Tectonically Induced Fracturing, Folding, and Groundwater Flow in South Florida

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Abstract

Groundwater flow in the confined aquifers of South Florida is strongly influenced by the diagenesis and structural deformation of aquifer rock. Fractured dolomites are often the main flow zones. Deformation observed in post-Paleocene-aged rocks has often been attributed to karstic collapse related to the dissolution of Paleogene carbonates or Paleocene and Late Cretaceous evaporates. Seismic and borehole stratigraphic data from scattered locations in Florida reveal that regional folding is more common than previously recognized. The typical continuity of strata and paucity of steep-sided collapsed structures suggest that the folding is related to regional compressional events rather than karstic collapse.

The most widespread compressional event occurred in the late Miocene and early Pliocene, towards the end of the deposition of the Hawthorn Group. The subsurface folding has maximum relief on the order of 70 meters. Seismic surveys from both the east and west coasts of Florida, and stratigraphic correlations across wellfields in Lee and Collier counties, show that latest Miocene to recent sediments buried the folds. The late Miocene compressional event correlates with a regional tectonic event. The stratigraphic distribution of fractured dolomites and subsurface stratigraphic data document earlier structural events. The combination of a paleohydrogeologic control over the geometry of dolomite bodies and a potential tectonically controlled preferred orientation of fractures introduces considerable anisotropy to aquifers, which may be at least qualitatively predictable.

Introduction

The Florida Platform has historically been considered a tectonically quiescent environment in which successive formations were deposited largely in a 'layer-cake' manner. In southern Florida, approximately 1000 m of predominantly shallow-water carbonates and to a lesser degree siliciclastic sediments were deposited during the Eocene to Holocene Epochs in a slowly subsiding basin. The long-term rate of deposition approximately equaled the rate of subsidence based on the predominance of shallow-water deposits in the stratigraphic section. The Eocene to lower Miocene carbonates constitute the Floridan Aquifer System, which is one of the most productive aquifers in the United States.

Some structural movement affecting Floridan aquifer strata has long been recognized. Known or suspected faults were documented by Miller (1986) along the southeast coast of Florida in his regional study of the Floridan Aquifer System. The faults are apparently of limited vertical extent, generally show little vertical displacement, and do not appear to have any effect on groundwater flow in the Floridan Aquifer System (Miller, 1986). However, some faults identified in southwest Florida do impact local hydrology as evidence by groundwater temperature and salinity anomalies (e.g., Sproul et al., 1972). Suspected faulting in Brevard County in east-central Florida may have induced fracturing in the confining strata of a deep injection well system (Duncan et al., 1994). It has also been suggested that some surface water features in South Florida, such as the Caloosahatchee River and Lake Okeechobee, may be controlled by faulting (Bond et al., 1981).

The presence of subsurface folding in Florida has been uncommonly identified as such. Seismic reflection profiles by Meisburger and Field (1975) and Missimer and Gardner (1976) clearly revealed the presence of pronounced folds in the shallow subsurface. Similar type folds or flexures have been identified in other studies but have been attributed to karstic collapse (e.g., Wolonsky et al., 1983). The

objective of this investigation was to evaluate the extent, timing, and origin of subsurface folding in South Florida and adjoining areas, and the impact folding may have on groundwater flow.

Regional Hydrogeology

The post-Paleocene strata in South Florida can be subdivided into a predominantly carbonate section (Eocene to Oligocene), which comprises the Floridan Aquifer System, and an overlying mixed carbonate and siliciclastic section (mostly Miocene to recent), which comprises the Intermediate Aquifer System (sometimes referred to as the intermediate confining unit) and the Surficial Aquifer System (Fig. 1). The Floridan Aquifer includes the Suwannee Limestone, the Ocala Limestone, the Avon Park Formation, and the Oldsmar Formation. Permeable limestone intervals in the lower part of the Hawthorn Group in South Florida (lower Arcadia Formation) are also locally included in the Floridan Aquifer System, where confinement between lower Hawthorn and Suwannee Limestone aquifer zones is absent or poorly developed. The Suwannee Limestone and Ocala Limestone are absent in parts of southeastern Florida, where they were removed by pre-Hawthorn Group erosion (Guertin et al., 2000). The base of the Floridan Aquifer System is generally placed at the top of the uppermost evaporite bed in the Paleocene Cedar Keys Formation.

The Intermediate Aquifer System (sometimes referred to as the intermediate confining unit) lies between the Surficial Aquifer System and the Floridan Aquifer System. The Intermediate Aquifer System in southwestern Florida contains several limestone aquifers separated by clay or marl confining units.

The Surficial Aquifer System extends from the water table down to the top of the uppermost thick continuous marl or clay bed in the upper Peace River Formation. Several formations of Pliocene or Pleistocene age are locally recognized in the Surficial Aquifer System including the Tamiami Formation, Caloosahatchee Formation, Fort Thompson Formation, Anastasia Formation, Key Largo Limestone, Miami Limestone, and Pamlico Sand.

Documented Folding

Folding has been documented at scattered locations in south and central Florida (Fig. 2). The folding is often referred to as ‘flexures’ or ‘deeper structures’ to avoid the connotation of a structural origin. The term ‘fold’ is used herein in the descriptive sense. The maximum age of folding can be estimated from the youngest stratum that is folded and/or the youngest stratum that infills synclines or covers folded strata.

Caloosahatchee River

High-resolution seismic profiling of the Caloosahatchee River estuary and San Carlos Bay, Lee County, revealed extensive subsurface folding (Missimer and Gardner, 1976; Fig. 3). The maximum relief (trough to apex) is approximately 40 m. The axis of the folds are oriented roughly north-south (about 330° to 350°). The folding is well developed in the lower Peace River Formation and Arcadia Formation. At several localities upper Peace River Formation and Pleistocene strata are also folded (Missimer and Gardner, 1976). Seismic reflection profiling of the Caloosahatchee River and San Carlos Bay subsequently performed by Cunningham et al. (2001) shows the same folding as reported by Missimer and Gardner (1976) (Fig. 4). Detailed chronostratigraphy indicates that lower Peace River Formation in the study area is of late Miocene age (Cunningham et al., 2001; Missimer 2002,), which indicates a late Miocene or later timing of the main episode of deformation.

Missimer and Gardner (1976) suggested that the folding is probably related to differential subsidence by tensional basement displacement. Cunningham et al. (2001) indicated that the folding (deep structures) were probably created by karstic collapse.

