Early Load-Induced Fracturing in a Prograding Carbonate Margin

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Abstract

The description of early non-tectonic fracturing of carbonates is rare because (1) fractures in young carbonates occur in areas not easily accessible, and (2) burial and diagenesis often precludes the determination of the exact timing of (early) fracturing in older rocks. The Bahamas Drilling Project core Clino recovered the upper part of a young prograding platform margin containing a set of fractures interpreted to be non-tectonic; formed by rapid loading of a clinothem package. Three intervals with open and partially infilled fractures were recovered in Clino, and those fractures are closely related to the lithologic variation in the slope sediments. Fracturing occurred specifically within coarse, well-cemented skeletal deposits. These coarser deposits are generally margin-derived sediments within the background sediment. The overlying and underlying finer-grained sediments are significantly less fractured. The fractures occur within a 45 m thick interval immediately below a surface of non-deposition or erosion with a hiatus of >0.5 my. Our model suggests that early cementation of the skeletal sands, followed by rapid margin progradation, provided significant load to generate brittle fracturing (shear and extensional) in lithified strata. Laboratory deformation experiments, magnetic fracture-plane orientation and the timing of load emplacement are consistent with load-induced fracturing. Fracture planes preferentially dip westward which is parallel to the depositional slope. Similar early fracture porosity can act as high permeability conduits for diagenetic fluids and hydrocarbons in platform margin and slope strata.

Introduction

Early fracturing of lithified carbonates is a rarely reported phenomenon. Observation of fractures in young carbonates is difficult because such features generally occur in relatively inaccessible near-surface settings. In older rocks, burial and diagenetic history may preclude the identification and the exact timing of fracturing, making it difficult to determine that fracturing occurred *early*. The Bahamas Drilling Project core Clino recovered, for the first time, a complete section of a

young (Neogene) prograding platform margin along the western margin of Great Bahama Bank (Figure 1). This core recovered a set of fractures in the clinotherm package, and they are described here. These fractures are natural and clearly not drilling induced (Kulander *et al.*, 1990). Our interpretation of the fractures benefits greatly from existing studies. A detailed lithologic (Kenter *et al.*, 2001), stratigraphic (McNeill *et al.*, 2001; Eberli *et al.*, 2001) and diagenetic (Swart *et al.*, 2001; Melim *et al.*, 2001) framework has been produced for core Clino. This extensive dataset allows a comprehensive evaluation of the conditions that contributed to early rock fracturing. The objectives of this paper are to use the fracture inclination, fracture orientation, fracture density and constraints on fracture timing to illustrate a mechanism of early fracturing. Our hypothesis relates early diagenesis and rapid progradation of the platform margin to invoke fracturing. The mechanism of early fracturing in our model has implications for preferential fluid exchange and might be a contributing factor in the collapse of platform margins (Hine *et al.*, 1992).

Stratigraphic Setting of the Fracture Interval

Three intervals of open and partially infilled fractures were recovered in core Clino within mid-Pliocene seismic sequences *e* and *f*, just below their respective seismic sequence boundaries (SSB) D and E (Figure 2) (see Eberli *et al.*, 2001 for a description of the seismic units and sequences). In these two sequences, core Clino penetrated the relatively steep (~4°) part of the prograding clinoform (Eberli & Ginsburg, 1987). The two main fracture intervals (upper and middle) are within sequence *e*, and a third, thin fracture interval (lower) is at the top of sequence *f* (Figure 2). The SSB-D and a disconformity just above it, represent an interval of non-deposition and/or erosion with a duration of about 0.5 to 0.8 my. Above SSB-D, a ~275 m thick package of sediment associated with prograding sequence *d* was deposited in a period of between 0.1 and 0.2 my. The three fractured intervals are closely tied to the lithologic variation in the slope sediments. The majority of fractures (upper and middle interval) occur specifically within coarse, well-cemented skeletal deposits. These skeletal deposits, termed "interruptions" by Kenter *et al.* (2001), represent margin-derived sediments deposited within (or interrupting) the background platform-derived sediment. The sediment "interruption" beds are interpreted by Kenter *et al.* (2001) as transported to the slope during times when most of the platform was subaerially exposed. The overlying and underlying finer-grained hemipelagic or "background" sediments that are shed to slope during times of platform flooding and high sedimentation rates are generally less indurated and contain less fractures. Seismic sequence *e* represents sediments deposited during a major backstep of the platform margin (to the east) and a period of platform aggradation

(McNeill, 2005). The slightly coarser grain-size likely promoted more rapid cementation relative to the finer-grained, and less permeable hemipelagic sediments (Westphal & Munnecke, 1997; Kenter *et al.*, 2001). This preferential early cementation is also supported by rock magnetic studies on the fractured and non-fractured interval, where (very) early cementation appears to have preserved chains of magnetite crystal from magnetotactic bacteria (McNeill, 1997).

