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Evaporite sedimentation in a tectonically active basin: The lacustrine Las Minas Gypsum unit (Late Tortonian, SE Spain)

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ABSTRACT

Evaporite successions may undergo significant lithostratigraphic changes laterally and vertically in tectonically-active basins. The Las Minas Gypsum, a lacustrine unit of Late Tortonian age and up to 160 m thick in the Las Minas-Camarillas basin (SE Spain), consists of a number of shallowing-upward cycles. Each cycle is made up of a lower interval with marl and carbonate, and an upper interval with gypsum. In the upper interval, the base displays carbonate-gypsum laminites (couplets, yearly microcycles) showing a large variability of textures and fabrics; gypsum textures are cumulates and bottom-grown crystals. Laminites are overlain by selenitic gypsum. The carbonate is a primary dolomite induced by sulphate-reducing bacterial activity. Native sulphur was formed in early diagenesis and during exhumation was partly transformed into late diagenetic gypsum. The isotopic compositions of gypsum suggest that the sulphate mainly derived from chemical recycling of Triassic evaporites; however, marine sulphate was probably supplied by episodic marine incursions. A perennial saline lake characterized by irregular bottom topography and depositional settings with variable subsidence ratios is interpreted. In addition to climate, saline diapirism, Neogene volcanism, synsedimentary faulting and seismicity influenced the evaporitic deposition. Las Minas-Camarillas basin is an example of how in tectonically active zones different factors interplay to produce significant variability of the evaporitic sedimentation and cyclicity.

1. Introduction

Numerous evaporite formations were generated in the tectonically active basins of the Betic Chain during the Neogene. Some of these formations were of marine origin, as in the Messinian successions of the marginal Betic basins (Sorbas, Níjar, Carboneras, San Miguel de Salinas; Rouchy, 1982; Krijgsman et al., 2001; Rouchy and Caruso, 2006; Roveri et al., 2009). In some formations the origin was transitional, as in the Upper Tortonian to Lower Messinian successions of the inner Betic basins (Granada, Lorca, Fortuna–Mula; Dabrio et al., 1982; Dinarès-Turell et al., 1999; Playà et al., 2000; Krijgsman et al., 2000; García-Veigas et al., 2013). And in other formations it was lacustrine and more variable in age: Late Tortonian in the Cenajo basin (Calvo and Elízaga, 1994) and Tortonian to Pleistocene in the Baza basin (Gibert et al., 2007).

The present study seeks to improve our understanding of the evaporite sedimentation in one of the innermost Neogene Betic basins, the Las Minas-Camarillas basin, by means of lithostratigraphic, sedimentological, petrological and geochemical studies on the Las Minas Gypsum unit. This small, lacustrine unit is well known for its sulphur deposits that were exploited until the early 1960s (Gimeno, 1994). Besides the sulphur deposits, the study of this unit is significant for other reasons such as the variability in primary and diagenetic gypsum lithofacies, the cyclicity to macro and microscale, the abundance in siliceous (paper-shales formed by hypersaline diatoms) and organic matter (bituminous shales) facies, the presence of tuff horizons that facilitates stratigraphic correlation, and the supplies of marine water to the lake brines.

Apart from climate, the evaporitic sedimentation in this unit was strongly influenced by local factors (tectonics, volcanism, diapirism). Thus, another aim of this study is to draw attention to the variability of the cyclic deposition in this tectonically active basin. The example will provide further insight into the sedimentation of evaporites in similar geodynamic settings.

2. Geological and stratigraphic setting

The Neogene Las Minas-Camarillas basin is located in the SE of Spain, in the eastern sector of the Prebetic Zone (External Zones of the Betic

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Chain) (Fig. 1A). To the north, the basin is limited by marine Jurassic materials and by a normal fault. To the south, it is bounded by Cretaceous and Miocene marine deposits (Martín et al., 2009) that are unconformably overlain by the non-marine units of the basin infilling (Fig. 1B).