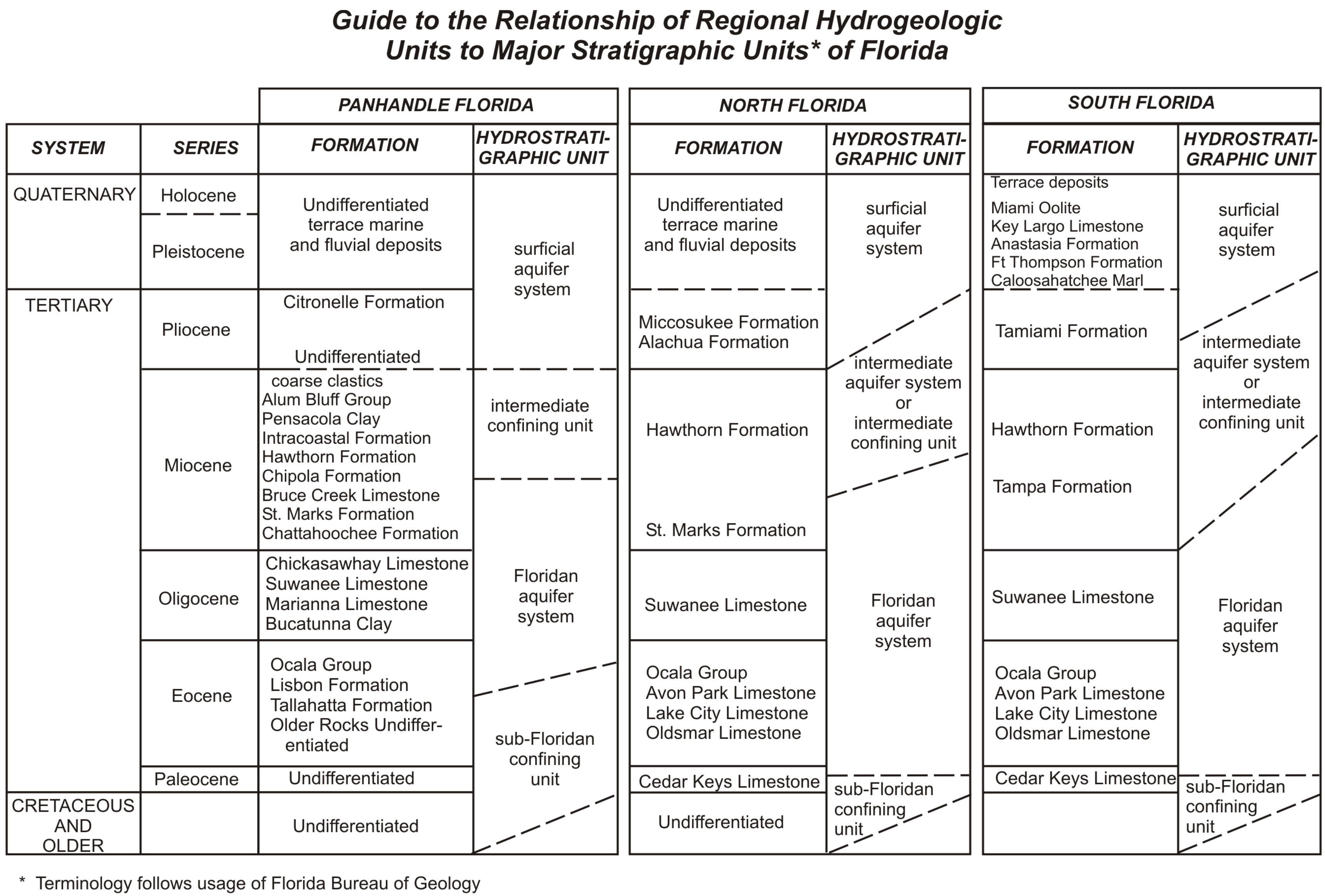

Figure 1. Terminology of the Floridan Aquifer System (after Vecchioli et al., 1986).

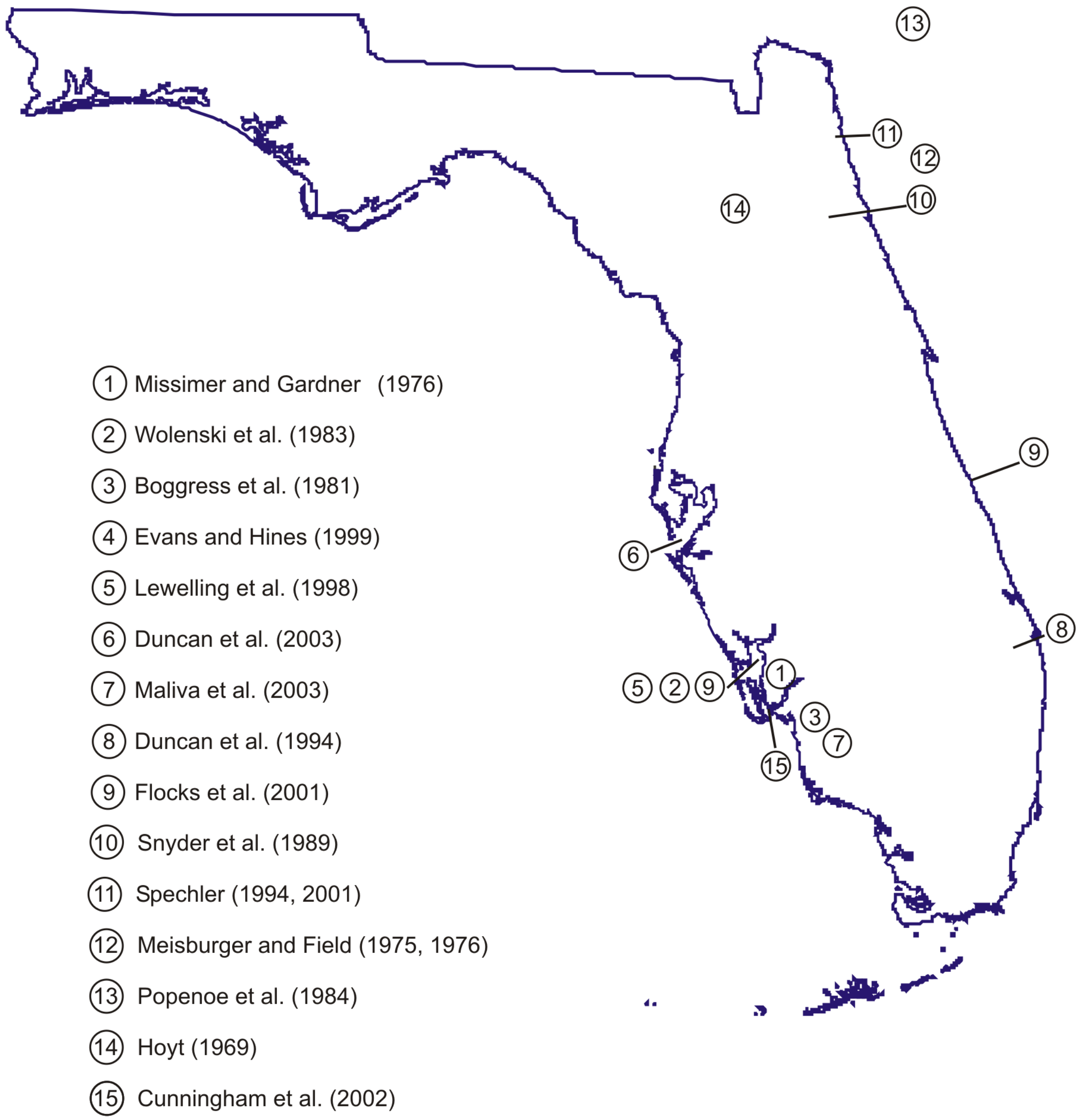

Figure 2. Map showing areas in Florida where folding or uplift is documented.