Methods

Core Data and Fracture Characterization

The high core recovery (>90%) in the middle and lower parts of core Clino provide a nearly continuous record of early diagenetic features such as the fractures we report here. One-third of the whole core (6.3 cm diameter) was cut and separated for archive purposes. The remaining two-thirds of the core was used to measure and to collect samples. The depth values reported here are consistent with those in Ginsburg (2001), where the depths are in metres below mud pit (subtract 7.3 m to obtain depth below mean sea level). The depth interval from about 375 to 450 m contains distinct fractures that were first noted on site during drilling. The fractures in the slabbled core were characterized by measuring fracture plane inclination, fracture length, fracture aperture, and noting if the fracture was open or filled. The vertical extent of the fracture was also recorded and was used to provide a rough estimate of total fracture length per metre of core. This calculation is used to approximate fracture density.

Fracture Orientation

The dip azimuth of the fracture plane was calculated using magnetic declination. This procedure consisted of measuring the fracture dip orientation relative to an arbitrary red line marked on the core (used to confirm the up direction). The offset angle of the red line was then measured relative to a paleomagnetic plug drilled from that piece of core. The declination direction measured from the plug (see McNeill *et al.*, 2001) was then used to reorient the core piece (red line), and calculate the true dip azimuth of the fracture plane. This reorientation method is fairly robust given the strength and stability of the magnetic signal in this section of the core (McNeill *et al.*, 1997; McNeill *et al.*, 2001). This method does, however, have a certain amount of inherent error (such as magnetometer error, least-squares calculation of declination, preservation of true declination), and the error range is *estimated* at $\pm 5^\circ$. All of the orientation data are from pieces of

core that contain either a magnetic plug sample or are from adjacent pieces that could be fitted together with a plug-oriented core piece.

Sr-Isotope Ratio on Fracture Fill

A single strontium-isotope ratio on the mineralized fill material (celestite) was obtained by Peter Swart and provided for this study. This data point followed the methodology described by Swart *et al.* (2001) for the strontium-isotope stratigraphy of core Clino material. The celestite value was normalized to a NIST-987 standard of 0.710248 and the age determined by the look-up table of McArthur *et al.* (2001), which is calibrated to the Berggren *et al.* (1995) timescale.

Uniaxial Deformation Experiments

To obtain an estimate of the force needed to fracture rock of similar composition to that which hosts the fractures, two uniaxial compression tests were conducted. Two whole-core samples from the fractured zone (440 and 447 m) were subjected to compression tests at ETH-Zurich. The effective pressure of brittle failure was determined with standard methods of comparing the confining pressure minus the pore pressure (water at 10 MPa). The nature of the fracture and fault produced was also recorded.

Results

Fracture Data Set

The fractures in core Clino were grouped into three classes: through-going shear, axial split, or cataclastic shear (following the usage of Paterson, 1978). The through-going shear type was often a simple, single fracture or fault with relatively little effect on the adjacent host sediment (Figure 3a,b). The axial fractures are those oriented vertically or near vertically ($>70^\circ$) along the axis of the core (Figure 3c). This type often had multiple fractures that radiated outward from a slightly larger central fracture, although it was difficult to trace these subfractures in a 6.3 cm wide core. The cataclastic shear fracture type showed a zone, 10-20 cm long, that contained abundant fractures of differing orientations, lengths and aperture sizes (Figure 3d,e). The cataclastic zones sometimes had a central through-going fracture surrounded by subfractures, or terminated abruptly on a bed of differing composition and integrity.

The inclination of the fractures ($n = 151$) showed a skewed distribution, with most fractures biased to higher angles between 30° and vertical (Figure 4). The mean inclination was $\sim 57^\circ$, with a large standard deviation ($\sim 24^\circ$). The fracture inclination with depth in each of the intervals shows a broad scatter of values (Figure 5). It is interesting to note that the two intervening hemipelagic intervals between the three fracture intervals do contain several fractures, and that these fractures are very steep to vertical. Unlike the fracture inclination with depth, the cumulative fracture length (total fracture length in centimetres per 3 m interval) does show a generally higher fracture density near the tops of the three intervals and a trend of decrease downward (poorly defined) (Figure 6).

Host Rock Lithology, Log Signature, and Fracture Fill

The two main fracture intervals are hosted by the well-cemented skeletal grainstones and packstone units, termed "interruptions" and derived from the shallow platform to the east. The differential cementation between the fracture-host sediment and the hemipelagic sediments is well illustrated in the downhole log signature (Figure 7). The cemented skeletal intervals tend to show a higher sonic velocity relative to the background hemipelagic intervals. Similarly, the caliper log across the fractured intervals shows borehole diameters very close to the size of the diamond core bit, whereas the hemipelagic units above, within and below the cemented skeletal intervals show larger diameters due to less cementation (Figure 7). Within the fracture intervals, both the sonic and caliper logs show high frequency variations, a signature that likely reflects the variability of fracture-derived porosity and density.

