Rockmagnetic and reversal stratigraphy in terrestrial deposits: Recovering fault slip rates in growth strata

Estratigrafía magnética en depósitos terrestres: Determinación de tasas de salto de falla en estratos de crecimiento

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Abstract: This study develops a high-resolution chronostratigraphy age model based on magnetic susceptibility to determine folding rates recovered from Eocene-Oligocene growth strata of the Berga Conglomerate Group, NE Spain. The syntectonic Berga Conglomerates were sampled for rock magnetic, magnetostratigraphy, and cyclostratigraphy analyses. Analysis of rock magnetic measurements indicates a mixed mineral assemblage with both paramagnetic and ferromagnetic minerals. Reversal magnetic stratigraphy constrains the time frame of folding. Time series analysis of magnetic susceptibility variations shows statistically significant power in expected orbital frequencies. The onset of deformation was at 33.85 Myr and the end of deformation is unconstrained but is younger than 31.06 Myr. Deformation and sediment accumulation rates were unsteady at 20 kyr time scales. Deformation rates range from 0-100 °/Myr and modeled fault slip predicts variable displacement rates ranging from 115-265 m/Myr. Because folding rates are variable and appear to be separated into long periods of quiescence punctuated by rapid changes, it seems that deformation in this region is not driven by changes in sediment supply, but rather by changes in tectonic activity.

Keywords: fault-related-folding, foreland basin, cyclostratigraphy, magnetostratigraphy, Pyrenees

Resúmen: *Se presenta una cronoestratigrafía de alta resolución basada en la susceptibilidad magnética para establecer tasas de plegamiento en estratos de crecimiento eoceno-oligocenos del Grupo de Conglomerados de Berga (NE España). Hemos muestreado para magnetismo de rocas, magnetoestratigrafía y cicloestratigrafía los Conglomerados de Berga. Los análisis de magnetismo de rocas revelan la presencia de ferromagnetismo y paramagnetismo. La estratigrafía magnética permite delimitar la cronología del plegamiento. Los análisis de series de tiempo de las variaciones de la susceptibilidad magnética muestran una potencia estadísticamente significante en las frecuencias orbitales esperadas. El inico de la deformación ocurre a los 33.85 Ma y aunque sin un valor absoluto para su final, debe terminar en posterioridad a los 31.06 Ma. Las tasas de acumulación de sedimento y de deformación son inconstantes a escala de 20 kya. Las tasas de deformación oscilan entre 0 a 100°/Myr, y el salto de falla es también variable, entre 115 y 265 m/Myr. Dado que la tasa de plegamiento es variable e interrumpida por períodos rápidos y de inactividad, se deduce que la deformación en la estructura estudiada responde a la actividad tectónica más que al aporte sedimentario.*

Palabras clave: *Plegamiento por falla, cuenca de antepaís, cicloestratigrafía, magnetoestratigrafía, Pirineos*

INTRODUCTION

Growth strata are exceptional candidates for studying deformational and related depositional processes and for recovering fault slip at intermediate timescales. Despite their widespread occurrence, an obstacle to terrestrial systems is that they are typically devoid of biostratigraphic control which makes high resolution timing of fault slip difficult. Magnetic polarity chronology has been used in foreland basins throughout the world when other chronologic methods are unfeasible. Rock magnetic cyclostratigraphy coupled with magnetic polarity chronology provides a robust method to date growth strata which can be used to constrain slip of buried faults. We seek to combine kinematic constraints and high resolution timing to recover orogenic fold evolution at 10^4 - 10^5 yr timescales. Rock magnetic properties (e.g., magnetic susceptibility) were used as a method for providing a high resolution chronostratigraphy in many kinds of studies related to climate, deposition, and deformation (Kodama and Hinnov, 2014 and references therein). In this study we (1) develop a magnetic reversal stratigraphy to provide a chronology for the Berga Conglomerates and (2) tune the relative astrochronology generated with the rock magnetic study. The goal of our study is to determine folding and fault slip rate unsteadiness using the famous syntectonic unconformities exposed in the Cardener valley, N Spain (Riba, 1976) and to further develop rock magnetic-based cyclostratigraphy in terrestrial strata.