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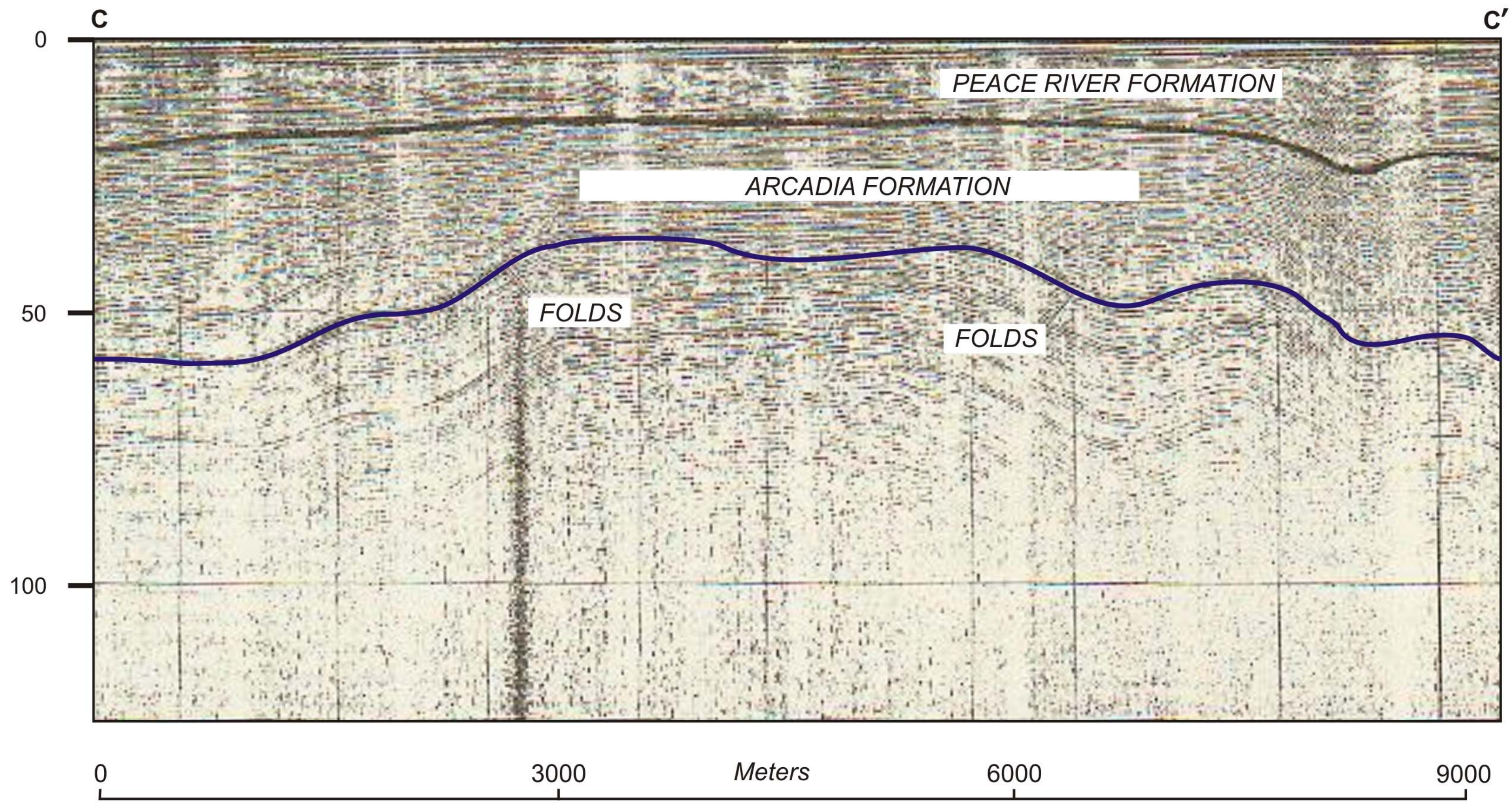

Figure 3. Concentric folding in central Lee County (from Missimer and Gardner, 1976).

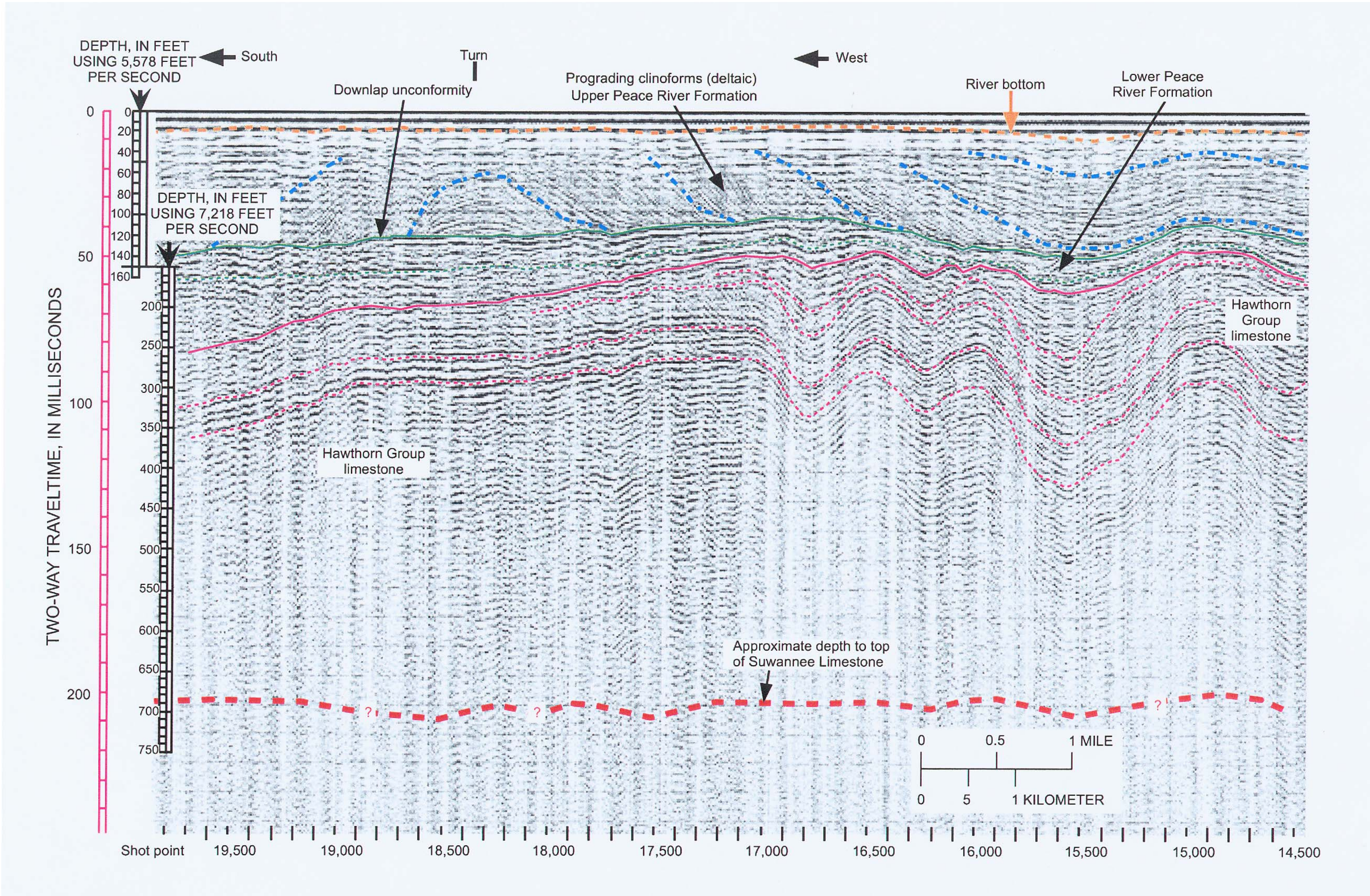

Figure 4. Folding in the Hawthorn Group, Arcadia and Peace River Formations, in Hendry County, Florida (after Cunningham et al., 2001).