The more intensely fractured rock in the middle and upper intervals sometimes contain secondary mineralization in the form of celestite (Melim *et al.*, 2001) (SrSO_4 also known as celestine, Figure 3f). The infill of fractures by celestite is highly variable with respect to depth and aperture size. In some cases, celestite has nearly filled the fracture (see Figure 3e), while in some of the larger fractures elongate individual celestite crystal are found lining the fracture surface (as in Figure 3f). The celestite infill clearly demonstrates the natural origin of these fractures. The timing of the celestite infill can be only poorly constrained. A celestite crystal at ~ 386 m produced a Sr-isotope ratio with an age range of 1.34-2.15 Ma. The uncertainty is high for this age as the time of crystallization due to the two possible origins of the strontium; either from dissolution of the aragonite or from seawater entering the platform. Most likely, it is some combination of the two, as Melim *et al.* (2001) suggest a temporal overlap of celestite precipitation and aragonite

neomorphism. They also argue that abundant celestite precipitation would require the import of sulphate by active fluid circulation. Even with the temporal uncertainty, it is interesting to note that the celestite age is coincident with the end of a major progradational pulse in the latest Pliocene (see Discussion below).

Fracture Orientation

The dip azimuth of 19 through-going shear fractures, determined using magnetic declination, shows a bi-directional, conjugate distribution (Figure 8). Two general groupings are approximately 180° apart, one westward and one eastward. These two orientations are roughly equivalent to seaward (west) and bankward (east) of the bank margin (oriented just east of north). The majority of the fracture planes dip to the west (14 of 19) in the direction of the depositional slope and basin.

Discussion of Fracture Origin

Origin of the Fractures: A Loading Model

The origin of the fractures is clearly not related to drilling (as celestite partly infills many fractures), and there is no evidence of local tectonic forces that could generate such localized fractures. Several key features and lines of evidence (shear/cataclastic fracture type, steep angle, conjugate fracture sets orientated perpendicular to the margin, and downward cumulative fracture length) suggest that fracture formation is related to vertical compression from sediment loading. Our model for fracture formation involves several factors: the integration of the coarse, permeable skeletal sand "interruptions", a prolonged period of non-deposition or erosion associated with a sequence boundary, and the subsequent rapid deposition of overlying sediment related to clinothem progradation (Figure 9). The fractures occur within a 45 m thick interval immediately below a non-depositional surface (SSB-D). This period of non-deposition (3.5-3.0 Ma) may have promoted cementation within the skeletal sediments of sequence *e* and at the top of sequence *f*. Malone *et al.* (2001) dated similar Quaternary "lowstand" deposits and corroborated the interpretation that the better cemented coarser-grained slope deposits are indeed deposited during times of lowered sea level and reduced sedimentation rates. The circulation of seawater through the permeable skeletal "interruptions" likely promoted lithification relative to the less permeable and finer-grained hemipelagic "background" sediments. The onset of platform progradation in the late Pliocene rapidly loaded the partially cemented "interruption" intervals

and promoted shear and extensional fracturing (see model summarized in Figure 10).

Experimental rock mechanics has shown that compressional loading can produce conjugate shear fractures with inclinations ranging from 40° to 70°, as well as near vertical extensional (axial splitting) fractures. The inclinations of the fracture planes in core Clino are generally consistent with the features generated from laboratory experiments.

Laboratory Support for Loading and Early Fracturing

Uniaxial deformation experiments of the two Clino “interruption” samples (at a depth of 440 and 447 m) showed brittle behavior at laboratory strain rates of ~10 MPa (effective pressure). The resultant brittle failure produced a single, steeply inclined, through-going fault (D. Olgaard, personal communication). This brittle fracturing is consistent with the current overburden pressure of a 425 m rock column (at 2.1 g/cc), within today's depth range of the fractures. If fracturing occurred after the progradation load (275 m column) was emplaced (~1.5 Ma) it is reasonable to assume that the "interruption" horizon was at an earlier stage in its lithification history and thus susceptible to early load-induced fracture.

Ancient Analogs for Loading and Early Fracturing

Documentation of early fracturing on carbonate platform margins is rare. One example from a prograding margin is the Permian, Capitan reef of west Texas and southeast New Mexico where marine cement and fossils filling fractures indicate early fracturing (Saller, 1996; Kosa & Hunt, 2006). The Capitan reef also shows a conjugate fracture set oriented perpendicular to the shelf margin. The fractures parallel to the Capitan reef front are generally steeper than Clino, and are concentrated in reefal facies. Differential compaction and basinward tilting (extension) are invoked to explain the steep axial fractures (Saller, 1996; Harwood & Kendall, 1999; Hunt *et al.*, 2003; Stanton & Pray, 2004). Although a different setting, this Permian example suggests that early cementation (in this case the reef margin) can fracture relatively early under load-related influences. In the case of Clino, the affect of down-to-the-basin compaction is hard to assess (in core), but perhaps the preferential fracture dip direction to the basin (west) (Figure 8) might be explained by this influence.