GEOLOGICAL SETTING

Along the northern boundary of the Ebro foreland basin, the footwall of the Vallfogona thrust exposes a spectacular regional-scale growth fault-propagation fold in the syntectonic Berga Conglomerates. At a regional scale, unconformity geometries vary from angular to the west at Serres de Lord to progressive east of Serres de Busa. Across the structure, bedding dips change from 70° overturned to upright and horizontal over a few kilometers of section (Fig. 1). In a classic study, Riba (1976) defined "progressive unconformities" at this location and showed that they accumulate on a tilting depositional surface and the geometry of a cumulative wedge of unconformities depends on the relative rates of uplift, rotation, and deposition. Williams et al. (1998) have thoroughly studied the depositional genesis of the Berga Gp. growth section and showed that the growth of the Puigreig anticline and Busa syncline was unsteady based on relative dating. Balanced and restored cross sections and forward geometric modeling by Ford et al. (1997) and Suppe et al. (1997) agree on the geometry of the fault propagation fold pair but not all the kinematic details. Kinematic uncertainty remains as to whether limb rotation of limb lengthening produced the fold amplification during fault slip. The authors note that the critical data to reconcile the deformation history is the temporal variability of the sedimentation and the deformation rates of the growth sequence. Just south of the town of Sant Llorenç de Morunys, the Berga Conglomerates lie conformably on the marine marls and marly limestones assigned to the Bartonian-Lower Priabonian (Solé-Sugrañes, 1972). The Berga Conglomerate Group consists of conglomerates, sandstones and siltstones of alluvial, fluvial, and lacustrine origins. Changes in drainage location, drainage area, and tectonic rates all influence the sedimentary depositional environment through time.

METHODS

Samples were collected for magnetic reversal stratigraphy during multiple field seasons and sample spacing was refined after a preliminary magnetostratigraphy was constructed. Preliminary results suggested a minimum polarity interval of 290 kyr and an average deposition rate of 25 cm/kyr. Therefore, a sampling interval of 10-15 m was selected to allow for multiple sites in the shortest interval while maintaining enough spacing to make >1.5 km sampling feasible. In total, 119 sites were analyzed. Paleomagnetic measurements were made on a 2G Enterprises 755R superconducting rock magnetometer, and thermal demagnetization was conducted with a ASC Thermal Demagnetizer in up to 15 temperature steps from 150°C to 660°C. Alternating field

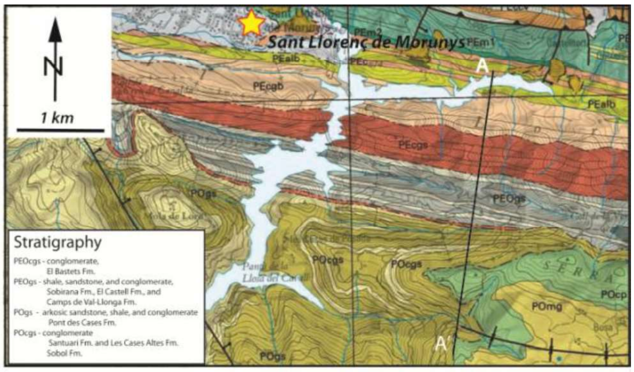

FIGURE 1. *Geologic map of Sant Llorenç de Morunys structure and surrounding area (Geologic Survey of Catalunya, 2006).*