Lee County Corkscrew Road Wellfield

The Lee County Corkscrew wellfield, located in southern Lee County, was constructed in an area of abnormally thick Surficial Aquifer System. East-west cross-sections show the presence of a synclinal structure with a maximum relief of at least 70 m (Missimer 1974; Boggess et al., 1981; ViroGroup and Camp Dresser and McKee, 1997) (Fig. 5). The current land surface is essentially flat lying. The axis of the syncline is oriented north-northeast. The youngest folded stratum is the Peace River Formation (early Pliocene), which indicates an early Pliocene deformation. The sedimentologic patterns of infill in this structure suggested a deformation with subsequent infilling (Missimer, 1974).

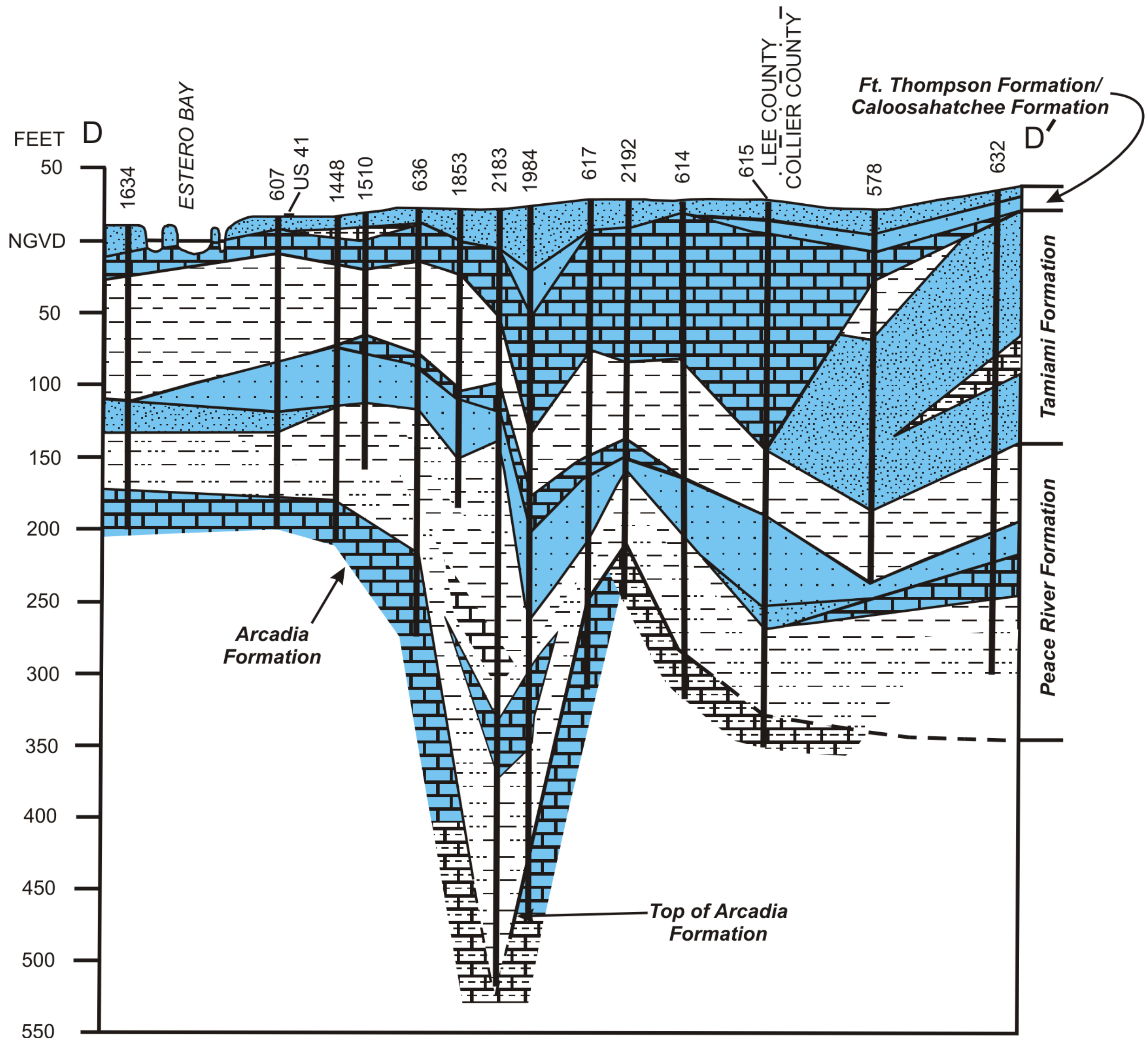

Figure 5. East-west section across south-central Lee County showing a synclinal structure in the Arcadia Formation with a thickened section of Peace River Formation and Tamiami Formation in the trough (modified from Boggess et al., 1982).

Charlotte Harbor and Peace River

Seismic-reflection profiles of the Charlotte Harbor area published by Wolansky et al. (1983) show the presence of subsurface folds. Sinkholes are evident, which are distinctly different from the more widespread folding. The deformation occurred after the deposition of seismic stratigraphic unit 3 of Wolansky et al. (1983), which suggests a late Miocene or earlier timing of the deformation. A subsequent seismic investigation by Evans and Hine (1991) also documented subsurface folding. The seismic profiles show broad troughs in the R3 unconformity surface of Evans and Hine (1991) with maximum reported depths of 70 to 90 m. The R-3 surface is interpreted to mark the 10.5 Ma sea level lowstand (Evans and Hine, 1991). The folding is evident in overlying sequences D and E, which based on the biostratigraphy of Evans and Hine (1991) indicates that deformation occur in the late Miocene (Tortonian) or later. A structure contour map of the R-3 surface shows north-south and northwest-southeast axis of the folds (troughs). Sinkholes are present and aligned with the troughs (Evans and Hine, 1991).

Seismic profiling along the Peace River by Lewelling et al. (1998) revealed common sinkholes and fracture zones as well as folding. The top of the folding occurs 20 m or less below the river bed, within the upper Peace River Formation. The deformation therefore occurred during the late Miocene or later.