Conclusions

Studies of fracturing within prograding carbonates are relatively rare. In one example, Saller (1996) and others describe fractures within the reefal facies of the Capitan that have dip directions normal to the depositional strike of the platform margin. The Capitan fractures range between 75° and 85° and were interpreted to have formed because of extension during down-to-the-basin differential compaction. The Bahamas fractures may have also experienced some of the same differential compaction, but fracturing was likely driven largely by the loading effects of the overlying, rapidly-emplaced prograded sediment that accumulated on the seaward (basin) side of the Clino location. We propose that this fracturing formed during a period of tectonic quiescence on Great Bahama Bank and is thus essentially non-tectonic in origin.

The Clino fracture data support a non-tectonic mechanism for the formation of macroscopic fractures. The combination of early diagenesis (cementation) and the subsequent load emplacement by the prograding platform margin have produced very early fracturing in the burial history of the platform. These fractures (at least for their early burial history) have distinct geophysical log signatures, and have largely remained opened and unfilled (except for some celestite infill). The original porosity, or later re-opened fracture porosity, may act as major fluid-flow pathways within the platform margin slope. Those pathways may be conduits for the upward movement of burial fluids and focus diagenetic alteration associated with those burial fluids. In the deeper subsurface, associated fracture permeability may enhance vertical and lateral fluid flow.

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Figure Captions

Figure 1. Map showing the location of core Clino on the western margin of Great Bahama Bank. The location of the seismic line on which the line drawing (Figure 2) is based is also shown.

Figure 2. Line drawing of the seismic sequences penetrated by core Clino (from Eberli *et al.* 2001). Clino fractures occur in sequence *e* (bounded by red lines). Fractures in sequence *e* occur primarily in beds of coarse skeletal sediment redeposited downslope from a shallow-water source area east of core Unda. The shaded areas indicate onlapping packages.

Figure 3. Photographs of fracture core. a-b) through-going shear fracture at 441 m depth; c) axial fracture at 379 m, note central fracture with small subfractures radiating outward; d) cataclastic shear fracture with a central through-going shear, 431 m depth; e) cataclastic fracture at a bed contact at 437 m; celestite infill of larger fracture openings, this photo illustrates how minor differences in the degree of cementation likely affect fracture potential; f) fracture surface with large crystals of celestite at 401 m depth.

Figure 4. Histogram of inclination angles for the whole fracture interval in core Clino. The domination by intermediate to vertical fractures suggests compressional and perhaps some extensional forces are influencing the fracture formation.

Figure 5. Fracture plane angle versus depth. The skeletal "interruptions" exhibit a wide scatter in inclination, but most are in excess of 30°. Note that relatively few fractures occur in the hemipelagic intervals.

Figure 6. Cumulative fracture length (total fracture length in centimetres) per 3 m interval. A slight trend of decreased fracture density with depth can be observed in these histogram plots. This trend may be a result of greater cementation at the sequence boundaries that cap the upper and lower interval, or simply related to the higher permeability in the skeletal "interruptions".

Figure 7. Sonic velocity and caliper logs over the fracture interval. The fractures show greater velocity than the adjacent hemipelagic sediments, a result of greater cementation. Likewise, the caliper log reflects a smaller diameter borehole in the skeletal interruptions relative to the less cemented hemipelagic intervals.

Figure 8. Attitude of the fracture surfaces (dip angle from the horizontal) in Clino as determined by paleomagnetic orientation. The conjugate fractures reflect an orientation perpendicular to the platform margin, with the majority of the fractures dipping seaward.

Figure 9. Age-depth plot for core Clino from McNeill *et al.* (2001). The upper, middle, and lower fracture intervals are shown in middle Pliocene age host sediments. Progradation loading above SSB-D in the latest Pliocene rapidly added over 300 m of sediment on top of the skeletal "interruptions" to produce compression fractures.

Figure 10. A cartoon summarizing the general forces and fracture types at the progradational margin of western Great Bahama Bank. The key to early fracture is the preferential early cementation of the skeletal "interruption" beds.

McNeill & Eberli Figure 1

McNeill & Eberli, Figure 2

McNeill & Eberli Figure 3

McNeill & Eberli Figure 4

McNeill & Eberli Figure 5

McNeill & Eberli Figure 6

McNeill & Eberli Figure 7

Attitude of fracture surfaces Bahamas Drilling Project Core CLINO

McNeill & Eberli Figure 8

McNeill & Eberli Figure 9

McNeill & Eberli Figure 10