During the Early and Middle Miocene times, the sector of the Prebetic Zone to which the Las Minas-Camarillas basin belongs was the site of marine sedimentation in platform and pelagic environments. During the Middle–Late Miocene times, this region was part of the North-Betic seaway, where extensive calcarenite deposits occurred. After a compressive phase, the connection with the sea was cut off in wide areas of the region. During a Late Tortonian extensional phase, a series of basins were generated in horst and graben-to-semigraben systems (Fig. 1A), in which non-marine sedimentation occurred (Elízaga and Calvo, 1988; Bellanca et al., 1989; Calvo and Elízaga, 1990; Servant-Vildary et al., 1990).

Intensive volcanic activity occurred in the Eastern Betic Chain during the Late Neogene. This activity generated the ultrapotassic lamproites of the El Monagrillo hill in the Las Minas-Camarillas basin at the end of the Miocene (Fúster et al., 1967; López Ruiz and Rodríguez Badiola, 1980). Moreover, extensive saline diapirism of Upper Triassic materials occurred within and around the basin in the Late Neogene, which could have influenced its depositional infilling (Elízaga and Calvo, 1988).

The Neogene sedimentation of the Las Minas-Camarillas basin has been dealt with in a number of papers such as Calvo and Elízaga (1985, 1990), Foucault et al. (1987) and Servant-Vildary et al. (1990). In the Cenajo and the Las Minas-Camarillas basins, Calvo and Elízaga (1985, 1990) studied a lacustrine succession of up to 500 m in thickness composed of six lithostratigraphic units: 'facies' A to F or 'stages' I to VI (Fig. 2A). Elízaga and Calvo (1988) and Calvo and Elízaga (1994) grouped the six facies in a lower tectono-sedimentary unit (Cenajo Lower Unit) formed by facies A, B and C and an upper tectono-sedimentary unit (Camarillas Upper Unit) formed by facies D, E and F. The equivalence of these facies with respect to the stratigraphic units (1 to 5) of Foucault et al. (1987) and Servant-Vildary et al. (1990) is shown in Fig. 2B.

Subsurface information of the Neogene infilling in the basin is found in the unpublished report by MINERSA (*Investigación de azufre Hellín. Diciembre 1988. Departamento de Geología, Hellín, 19 pp. y Anexos. Albacete*), which refers to a prospection survey of native sulphur including boreholes that was carried out in the Las Minas area during 1986–1988.

The present study is focused on the 'lower part of facies C', i.e. the evaporitic cycles of Calvo and Elízaga (1985) or the 'Gypsum and marls of the Las Minas Formation' of Foucault et al. (1987) and Servant-Vildary et al. (1990). Foucault et al. (1987) and Servant-Vildary et al. (1990) deduced a marine influence in this unit after studying the diatomitic content. An age of 7.65 ± 0.09 Ma was obtained by Rosell et al. (2011) for the youngest lamproites in the El Monagrillo hill, which extruded the evaporite unit and the upper part of facies C, by means of $^{40}Ar/^{39}Ar$ determinations on phlogopite crystals. This dating agrees with that of Nobel et al. (1981) in the same locality (7.2 ± 0.3 Ma), indicating a Late Tortonian age for the upper part of facies C and a minimum age for the underlying evaporite unit.

3. Materials and methods

Geological mapping to the scale 1:10,000 was carried out in the study area, and stratigraphic sections (S1 to S9) were measured and sampled. Isobate lines of the top of the evaporite unit were calculated in the non-outcropping central part of the study area using the subsurface data of the MINERSA boreholes. Selected samples (60 samples) were studied mineralogically (X-ray diffraction) in unoriented powdered aggregates (*Centres Científics i Tecnològics* of the *Universitat de Barcelona, CCiTUB*). The petrographic study (82 thin sections sized 4.7 × 5.5 cm or 2.8 × 4.7 cm) was carried out using an optical polarised light microscope. Some of the carbonate thin sections were examined using cathodoluminescence (CL); Technosyn Cold Model 8200 MkII,15-20 kv and 400 μA. Additionally, scanning electron microscopy (SEM) was used to determine the crystalline textures in gypsum samples (SEM Cambridge microscope model S-360; ESEM (Environmental SEM) model Quanta-200 FEI XTE 325/D8395 equipped with backscatter image technology; *CCiTUB*).

