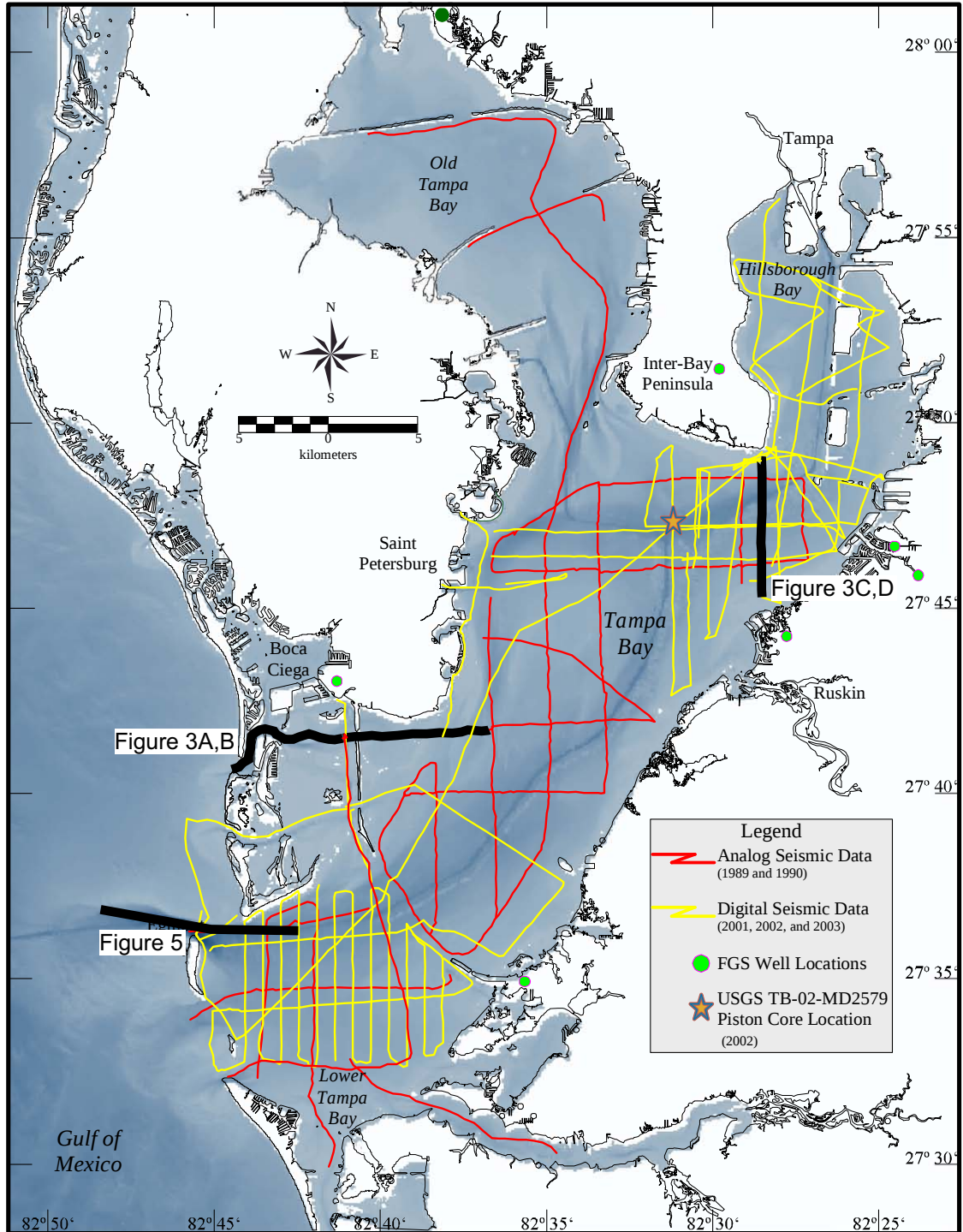
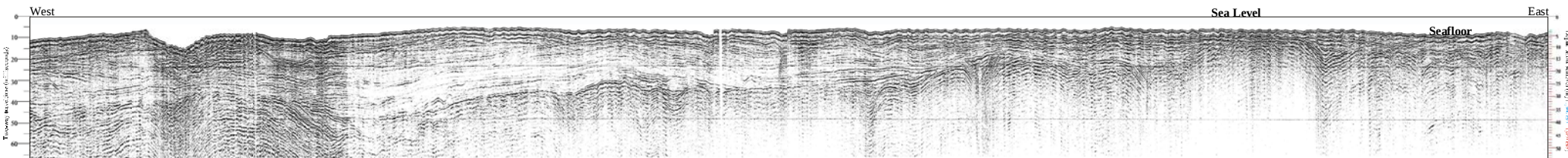


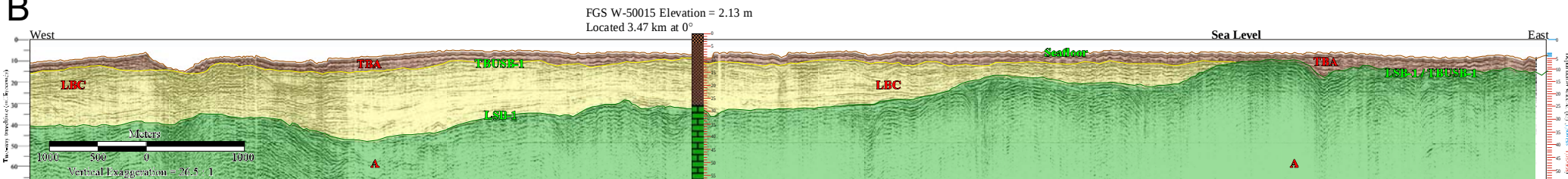
Figure 1; Hine et al.



