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Rates and Kinematics of Folding based on Milankovitch Rhythms in Cretaceous Carbonates, NE Mexico

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Cretaceous stratigraphy within Sierra del Fraile, a regional-scale décollement fold in northeastern Mexico, dutifully record Milankovitch rhythms and growth strata providing a high-resolution deformation chronometer. Sierra del Fraile (**Figure 1**) contains Cretaceous cyclic carbonates that are important hydrocarbon targets within similarly evaporite-cored detachment folds in the Texas and Louisiana Gulf Coast and the deepwater Gulf of Mexico. Sierra del Fraile is composed of two tight anticlines separated by two broad plunging synclines. The entire ~150 km^2 structure has multiple detachment levels, the lowest in the underlying thick Jurassic evaporites of the Minas Viejas Fm. Potrero Garcia, the southernmost anticline, is a concordant structure, while Potrero Chico, the northern fold, was locally pierced. Facies correlation and transition from pregrowth to growth strata across the fold complex suggests deformation initiated at an earlier time in Potrero Garcia than Potrero Chico.

Although many mark the onset of deformation in the Sierra Madre Oriental and the adjacent foreland basin at the earliest Coniacian time (e.g. de Cserna 1989, Laudon 1996) and in the hinterland of the Sierra Madre Oriental at Cenomanian time (e.g. Gray et al. 2001); facies distribution and bedding geometry within the nearby La Popa Basin demonstrate that salt was actively moving at least from the late Aptian (e.g. Lawton et al. 2001). This is corroborated by growth strata within Cenomanian through Santonian age units exposed on the plunging end of the Garcia anticline within Sierra del Fraile (**Figure 2**). The synorogenic Cuesta del Cura, Agua Nueva, and San Felipe Fms. are characterized basinwide by rhythmically interbedded pelagic limestone and shale/marls (couplets ~0.20-1.5 m thick). This style of deeper water cycles is common in mid to Upper Cretaceous deposits worldwide (e.g. Fischer et al. 1991, Kauffman et al. 1993) and are interpreted to reflect precessional and/or obliquity climatic forcing, which influenced marine primary productivity, rainfall/humidity patterns, wind patterns, and water-column stratification (e.g. ROCC 1986, Pratt et al. 1993, Sageman et al. 1997). Within the pregrowth strata of the Cupido Fm., Milankovitch based cycles are recorded by magnetic susceptibility and anhysteretic remanent magnetization (ARM) measurements, which correlate to sedimentary cycles. The occurrence of Milankovitch-driven climatic cycles in the stratigraphic section within Sierra del Fraile provides a powerful high-resolution chronometer to determine deposition and deformation rates.

Magnetic susceptibility and ARM measurements from Garcia Canyon indicate that Milankovitch cycles are recorded by the Cretaceous age carbonate strata in northeast Mexico (**Figure 3**). Large spikes within the magnetic data correspond with cycle tops identified sedimentologically (e.g. Goldhammer et al. 1991). Independent time series analysis of the two datasets reveal four cycle frequencies consistent with the ratios of Cretaceous Milankovitch periodicities (after Berger et al., 1989). The magnetic data are able to discern all of the orbitally forced rhythms within the sampled section, including the precessional cycle, not recognizable by sedimentological facies changes. The ability to record all Milankovitch frequencies by magnetic means independent of sedimentary facies allows for the astronomical tuning of growth strata within the more basinal facies of the Cuesta del Cura, Agua Nueva, and San Felipe Fms. that lack obvious facies cyclicity. The presence of the ~20,000 year period in the magnetic data allows for the refinement of accumulation rates from previously established rates based on the observation of ~41,000 yr facies based obliquity cycles (Goldhammer et al. 1991). The magnetic data also confirm that the main control on carbonate cycles within the sampled section is the obliquity rhythms, as interpreted by the observation of multiple precessional rhythms within a single carbonate cycle.

Each water depth dependent carbonate facies is composed of differing grain sizes, siliciclastic clay ratios, bed thickness, and bioturbation abundance, and as a consequence have differing anisotropy and competency. The stratigraphic and structural distribution of these predictable facies-based lithotectonic units can be used to characterize deformation patterns. Since facies migrate with changes in sea level and evolving fold formation, kinematic patterns are similarly expected to migrate during progressive deformation. Fossil-rich organic buildup and karstified facies, because of their lack of anisotropy, serve as the position of pin lines during folding. Back buildup environments, which are carbonate-rich and competent, but well-bedded and more anisotropic than the adjacent buildup facies, experience dominantly flexural slip deformation with low penetrative strains and numerous faults on mechanically active bedding surfaces. Offshore lagoonal facies, on the other hand, are more clay-rich, therefore more incompetent, but substantial anisotropy variation results from varying levels of bioturbation. As such penetrative strain vary as a function of mechanically viable bedding thickness.