demagnetization was used on a small number of samples using an in-line 2G 600 AF sample demagnetizer. Characteristic remanent magnetization (ChRM) directions were completed for all specimens using principal component analysis and Vitural Geomagnetic Pole (VGP) latitudes used to determine local magnetostratigraphy. Rock magnetic data have sample spacing of 50-100 cm intervals to ensure the 4-5 kyr spacing needed for precessional index resolution. Small samples of 10-20 cm^3 were collected, in addition to large hand samples and drilled cores. All hand samples were crushed and sieved to <2.5ϕ and care was taken to prevent any crushing of obvious clasts. For conglomerate beds matrix-rich sample sites were chosen to limit clast contamination. The crushed sediment was packed into pre-weighed 8 cm^3 nonmagnetic containers and solidified with sodium silicate to prevent movement of sediment during analysis. Processed unoriented samples underwent magnetic analyses for bulk susceptibility because of success of previous studies as a proxy for climate variation. Gaps larger than 5 m were filled using single spectrum analysis (SSA) utilizing the SSA-MTM toolkit (Ghil et al., 2002) to eliminate gap artifacts. In total, 13 % of the susceptibility data is from SSA gap filling. The entire data series was used to better constrain low frequency signal. After all the gaps were filled the data series was resampled at equal intervals using a linear interpolation every 15 cm. The data series were analyzed using the multi-taper method (MTM) spectral analysis with 2π-prolate multitapers to identify significant periodicities. The data series were tied to absolute time using the magnetic reversal chronology correlated to chron boundary ages obtained from the GPTS using the astrochron package for R (Meyers, 2014). After the data series was correlated to time it was equally resampled every 1 kyr. Power spectra were produced for a GPTS2012 tuned data series using the SSA-MTM toolkit (Ghil et al., 2002). We identified significant frequencies in the power spectra at the 90%, 95%, 99% confidence interval. After Milankovitch-scale frequencies were observed in the data a detailed astrochronology was constructed by tuning the Gaussian filtered timeseries to the theoretical obliquity signal (41 kyr) in the data series.

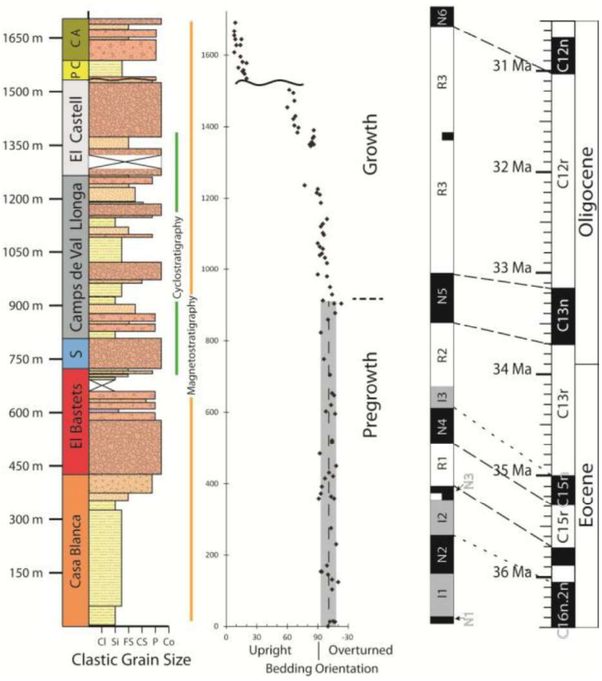

FIGURE 2. (From left to right) Stratigraphic column for the Berga Conglomerates sampled; bedding inclination; local magnetostratigraphy, and correlation to the Global Polarity Time Scale.