Wolanksy et al. (1983) suggested that buried karst, bioherms or banks are more likely interpretations of the folding than structural deformation. Evans and Hine (1991) attributed the relief of the R-3 unconformity surface to karstic dissolution of underlying Paleogene and Neogene limestones. Lewelling et al. (1998) interpreted the folding as large-scale subsidence features that formed in response to a loss of structural support at depth.

Tampa Bay

Duncan et al. (2003) documented trough-like depressions or folds in their seismic line 13 in the southern Tampa Bay area. The folding is evident as high up-section as the SB-4 conformity of Duncan et al. (2003), which separates the late Miocene-Pliocene and the Pleistocene. The axis of the folding appears to be approximately north-south, perpendicular to the east-west seismic section. Duncan et al. (2003) notes that the similarity of the seismic expression of the folding in the Tampa Bay area to that documented elsewhere in Florida suggests comparable origins.

Collier County North County Regional Water Treatment Plant

Subsurface structure at the North County Regional Water Treatment Plant can be distinguished using geological and geophysical data from 11 production wells installed along an east-west alignment (Maliva et al., 2002). A buried syncline was evident with a maximum relief of 32 m (Fig. 6). The folding extends upwards through at least the base of the sandstone aquifer of the upper Peace River Formation and extends downwards through at least the Arcadia Formation. The folding occurred no earlier than the late Miocene (Maliva et al., 2002). The axis of the fold appears to be oriented approximately north-south, perpendicular to the wellfield.

Palm Beach County—East Coast Regional Wastewater Treatment Plant

Duncan et al. (1994) reported a subsurface structural feature at the East Coast Regional Wastewater Treatment plant deep injection wellfield that is characterized by counter-regional (east to west) dips in the upper Oldsmar Formation and Avon Park Formation. The structural feature was interpreted to be either a fault or monoclinal flow (Duncan et al., 1994). The dip gradually decreases up-section. The dip is approximately 43 m over a 30.4 m distance at the top of the Oldsmar Formation, and only 12 m over the same distance near the top of the Avon Park Formation. There is little relief at the base of the Hawthorn Group, which is a major unconformity. The subsurface structure is interpreted to be a pre-Miocene-age fold.

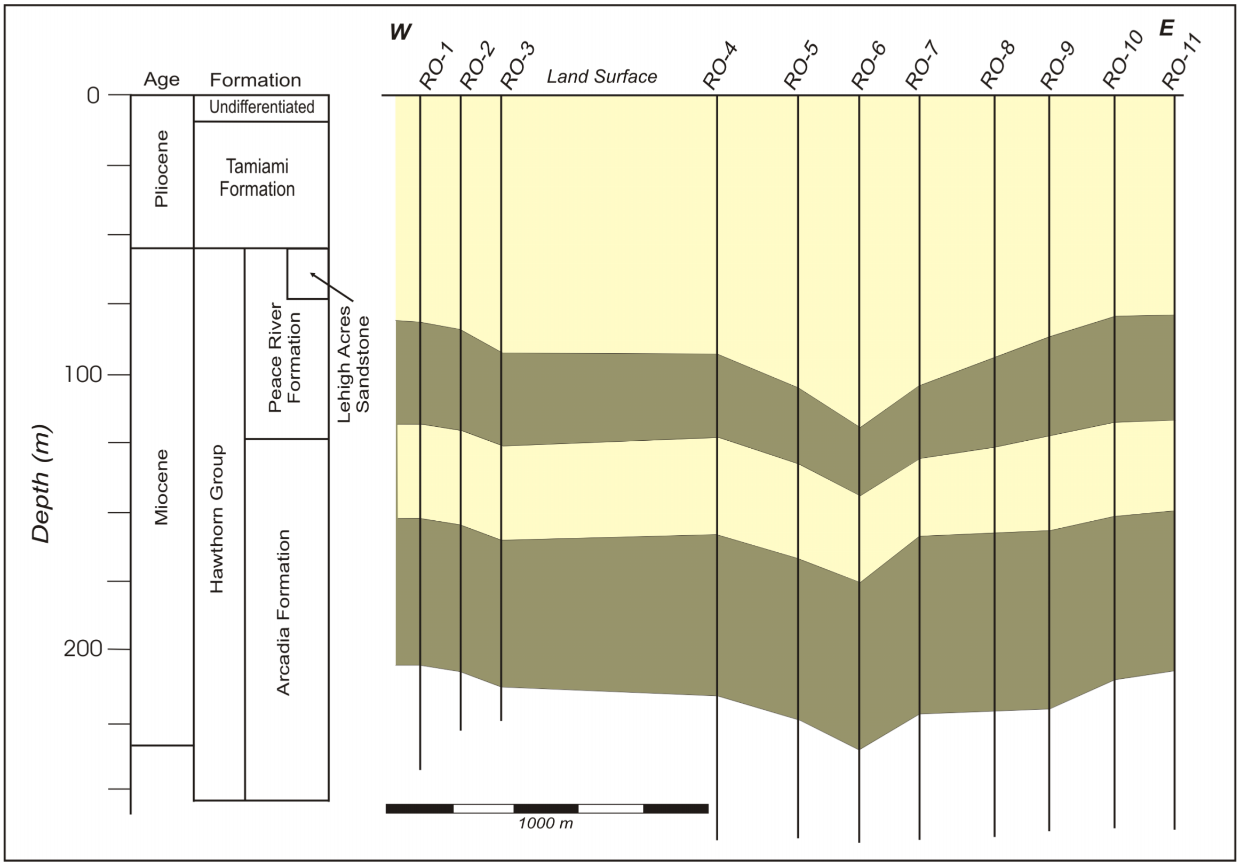

Figure 6. East-west section across north-central Collier County showing a synclinal trough developed in the Arcadia and Peace River Formations (modified from Maliva et al., 2002).

Indian River Lagoon, Near Vero Beach

High-resolution seismic profiling was performed in the central Indian River Lagoon Region in an area where faulting was suspected of allowing upward migration of saline water from the lower Floridan aquifer (Flocks et al., 2001). The seismic profiling shows folding of strata as well as small-scale solution collapse features. No faults were identified. The deformation (folding and down warping) affects the top of the Ocala and middle Hawthorn marker reflections. The truncation of reflectors and small infilled channel-like features at the top of the Hawthorn Group suggest a flooding surface (Flocks et al., 2001). The deformation occurred during the latter part of Hawthorn Group deposition and is thus of either late Miocene or Pliocene age. Flocks et al. (2001) suggested that the seismic pattern is more characteristic of karst systems.

St. John's River, Near Palatka and in Duval County

Broad folds having approximately 12-20 m of relief were documented in the St. John's River near Palatka by Snyder et al. (1989). The folding is expressed through the entire Miocene and upper Paleocene, indicating a Plio-Pleistocene timing of deformation. The seismic expression of the folding is distinctly different from the expression of solution shafts and large-scale cavern collapse features Snyder et al. (1989) document from the Lake Wales Ridge area of central Florida. The St. John's River folding, referred to as 'solution-valley subbottom flexures,' was interpreted as seemingly taking place by gradual subsidence that allows overburden settlement to keep pace with the formation of solution vugs (Snyder et al., 1989). Spechler (1994, 2001) documented similar folding in the St. John's River in Duval County.