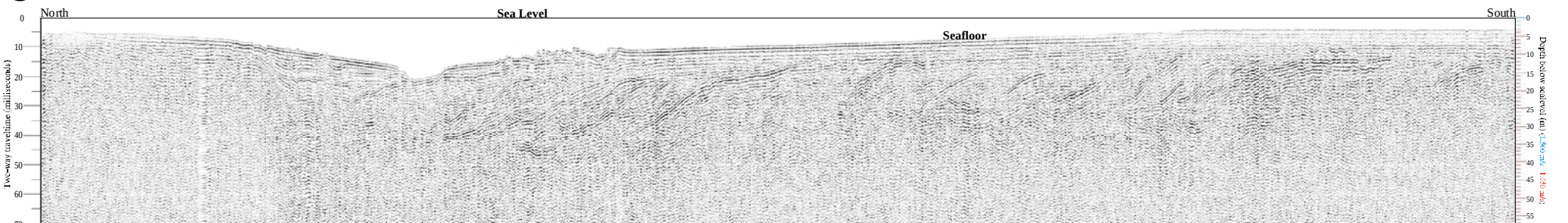
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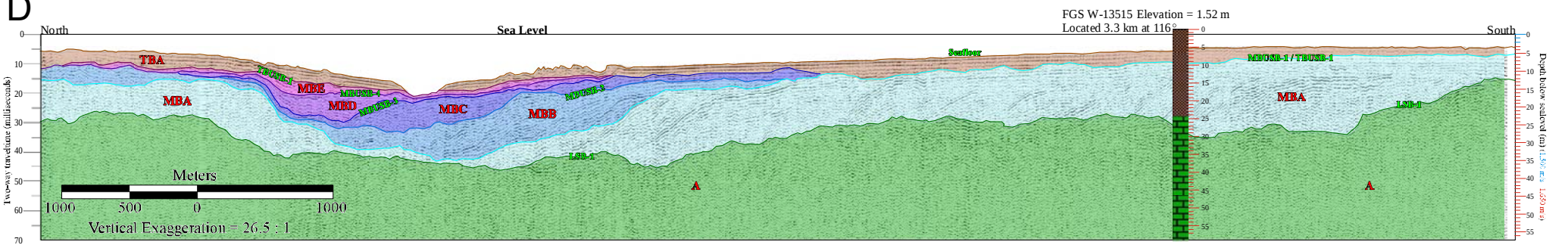


Figure 3; Hine et al.