RESULTS

A total of twelve magnetozones were identified, N1-N6, R1-R3, and I1-I3 (Fig. 2). Just north of the studied section, the Berga Conglomerates lie conformably on marine marls and marly limestones of which are laterally equivalent to the Igualada Formation. The Igualada Fm. and its lateral equivalences were studied by a number of authors (e.g., Costa et al., 2010; Rodríguez et al., 2012), and is shown to have a Bartonian age based on multi-species biostratigraphy and magnetostratigraphy (middle-upper Eocene) (Solé-Sugrañes, 1972; Puigdefábergas et al., 1992), or chron C17. Our local magnetic polarity stratigraphy begins with poorly resolved normal polarity chrons and shows a conspicuous long reverse chron (R3) in the mid-upper part. The GPTS (Gradstein et al.,2012) shows that after chron C17 (middle-late Eocene), the post quem of the Berga Conglomerate Group, the first prominent reverse chron appears to be C13r, which is followed by an even longer reverse chron (C12r). The most reasonable interpretation is that normal magnetozone N5 corresponds to Chron C13n, rendering the assignment of magnetozones R2 and R3 as Chrons C13r and C12r respectively. Continuing the one-to-one correlation downsection of magnetozones to chrons, normal magnetozones N4 and N1 would correspond to Chrons C15n and C16n respectively. The overall local magnetostratigraphy would then encompass Chrons C16n to C12n, rendering the age of the Berga Conglomerate Group Late Eocene-Early Oligocene (ca.36 to 31 Ma) in agreement with previous interpretations (Ford et al., 1997; Vergés et al., 2002). The resulting average sediment accumulation rate for the 1691 m sampled section is 27.8 cm/kyr. A robust cyclostratigraphy, with significant spectral peaks at expected Milankovitch periods, based on susceptibility variations has been developed for the Berga Conglomerates. This cyclostratigraphy spans from 31.6 Ma within the largest conglomerate in the El Castell Formation to 34.4 Ma at the contact between the El Bastets and Sobirana Formations at total stratigraphic distance of 653.4 m. Low temperature magnetic susceptibility measurements indicate that paramagnetic minerals dominate the mixed magnetic mineralogy in controlling the susceptibility variations. Because of the terrestrial nature of the Berga Conglomerate Group the paramagnetic minerals are interpreted to be clays formed by the weathering of source material during sediment transport. The Berga Conglomerate Group shows evidence of extensive weathering typical of terrestrial redbeds that would suggest paramagnetic clays as a likely source of variations. Magnetic reversal stratigraphy provided coarse sediment accumulation rates for correlation of spectral peaks to absolute time. Tuning the data series to modeled orbital obliquity for the Eocene - Oligocene allows corrections for variable sediment accumulation rates. Obliquity tuning was selected because of a strong spectral significance and high resolution. This cyclostratigraphy provides 20 kyr resolution for structural reconstruction of deformation caused by the fault propagated fold. Tuning to theoretical obliquity (Laskar et al., 2004) reduces noise caused by sediment accumulation variations. It also enhances precessional scale index by eliminating some peaks and enhances signal at 25.7 and 20 kyr frequencies. Additional tunes at short eccentricity (97-120 kyr) and long wavelength (>90 kyr) time scales were attempted for the data series. However, these did not significantly improve Milankovitch scale frequencies.

DISCUSSION AND CONCLUSION

The 20 kyr resolution obtained from our tuned cyclostratigraphy was applied to both sediment accumulation and fold growth to examine the interaction of both on growth strata formation. Cyclostratigraphy based accumulation rates vary from 0.10 - 0.37 m/kyr and average 0.24 m/kyr. Both the chron averaged and 20 kyr resolution methods predict similar accumulation rates in sites younger than 33,250 kyr. The 100 kyr folding rates provide a more consistent measure of folding, and display two periods of slow tectonic activity from 33,400-34,400 kyr and from 32,600-33,100 punctuated by periods of more rapid folding. In both sediment accumulation and percent of total folding cyclostratigraphic histories recover a higher frequency and variability in change. Folding cyclostratigraphic histories display tectonic quiescence which is not recovered in longer time scale reconstructions. The resolution of our depositional and deformational histories is limited to 20 kyr; however, because bedding orientation variability at 100 kyr timescales provide a more reliable deformational history.

A high-resolution time scale based on Milanikovitch orbital frequencies was recovered from magnetic susceptibility in terrestrial foreland facies. Susceptibility based cyclostratigraphy is an objective and robust method of timing in terrestrial systems that have sufficient sediment accumulation and accommodation space such as foreland basins. This cyclostratigraphy of the Berga Conglomerates allows for timing of deformation and sediment accumulation at 20 kyr resolution. Our new magnetostratigraphy confirms an Eocene-Oligocene age for Berga Conglomerates, in agreement with prior interpretations. We have recovered the onset of deformation of the growth strata at 33.85 Ma and provided a range for the maximum depositional hiatus between 100-400 kyr for the principal unconformity. The age model predicts little correlation between sediment accumulation and fold deformation. This suggests that the structural basin built by deformation was not sediment limited and sediment was supplied from a large drainage area. Sediment accumulation rates are fairly constant throughout the entire rock magnetic section. Folding rates are much more variable and appear to be separated into long periods of quiescence punctuated by rapid changes. This suggests that deformation in this region is not driven by changes in sediment supply, but rather by changes in tectonic activity.

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