Northeastern Florida Shelf—Fernandina Beach to Cape Canaveral

Meisburger and Field (1975, 1976) documented that broad shallow undulatory flexures are common in the subsurface of the Atlantic inner continental shelf off northern Florida. Less common is pronounced folding, which was interpreted as being of probable structural origin. Many of the flexures affect the entire vertical section, whereas others are confined to one or more lower units, indicating that intermittent structural deformation occurred over a long period of time (Meisburger and Field, 1975, 1976). The youngest deformed strata are of middle to late Miocene age (Meisburger and Field, 1976), which indicates that the last deformation occurred in the late Miocene or later. The axis of the flexures tend to have a N-NW to S-SE orientation.

Subsurface folding on the northeastern Florida shelf was subsequently documented by Popenoe et al. (1984), who proposed that the folds are a solution collapse phenomenon of beds deep within the Floridan Aquifer System and are not related to tectonic influences. The illustrated folds have up to 80 m of relief in places. Popenoe et al. (1984) noted that folding does not occur to the same degree off the continental shelf and that dissolution collapse features (i.e., folding) are not evidenced in the Eocene rocks where they are not underlain by Paleocene carbonate platform facies.

Popenoe et al. (1984) illustrate the seismic expressions of small-scale collapse features, which are characterized by local, steep-sided columns of disrupted bedding. On the contrary, the illustrated folds are characterized by continuous, concentric, non-disrupted bedding. Popenoe et al. (1984) suggested that the most pronounced dissolution and collapse occurred during sea level lowstands in the late Oligocene and early Miocene. However, some folding clearly occurred later. The documented folding affected Oligocene and Eocene strata.

North Florida—South Georgia Coastal Ridge Deposits

Variations in the altitude of former coastal deposits provide additional evidence of structural movements. Individual shoreline deposits are related to a common depositional datum; sea level (Hoyt, 1969; Winker and Howard, 1977). Variations in the present-day elevations of individual shoreline deposits may therefore document structural movements of the deposits. Salt marsh deposits are particularly useful because they are laid down close to mean sea level (Hoyt, 1969). The early Pleistocene or late Pliocene Trail Ridge (Wicomico) coastline deposits reportedly have a maximum displacement of 20-21 m over approximately 72 km, with elevation increasing to the south (Hoyt, 1969). Structural movement has continued into Quaternary time.

Discussion

Occurrence and Origin

Folding is likely much more widespread throughout the subsurface of Florida than is currently recognized because of the paucity of fine-scale subsurface data. Published seismic reflection profiles are largely restricted to some coastal areas and rivers. In the absence of seismic reflection profiles, recognition of the folding requires closely spaced deep wells in which detailed lithologic logs and/or geophysical logs were prepared. Deep wellfields with suitable data available to discern subsurface structure are uncommon.

Subsurface folding observed in seismic reflection profiles and geologic cross sections share common features, which suggests a common origin. Firstly, the folding is concentric and occurred without disruption of strata. Stratigraphic layers are continuous across structure. All layers observed below the top of the folds are also folded. The bottom of the deformation occurs at a greater depth than that of the seismic reflection profiles and wellfields. The folding throughout Florida also tends to have a preferred broadly north-south orientation. In addition, folding was also roughly concurrent at scattered locations across the state. Widespread deformation occurred in the late Miocene to early Pliocene, as indicated by the age of the youngest strata impacted.

The subsurface folding has been attributed to karstic collapse (Popenoe et al., 1984; Snyder et al., 1989; Evans and Hine, 1991; Cunningham et al., 2001; Flocks et al., 2001). However, the style of deformation is incongruent with a collapse origin, which typically results in chaotic deformation of overlying

strata, not continuous concentric folding (Fig. 7 shows a sinkhole). Furthermore, the folding occurs in both regions with large-scale karst development (central Florida) and regions where karst is not present on a scale that could produce observed folding (Lee and Collier counties). Inasmuch as the folding is widespread, a causative collapse zone would also have to be widespread, yet no evidence of a regional karstic collapse zone that could be responsible for the folding has been documented in deep wells.

Cavernous zones are present in wells completed in the so-called "Boulder Zone" of the Oldsmar Formation (lower Eocene) that have been interpreted as being dissolution features (e.g., Kohout, 1967; Vernon, 1970; Randazzo, 1997). However, it is now generally recognized that the cavernous zones form after drill bit penetration by the borehole collapse of fractured dolomites (Safko and Hickey, 1992; Duerr, 1995; Maliva and Walker, 1998). The Boulder Zone is also not present in the Tampa Bay area and northeastern Florida where folding is present. The subsurface folding is therefore not related to the Boulder Zone.