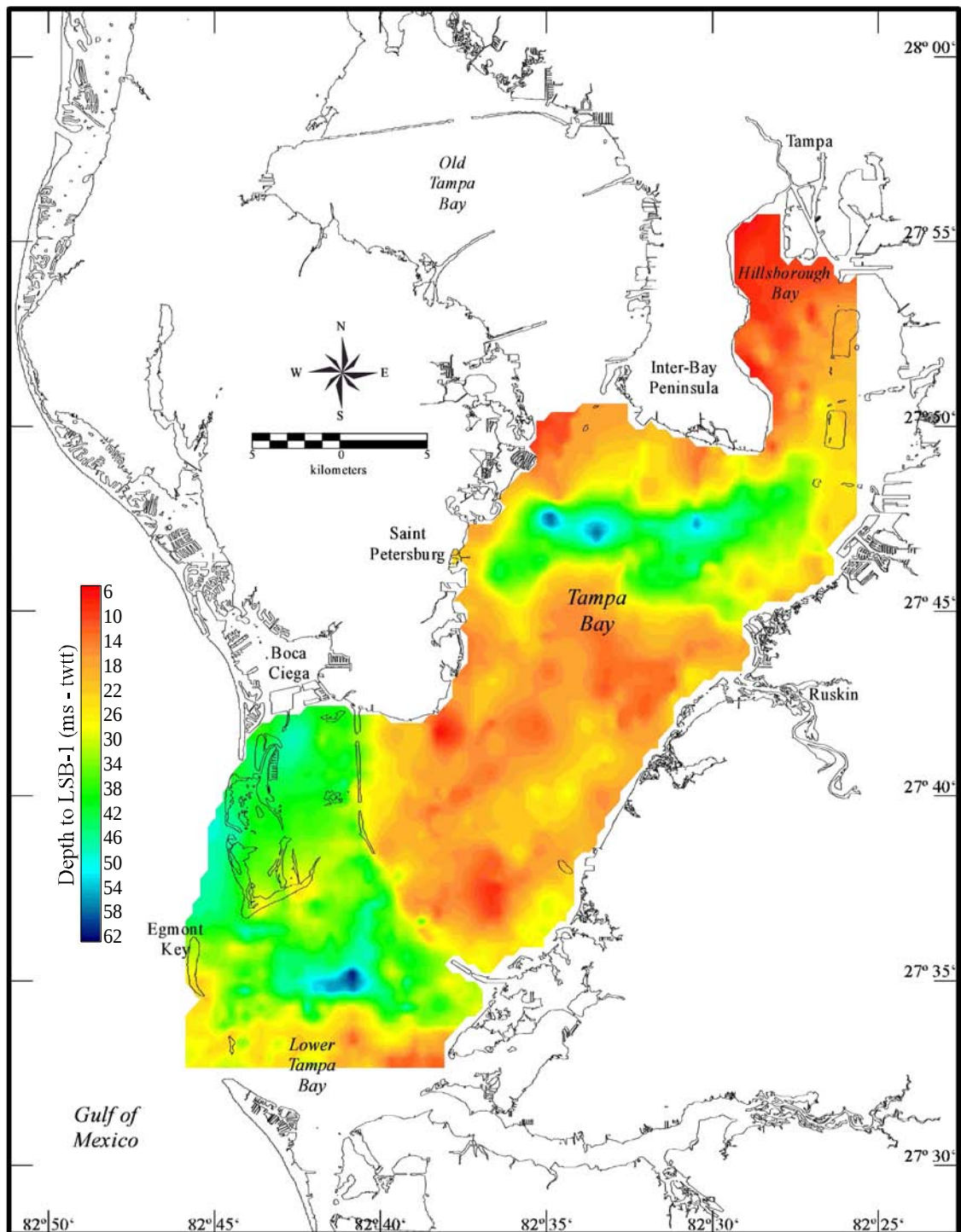


Figure 4; Hine et al.

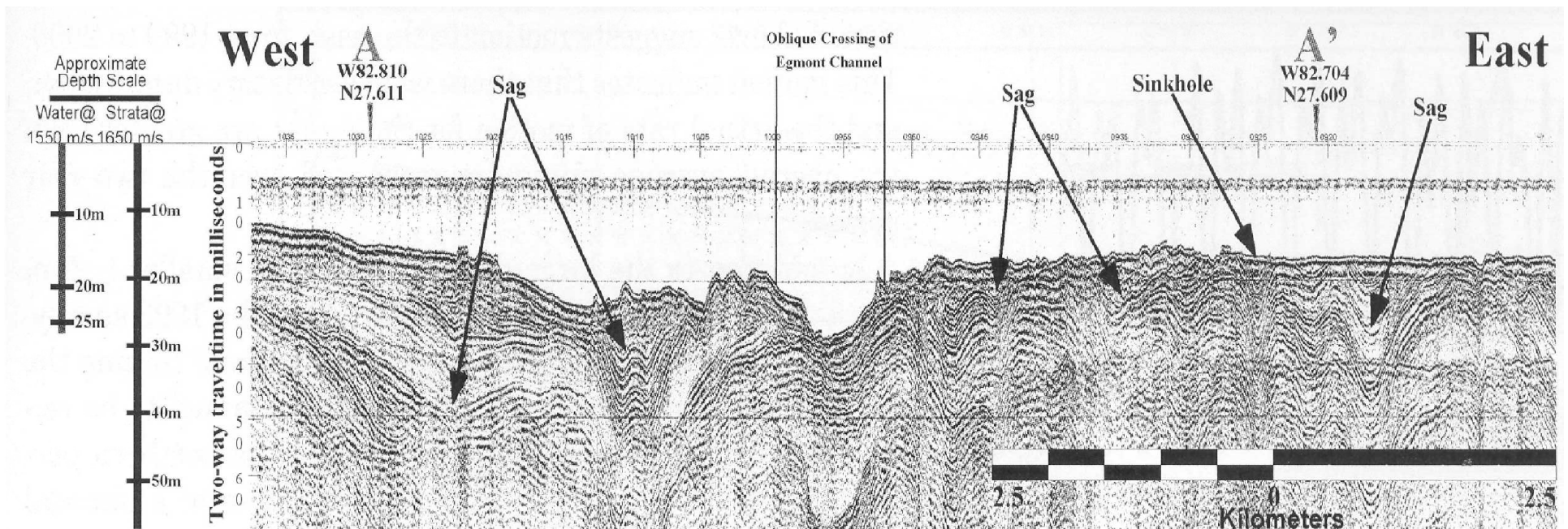


Figure 5; Hine et al.