Stable isotopic analyses of oxygen and sulphur in sulphates were performed in 57 gypsum samples, all of which were converted to $BaSO_4$. Moreover, stable isotopic analyses of sulphur were carried out in 4 native sulphur samples. The respective CO (for oxygen) and SO_2 (for sulphur) gases generated from the Ba-sulphates were obtained in an elemental analyser TC/EA pyrolyser for oxygen, and in a Finnigan MAT CHNS 1108 analyser for sulphur. Both analysers were coupled to a continuous-flow isotope-ratio mass spectrometer (IRMS; Finnigan DELTA plus XP). The results are expressed in ‰ with respect to V-SMOW (Vienna-Standard mean ocean water) for oxygen, $\delta^{18}O_{VSMOW}$, and to V-CDT (Vienna-Canyon Diablo Troilite) for sulphur, $\delta^{34}S_{VCDT}$. Analytical precision is ±0.5 for $\delta^{18}O_{VSMOW}$ and ±0.4 for $\delta^{34}S_{VCDT}$ values. Stable isotopic analyses of carbonate were performed in 23 samples. Powdered samples were dissolved in ultrapure water to eliminate soluble sulphates. About 50 μg of the non-soluble fractions (composed of carbonates and minor amounts of detrital silicates) were treated to react in an online Kiel Device with 103% H_3PO_4 for 3 and 15 min (calcite and dolomite, respectively) in vacuum at 70 °C. The obtained CO_2 was analysed in a Dual Inlet isotope-ratio mass spectrometer (IRMS; Thermo Electron Finnigan MAT-252). Values are reported in ‰ with respect to the V-PDB (Vienna-Pee Dee Belemnite) standard, with a precision of ±0.06‰ for $\delta^{18}O_{VPDB}$ and ±0.02‰ for $\delta^{13}C_{VPDB}$.

4. Results

4.1. Mapping and subsurface distribution of the evaporite unit

An informal terminology is used in this work (Fig. 2B) for the 'facies' constituting the lower tectono-sedimentary unit (Cenajo Lower Unit) of Calvo and Elízaga (1990): 'lower detrital-carbonate unit' for facies A and B; 'Las Minas Gypsum unit' or simply the 'evaporite unit' for the lower part of facies C (the evaporitic cycles); and 'upper carbonate unit' for the upper part of facies C.

The geological map of the Las Minas Gypsum unit and a general cross section (I–I′) are shown in Fig. 3. The unit can be observed in the 'Moharque outcrop' and in the 'Las Minas outcrop', in the western and eastern parts of the study area, respectively. In the Moharque outcrop, the unit shows a thickness of up to 160 m and a general dip of 20°–30° to the N, NW or NE. In the Las Minas outcrop, the unit is thinner (<50 m) and shows a general dip of 15°–25° to the WNW. No clear structural connection exists between these two outcrops. The evaporite unit is affected by a number of folds and normal faults in the two outcrops.

Cross section I–I′ (Fig. 3) shows the structure of the evaporite unit to the west of the Segura River. A monoclinal succession occurs to the north of the normal 'Moharque fault'. Borehole information in this area indicates that the top of the evaporite unit near the Triassic diapir to the west exceeds a depth of 150 m below the topographic level of the Segura River terrace (Fig. 1B). Near the El Monagrillo hill to the south, the top of the unit surpasses a depth of 120 m (below the level of the river terrace).

The upper part of the 'lower detrital-carbonate unit' intercalates gypsarenites and gypsiferous sandstones, and grades upwards into the evaporite unit. The top of the evaporite unit also grades gently into the 'upper carbonate unit' that is characterised by the presence of carbonate–marl cycles and the absence of gypsum beds.