Evaluation of décollement fold kinematics are being constrained by two independent means by measuring spatial variations in deformation patterns in pregrowth strata as a function of structural geometry, lithology, and stratigraphic position and by measuring the geometry and rates of deformation and deposition in growth strata within Sierra del Fraile (**Figure 4**). A study of anisotropy of magnetic susceptibility (AMS) across the fold gives insight into the accumulation of diagenetic and tectonic strains and demonstrates that penetrative strain is consistent with mesoscopic structures. In a separate AMS study, magnetic fabric was measured on tidal flat, lagoon, shoal, and buildup facies across the Sierra del Fraile anticlinorium. Analyses of tidal flat and shoal facies record stronger fabrics than buildup samples. Buildup, lagoon, and tidal flat facies record limb shear towards a fixed, relatively unstrained hinge, while shoal samples, record pin lines at limb inflections; hinting at complex fold kinematics that vary with lithology. These studies are being corroborated with calcite twinning studies at Sierra del Fraile and provide a detailed record of depositional and tectonic strains across the anticlinorium. The combination of magnetic susceptibility and ARM data and AMS measurements throughout Sierra del Fraile allow for high-resolution spatial and temporal analysis of décollement fold kinematics.

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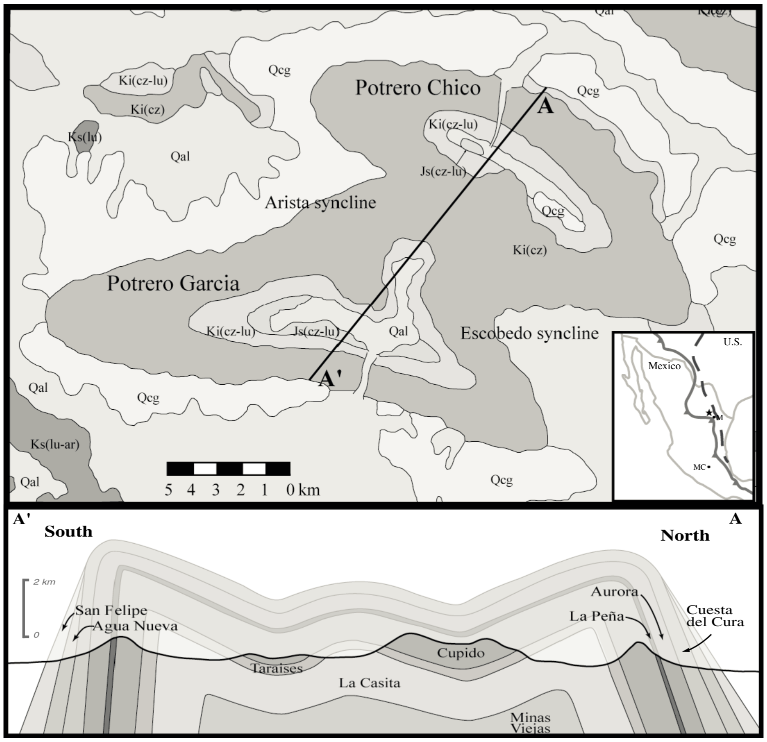

Figure 1. Geologic map and cross section through Sierra del Fraile.

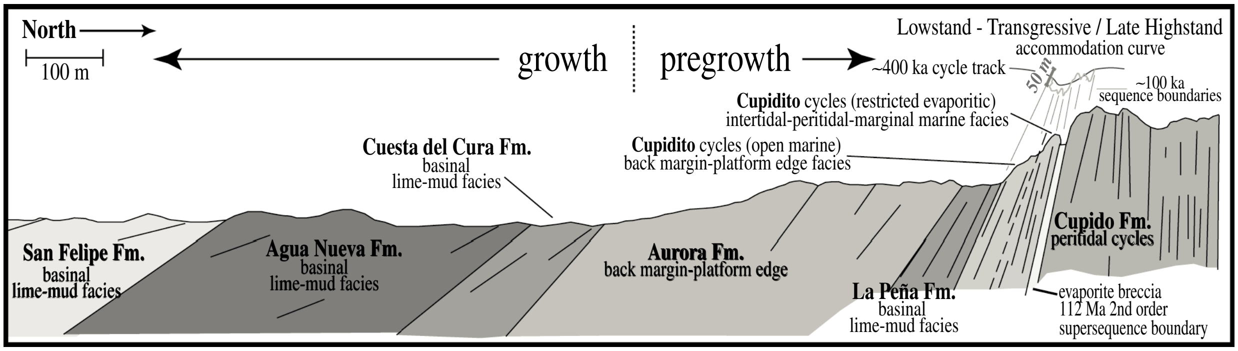

Figure 2. Sketch highlighting the growth and pregrowth Cretaceous cyclic carbonates units well-exposed in Potrero Garcia.