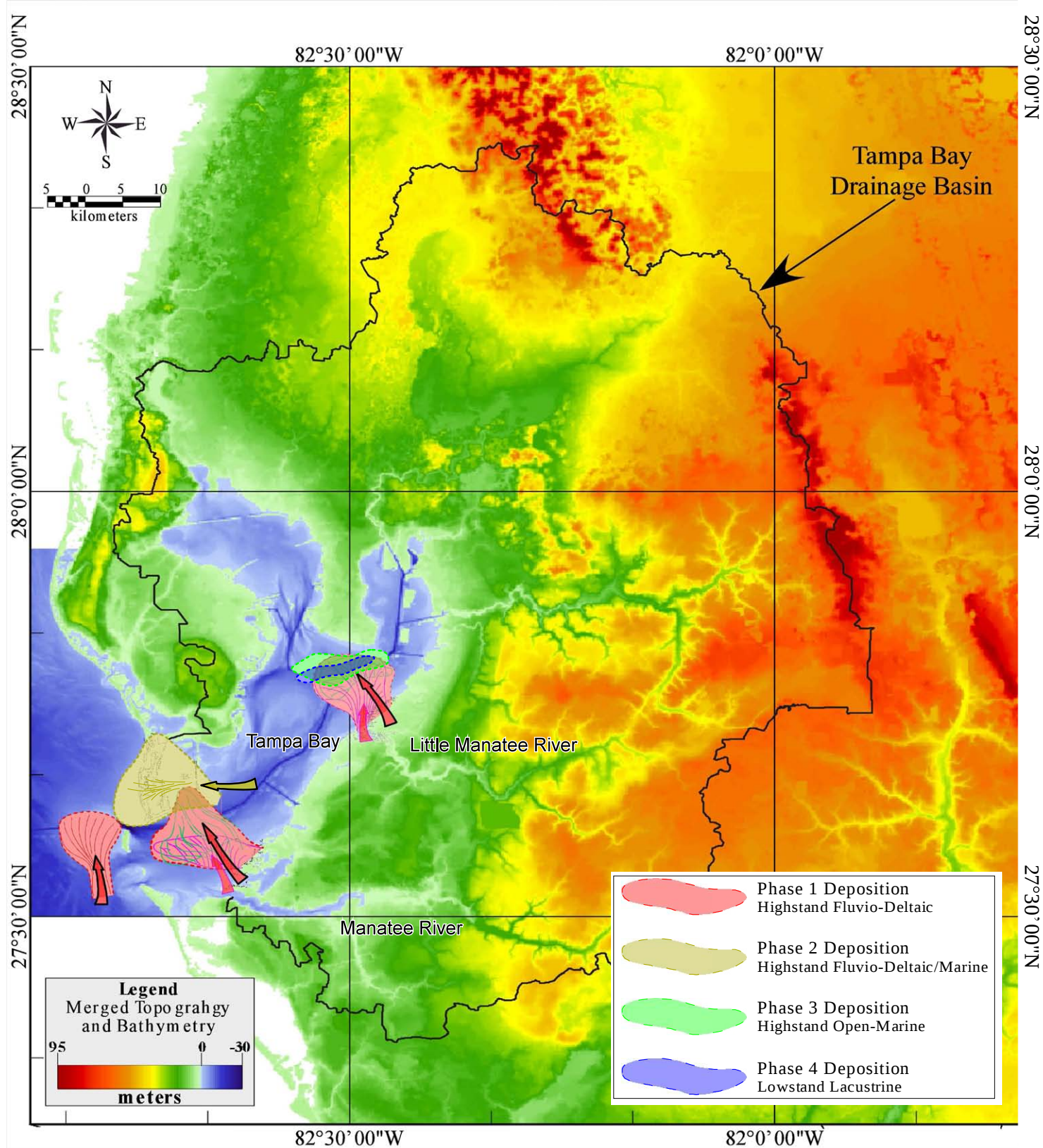


Figure 6; Hine et al.

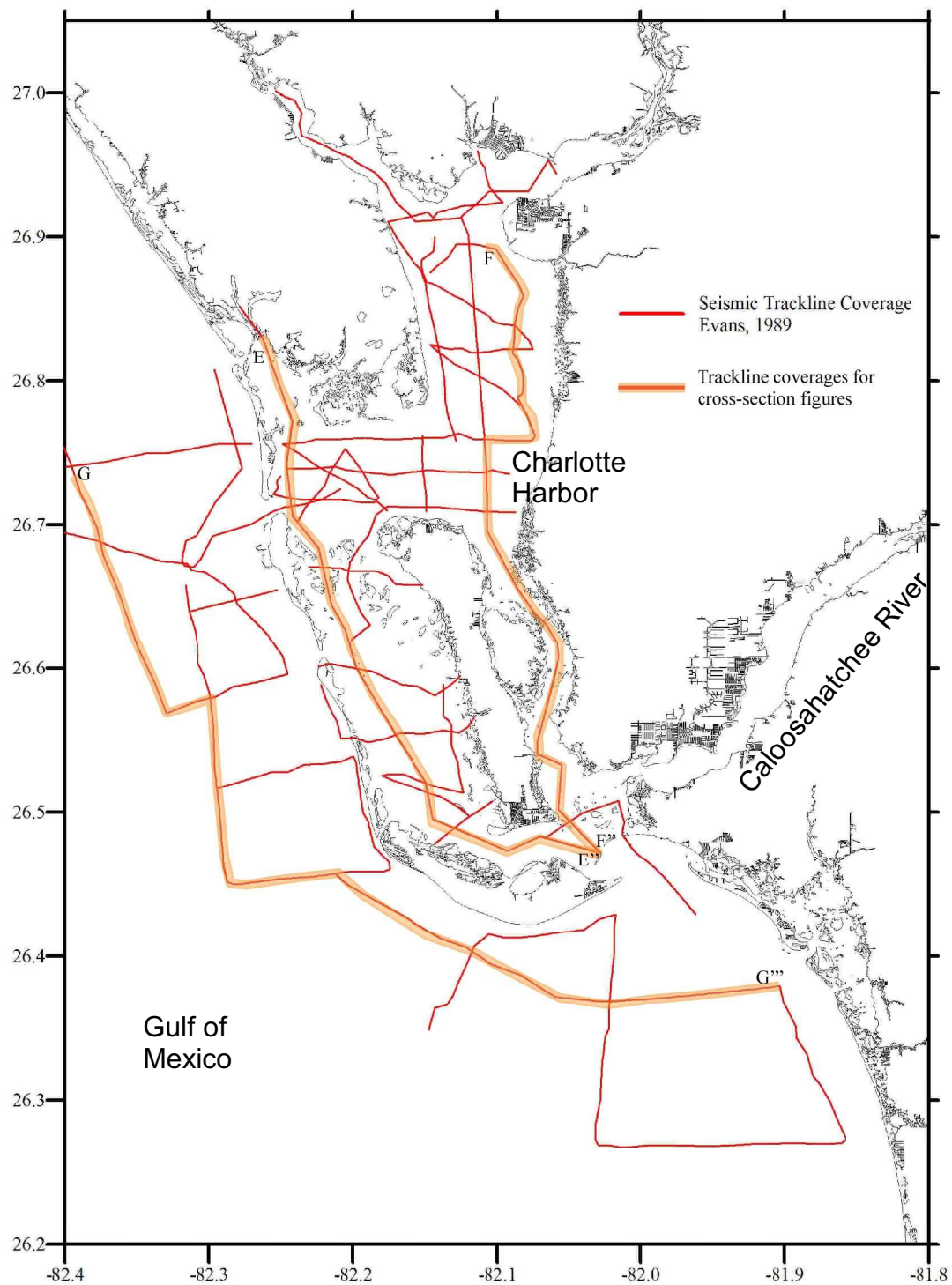


Figure 7; et al.