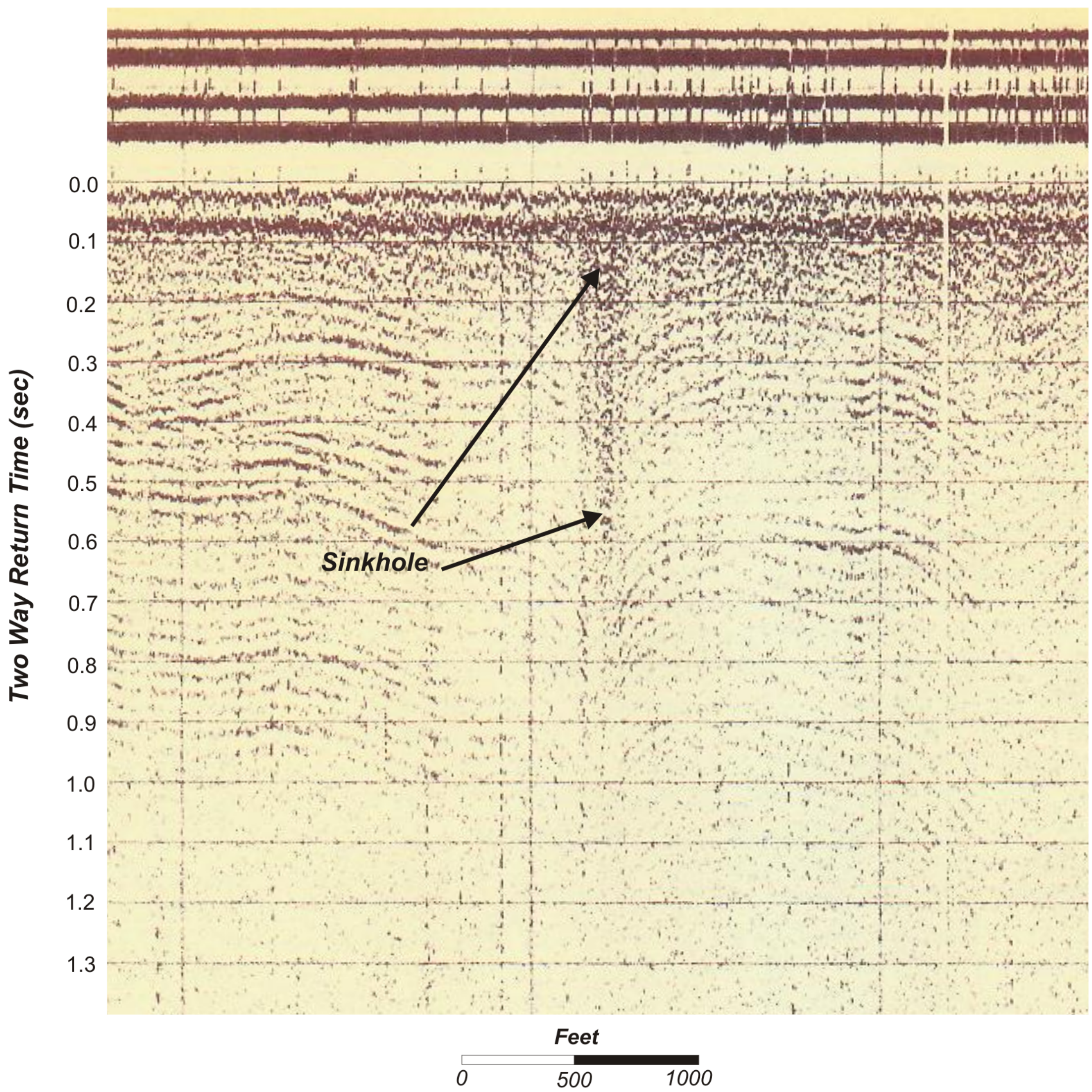

Figure 7. Section of seismic reflection record from a boomer (200 joule power input) near Fort Myers Beach (Lee County, Florida) showing a typical sinkhole/karst feature. Note the steep sides, chaotic bedding in the center, and the small horizontal scale.

The folding documented in the Intermediate and Floridan Aquifer systems may impact groundwater flow by inducing fracturing, particularly of dolomite beds. Fractured dolomites are often the main flow zones in Florida production and injection wells (fault associated with fold, Fig. 8) (e.g., Haberfeld, 1991; Safko and Hickey, 1992, Deurr, 1995, Knochenmus and Robinson, 1996; Maliva and Walker, 1998; Maliva et al., 2002). The tendency for dolomite beds to have high transmissivities can results in high degrees of aquifer heterogeneity (Maliva et al., 2002). Dolomitic strata in general have a greater tendency than limestones to develop effective fracture networks and thus have enhanced transmissivity (Schmoker et al., 1985). Dolomite tends to have greater mechanical strength and lesser ductility than limestone and therefore is more likely to yield to stresses by fracturing (Schmoker et al., 1985). Not all dolomitic units in the Intermediate and Floridan Aquifer systems are fractured. Unfractured dolomitic units often have very low hydraulic conductivities and act as confining units against vertical flow (Maliva and Walker, 1998).

If the fracturing of dolomites is indeed related to regional structural events then a preferred orientation of fractures would be expected, which would impact horizontal anisotropy to aquifers. Fractures in folded strata may have preferred orientations either parallel, perpendicular, or oblique to the axis of the folds (Stearns and Friedman, 1972; Domenico and Schwartz, 1998). Little data are available on the anisotropy of aquifers in the Intermediate and Floridan Aquifer systems. Calculated horizontal anisotropies from west-central Florida wellfields ranged for 2.5:1 to 25: 1 with an average of 5:1 (Knochenmus and Robinson, 1996). The direction of the anisotropy roughly coincided with the orientation of regional photolineaments. A regional structure control over dolomite fracturing raises the possibility of better prediction of aquifer anisotropy and thus groundwater flow directions and capture zones.

Regional Tectonism During the Late Miocene to Pliocene

Active tectonism has occurred along the boundary between the Caribbean and North American plates throughout most of Cenozoic time. Very complex tectonism occurred from the early/middle Miocene to the Recent in Puerto Rico and the Virgin Islands (Larue et al., 1998). This activity is associated with easterly transtensional motion of the Caribbean plate relative to North America (Jordan, 1975; DeMets et al., 1990). During this time period a 25 degree counterclockwise rotation of the Puerto Rico and Virgin Islands Platform occurred (Reid et al., 1991). Also, a late Miocene to Pliocene flexural event occurred along the north margin of Puerto Rico causing the basin to subside up to 4 km (Larue et al., 1998). Mattson (1984) found that the relative Caribbean Plate motion for the last 5 million years along the north margin was directed west at the boundary with a slight southwest direction within the northernmost part of the plate. The Caribbean Plate margins were underthrust and uplifted during this period (Mattson (1984). Lewis and Draper (1990) documented uplift along the northern Caribbean margin from late Miocene to recent in Cuba, Hispaniola, Puerto Rico, the Virgin Islands, and Jamaica. The uplift was accompanied by folding in Jamaica and by strike-slip faulting in Cuba, Hispaniola and Jamaica (Lewis and Draper, 1990). Pindell and Barrett (1990) suggested that transcurrent motion began along the Oriente fault accompanied by a gradual change from strike-slip to compression in southern Hispaniola. This eastward motion of Hispaniola from Cuba led to convergence between northwest Hispaniola and the southeast Bahamas at the Hispaniolian Bend (Fig. 9). The episodic compression caused by the collision of the Caribbean and North American plates to the southeast of the Florida Platform may have produced both compressionary thin-skinned folding and reactivation of basement faults in the Bahamas and Florida.

Other regional tectonic events had influences on the South Florida Platform. A middle to late Miocene structural event in the Southern Appalachians may have caused an uplift of the region in North Carolina and Georgia (Stuckey, 1965). Huddlestun (1998) found evidence of this event in the form of increased stream gradients, which produced, thickened sediment sequences in the late Miocene and younger sediments. Also, there is evidence for the development of stream-transported sediment the entire length of the Florida Platform from Georgia to the Florida Keys (Missimer, 1999). This could not have occurred without an enhanced gradient from the southern Appalachians into the Florida Platform.