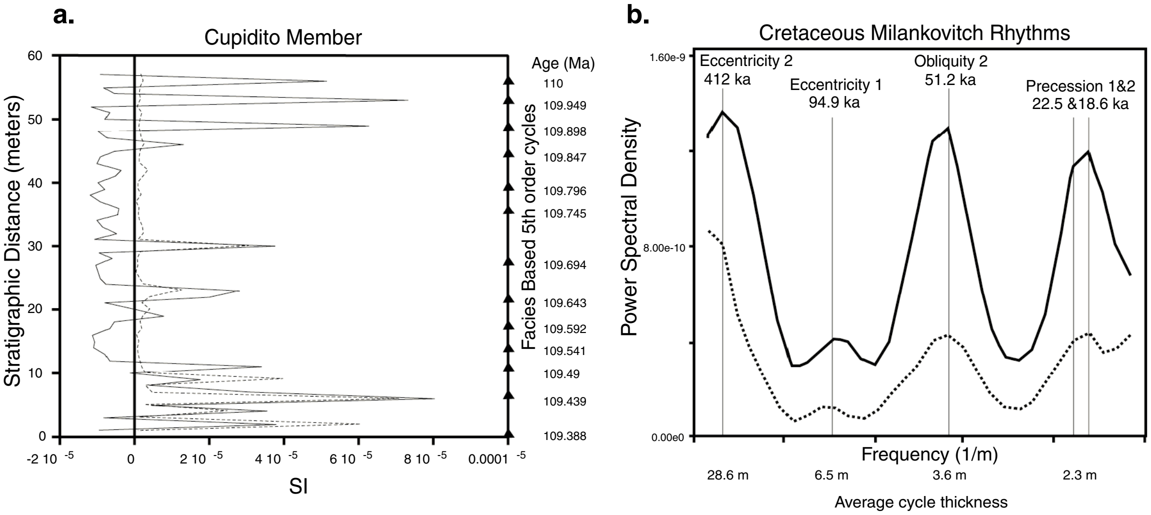

Figure 3a. Magnetic susceptibility *(solid line)* and anhysteretic remanent magnetization (ARM) *(dashed line)* variations dutifully record cyclicity within the Cupidito member of the Cretaceous Cupido Fm. providing a high resolution chronometer. Large spikes in the magnetic data correspond with cycle tops identified sedimentologically (i.e. Goldhammer et al. 1991). Ages are based on the 110 Ma formational boundary and the Cretaceous obliquity signal. **b.** Independent time series analysis reveal four frequencies of cyclicity whose ratios are consistent with Cretaceous Milankovitch rhythm predictions (Berger et al. 1989).

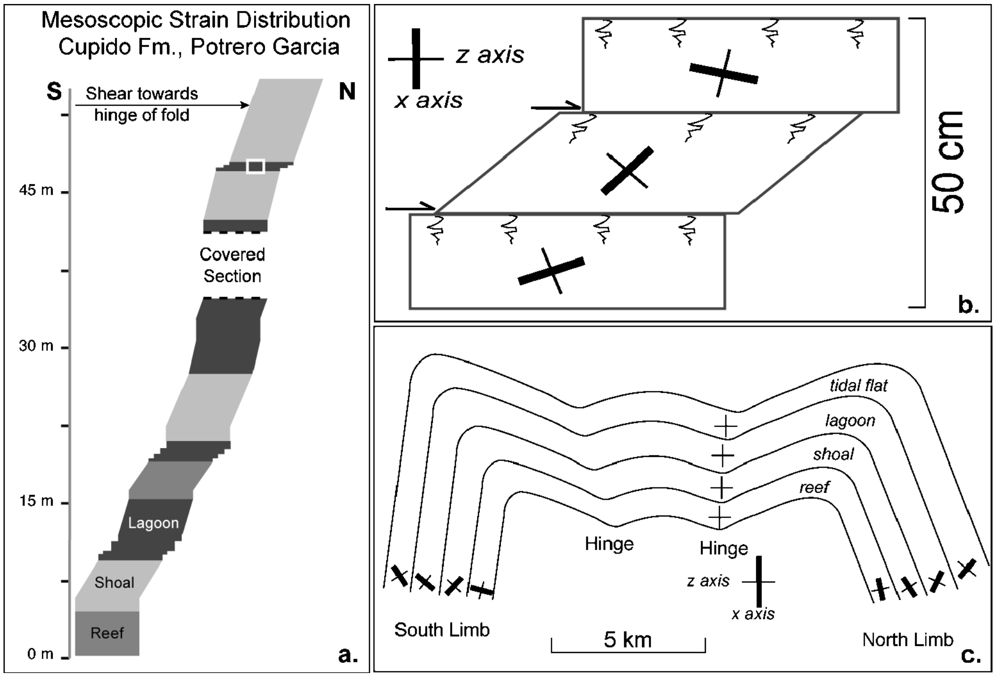

Figure 4. Lithotectonic control on strain distribution, Cupido Fm., Garcia Canyon. **a)** Mesoscopic **b)** box in **a**, AMS orientation within a discrete shear zone mimic orientations of macroscale strain indicators in the same layers. **c)** AMS geometry consistent with limb shear towards fold hinge in except in shoals. These measurements are consistent with mesoscopic shear indicators.