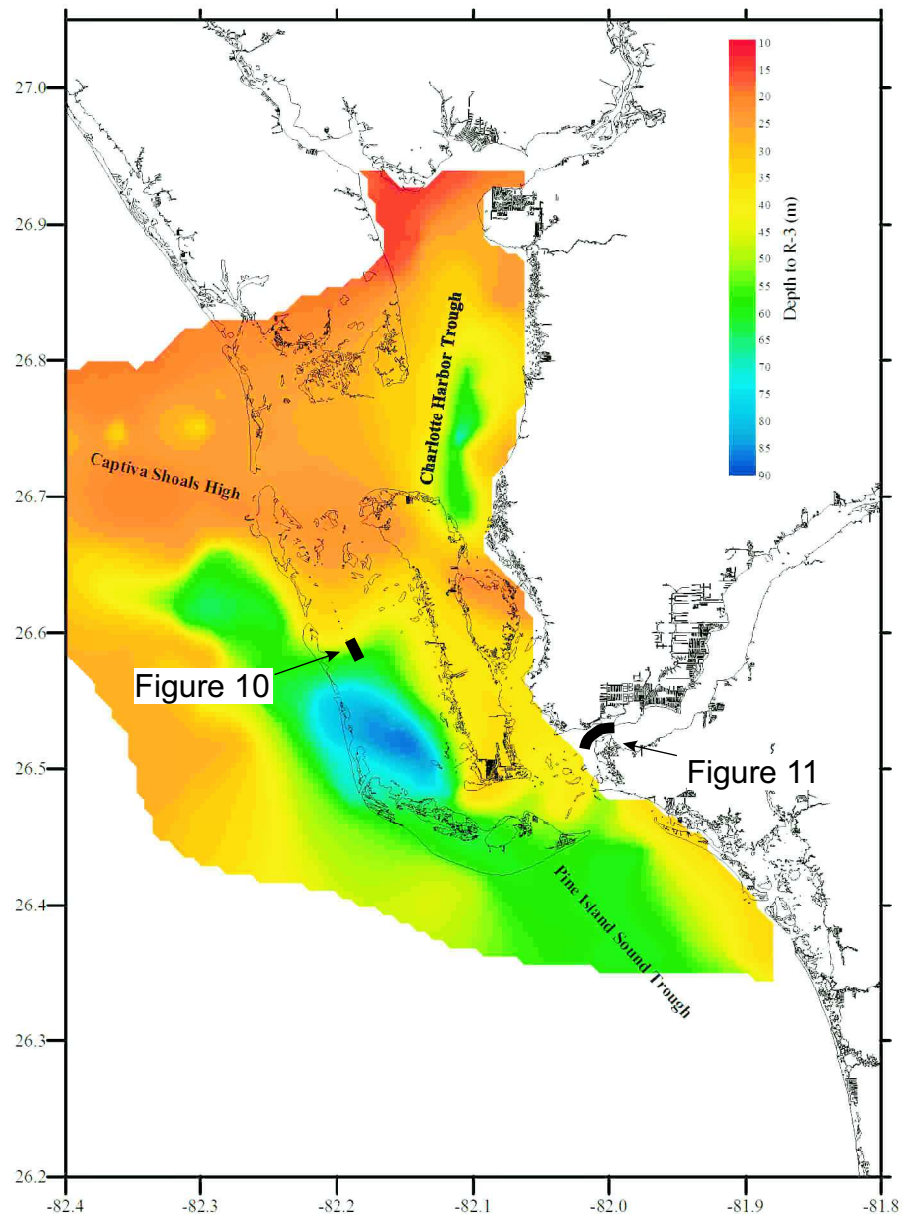


Figure 8; Hine et al.