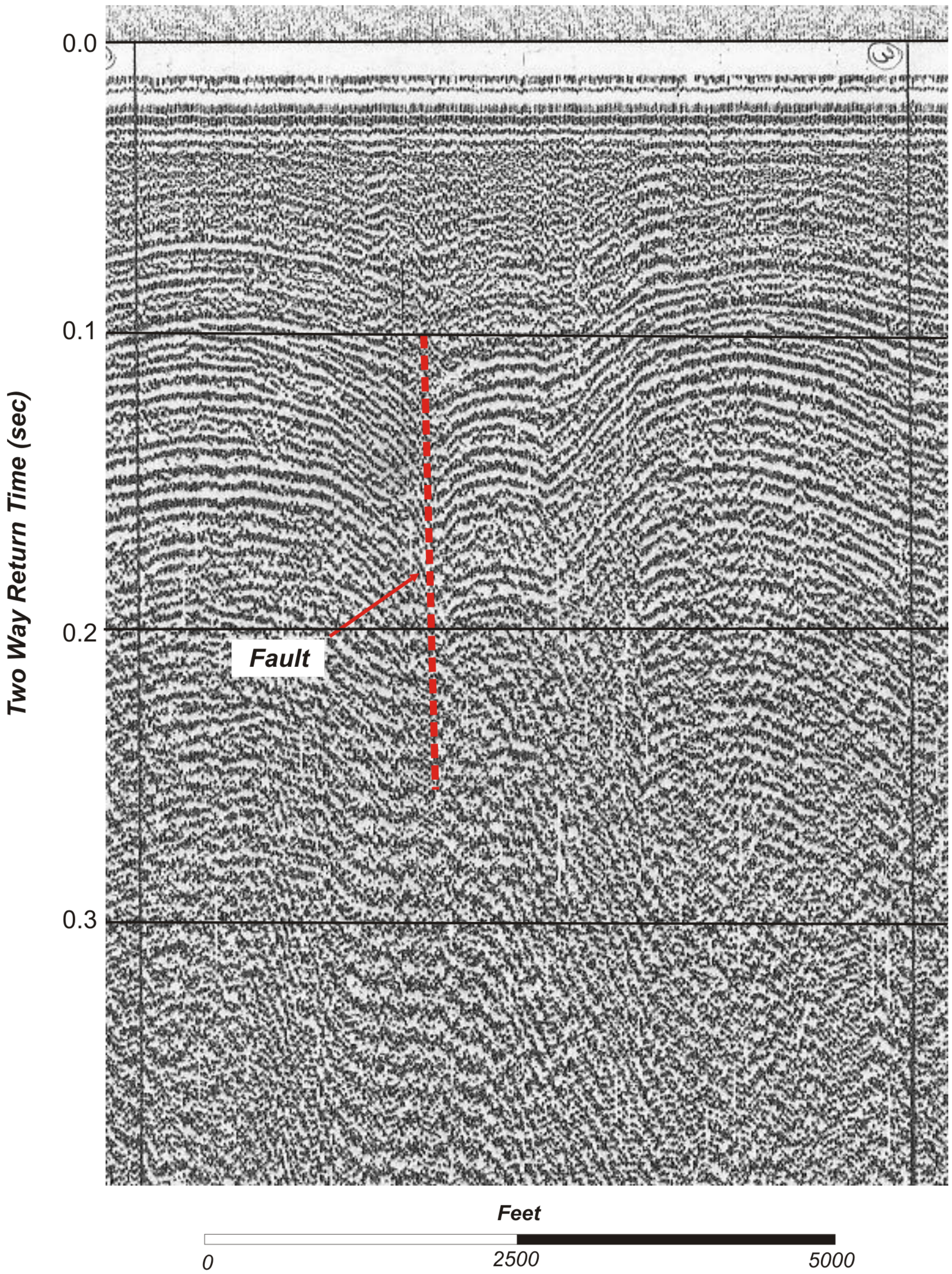

Figure 8. Deformed strata in the Eocene to Pliocene section with a fault. Seismic reflection record is from a multi-channel water-gun system. Section is located near Marco Island, Florida.

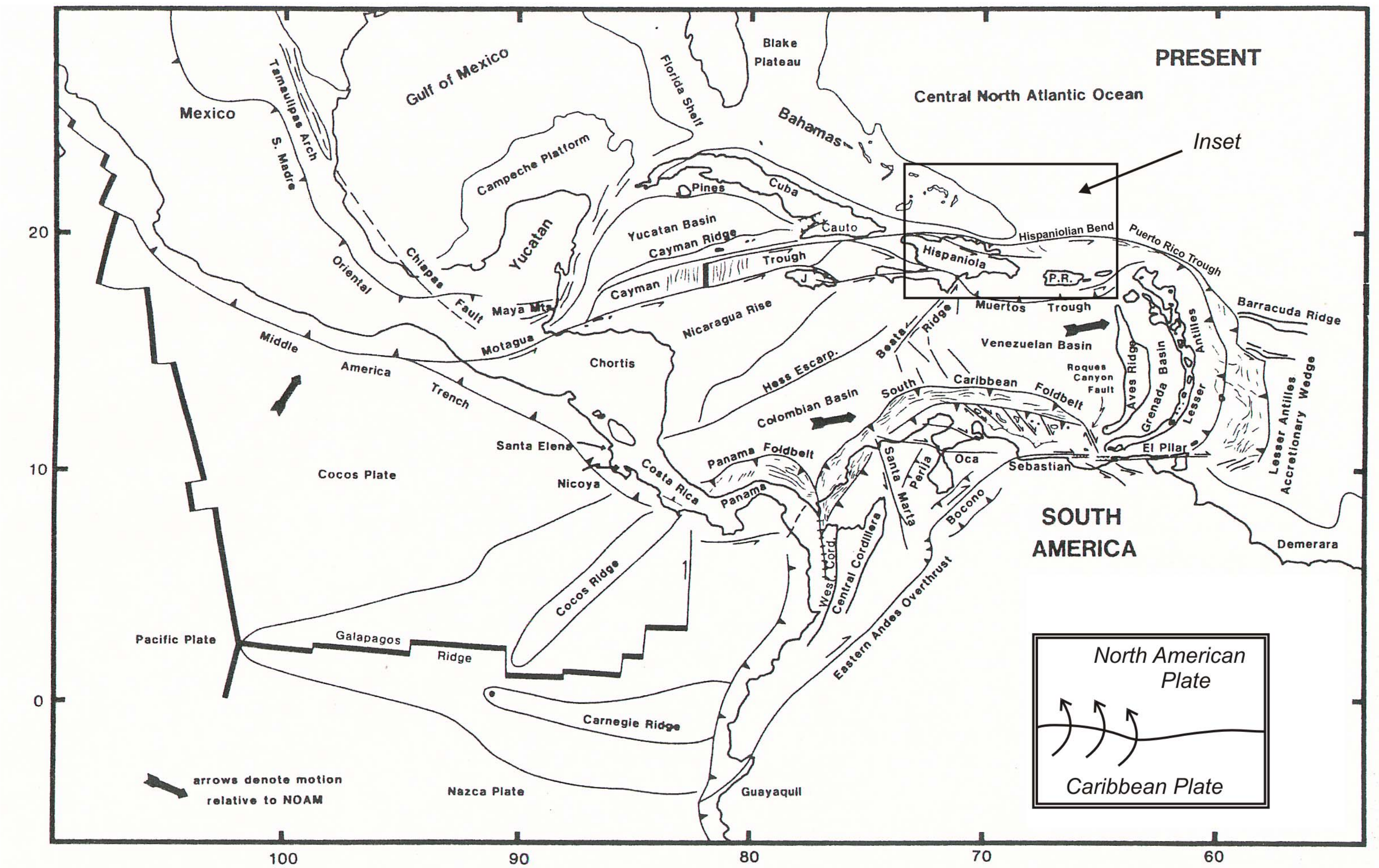

Figure 9. Tectonics of the Caribbean and North America Plate southeast of Florida showing the counterclockwise compression along the northern plate boundary in the late Miocene and early Pliocene (modified from Pindell and Barrett, 1990)

Conclusions

Evidence of widespread folding challenges the traditional view of the Florida Platform having been tectonically quiescent during the Cenozoic Era. The Florida Platform instead underwent multiple deformation events, including a regional event in the late Miocene to early Pliocene. The deformation events are likely subdued, peripheral responses to tectonic events occurring within the Caribbean Basin. The deformation may influence current groundwater flow by having caused the fracturing of dolomite beds. The fracturing of dolomite beds resulted in increased transmissivity and also possibly imparted a horizontal anisotropy to aquifers.

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