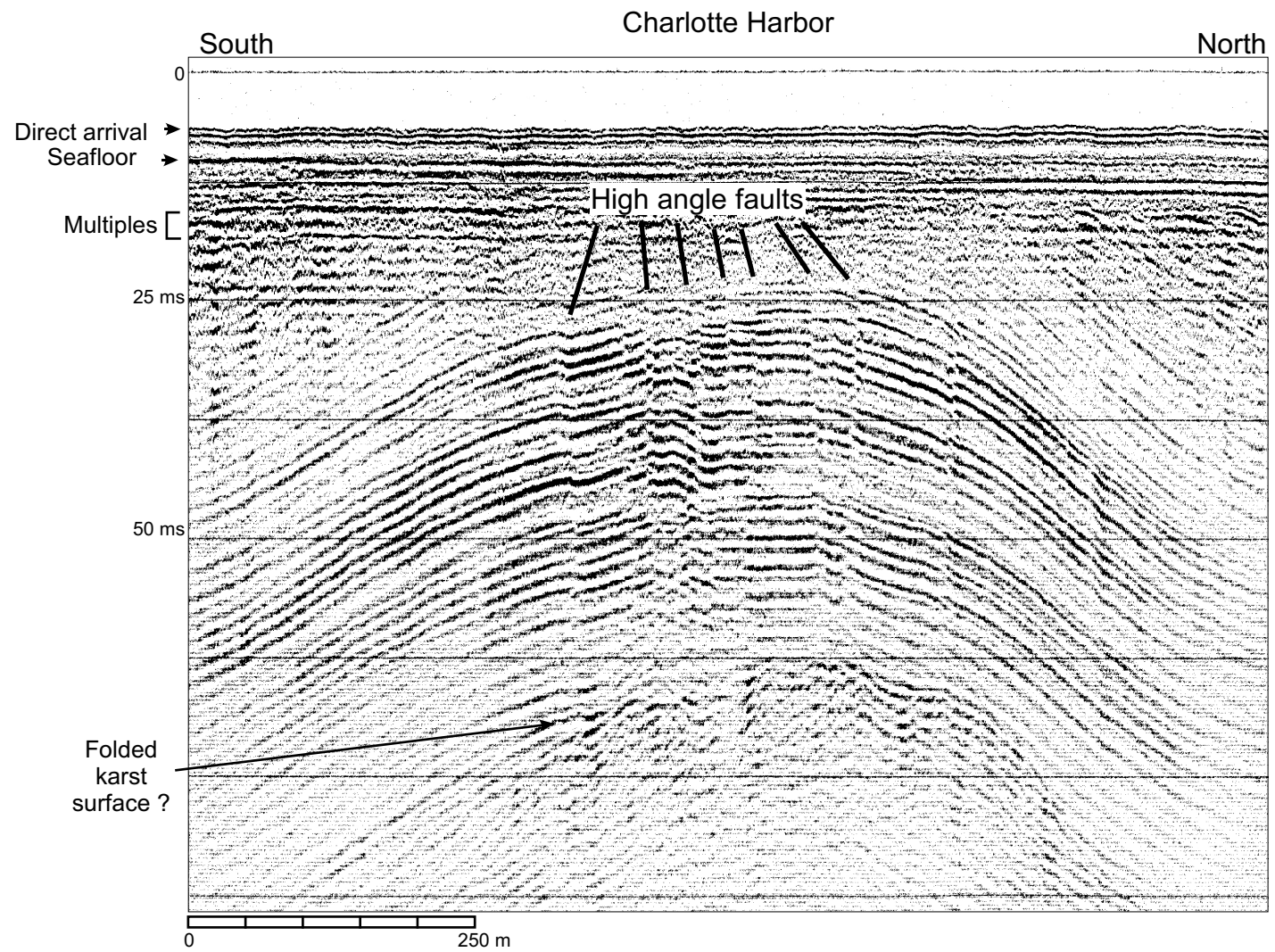


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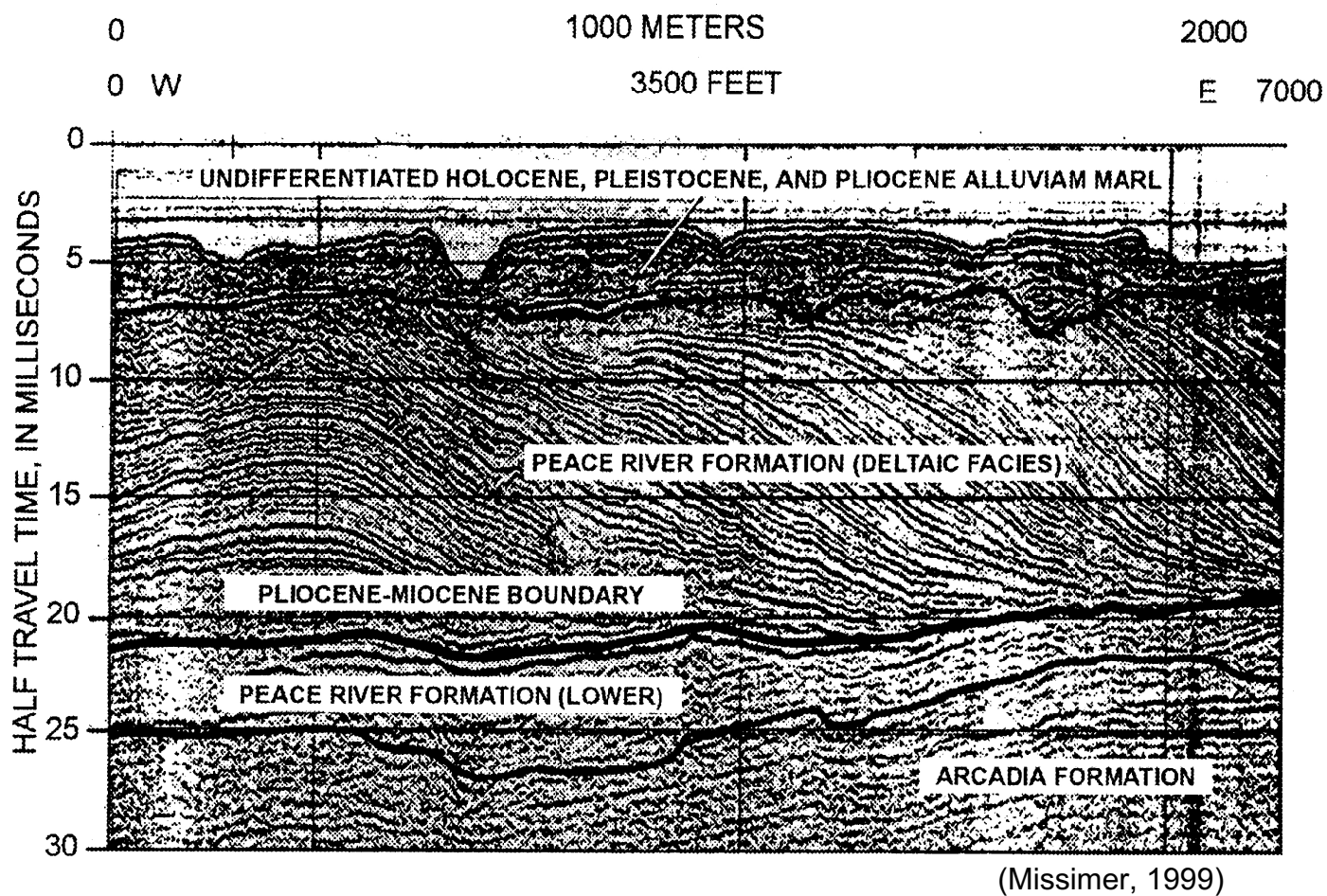


Figure 10; Hine et al.

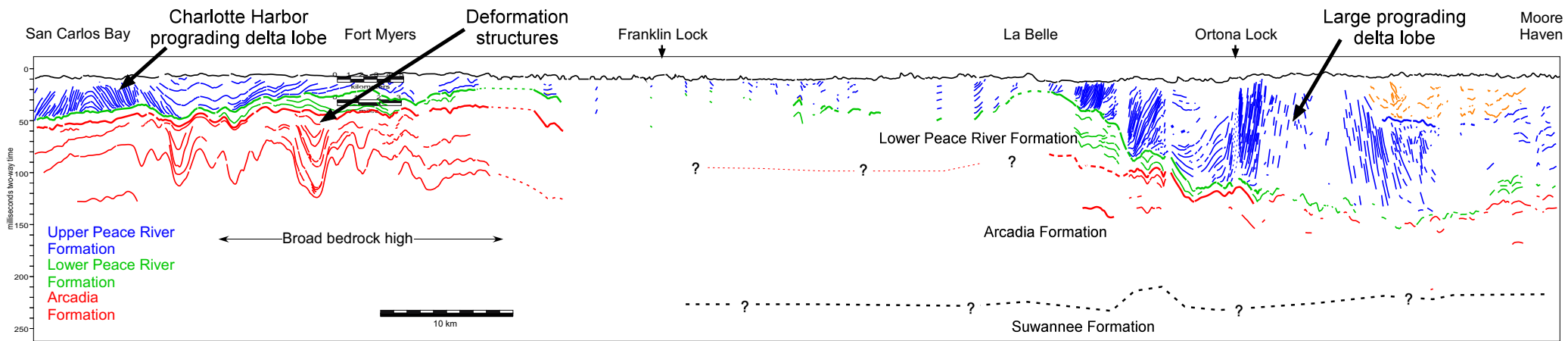


Figure 11; Hine et al.

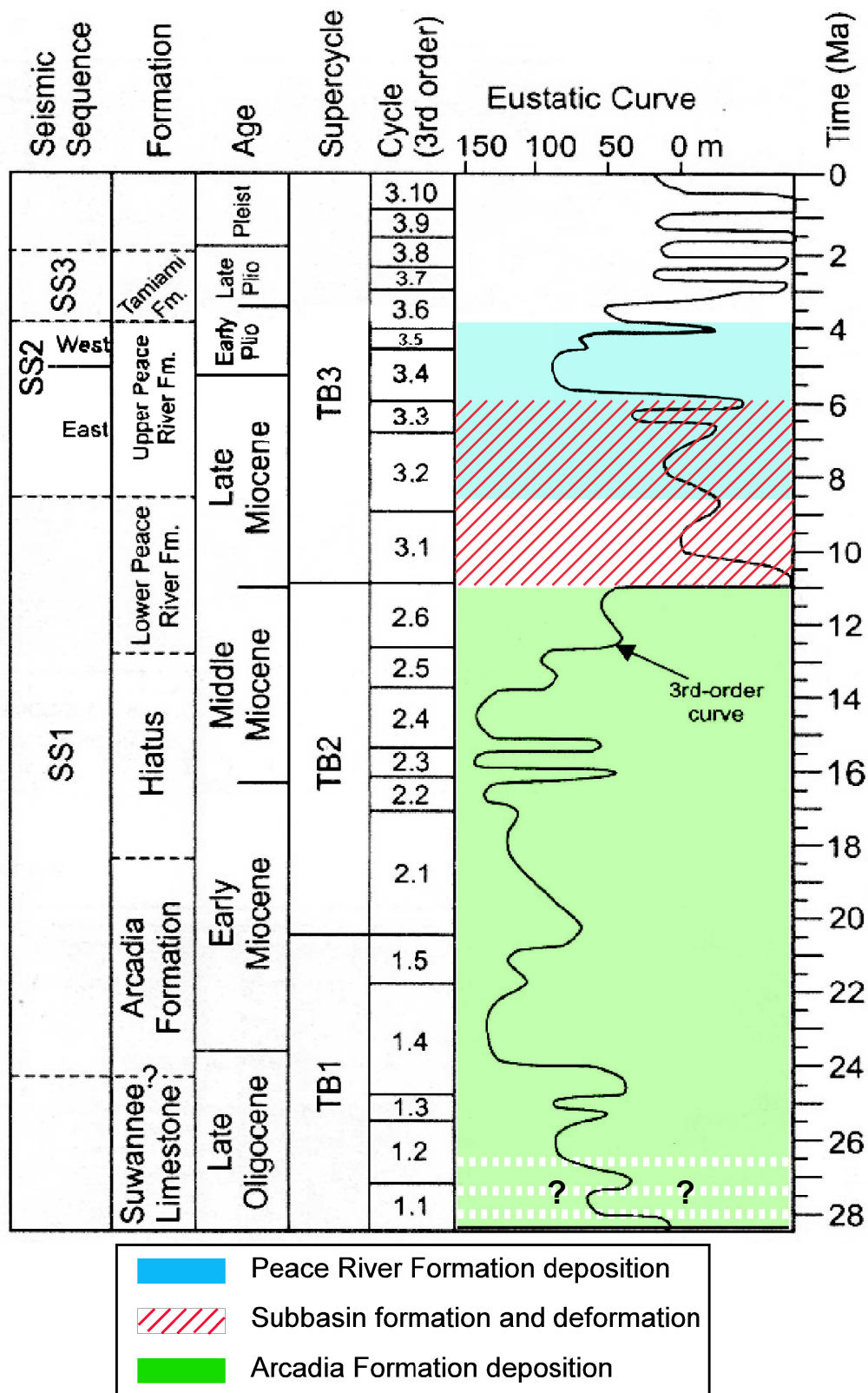


Figure 12; Hine et al.

Summary of Florida siliciclastic transport system

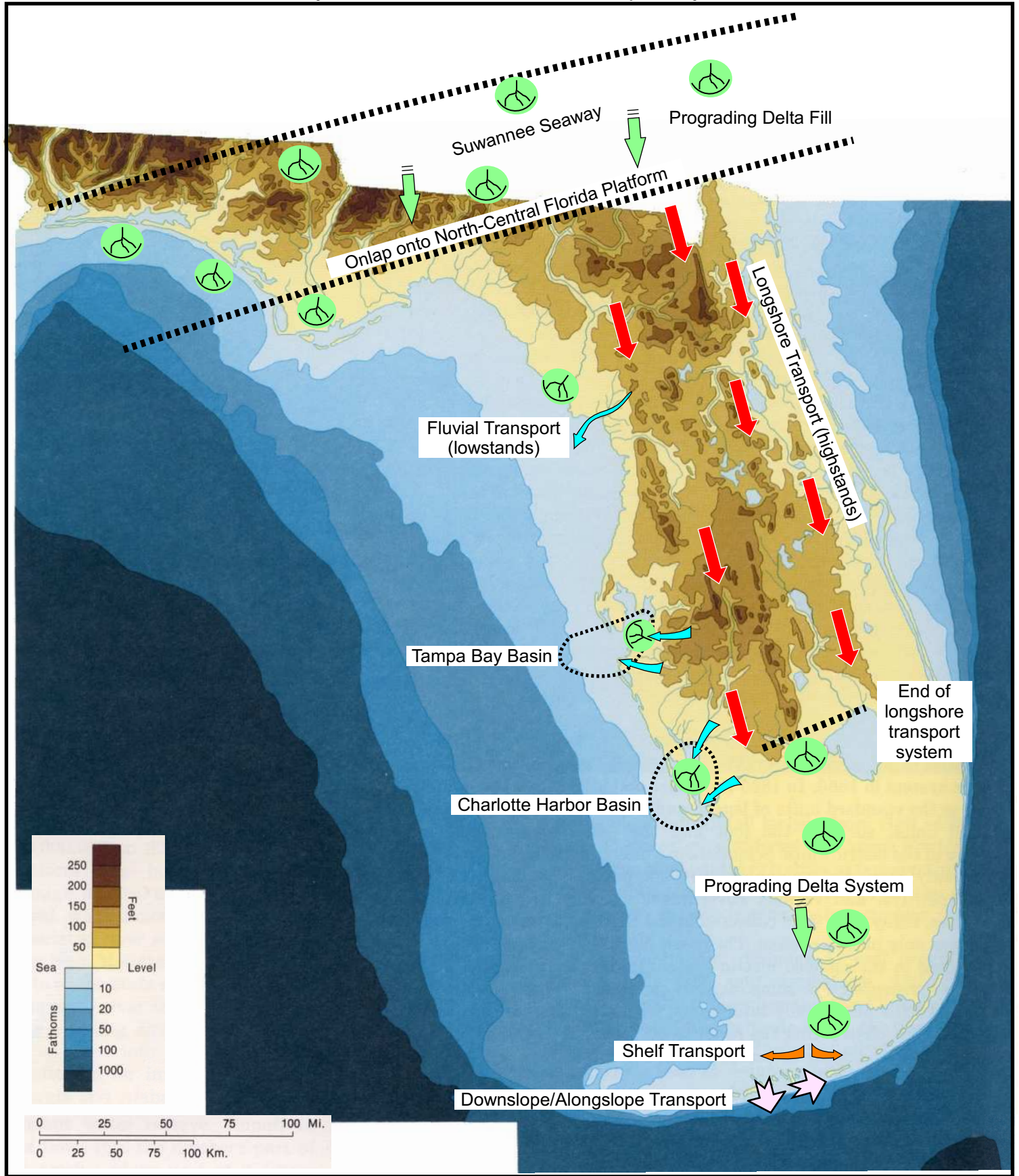


Figure 13; Hine et al.