Sociedad Geológica de España

GEOGACETA, 76, 2024

Gypsum crystal morphologies in lake sediments for paleoclimate reconstructions: a case study in Fuente de Piedra playa-lake (Málaga)

Morfologías de cristales de yeso en sedimentos lacustres para reconstrucciones paleoclimáticas: un caso de estudio en la laguna de Fuente de Piedra (Málaga)

Lucia Martegani[1, 2]*, Fernando Gázquez[1, 2], Claudia Voigt[1], Alejandro Jiménez-Bonilla[3], Miguel Rodríguez-Rodríguez[3] and Klaus Reicherter[4]

[1]Department of Biology and Geology, University of Almería, Spain. lm263@ual.es; f.gazquez@ual.es; cvoigt@ual.es
[2]Andalusian Centre for Global Change - Hermelindo Castro (ENGLOBA), University of Almería, Spain.
[3]Department of Physical, Chemical and Natural Systems, Pablo de Olavide University, Seville, Spain. mrodrod@upo.es; ajimbon@upo.es
[4]Institute of Neotectonics & Natural Hazards, RWTH Aachen University, Germany. k.reicherter@nug.rwth-aachen.de
*Corresponding author

ABSTRACT

Gypsum ($CaSO_4 \cdot 2H_2O$) is one of the most common evaporitic minerals on Earth. Its crystals exhibit diverse morphologies that can offer insights into their depositional environment. In this study, we analyzed the morphologies of gypsum deposits in a 14 m sedimentary sequence from Fuente de Piedra playa-lake (Málaga, Spain) to link the gypsum morphological variations and the lake sedimentary facies to changes in the past lake level. Precipitation of primary prismatic crystals prevailed during lake highstand periods. In contrast, lenticular gypsum crystals are consistently present throughout the entire core and do not seem to correlate to specific lake levels. An exception are macro-lenticular crystals, which seem to be associated with dry periods and high salinity water. Subrounded gypsum grains, eroded from former primary crystals, are also abundant along the sequence and usually concentrate in facies corresponding to stages of lake agitation during highstand periods. The absence of gypsum during lowstand periods can be attributed to relatively high contents of dissolved organic matter or, more likely, to reduced interaction between the lake and the saline groundwater aquifer beneath. Our results suggest that the occurrence of some gypsum morphologies can be used to infer paleo-lake levels.

Key-words: *gypsum, morphological varieties, lake level reconstruction, playa-lake, paleoclimate.*

RESUMEN

El yeso ($CaSO_4 \cdot 2H_2O$) es uno de los minerales evaporíticos más comunes en la Tierra. Sus cristales exhiben diversas morfologías que pueden proporcionar información sobre su entorno deposicional. En este trabajo analizamos las morfologías del yeso presentes en un testigo de sedimento de 14 m de la laguna de Fuente de Piedra (Málaga), con el objetivo de relacionar los cambios en las morfologías y las facies sedimentarias con las variaciones de los niveles del lago en el pasado. La precipitación de cristales prismáticos prevaleció durante periodos de nivel del lago elevados. Los cristales microlenticulares, por su parte, están presentes en todo el testigo y no parecen estar relacionados con condiciones específicas. No obstante, los cristales macrolenticulares parecen estar asociados a periodos más secos de alta salinidad. Los granos de yeso subredondeados se encuentran en toda la secuencia y suelen concentrarse en facies relacionadas con etapas de agitación durante niveles elevados del lago. Por último, la ausencia de yeso durante niveles bajos puede atribuirse a una menor interacción entre el lago y el acuífero salino, o bien a contenidos relativamente altos de materia orgánica disuelta. Nuestros resultados sugieren que la presencia de ciertas morfologías del yeso puede utilizarse para reconstruir niveles paleolacustres.

Palabras clave: *yeso, variedades morfológicas, reconstrucción del nivel del lago, playa-lake, paleoclima.*

Geogaceta, 76 (2024), 11-14
https://doi.org/10.55407/geogaceta104492
ISSN (versión impresa): 0213-683X
ISSN (Internet): 2173-6545

Fecha de recepción: 09/02/2024
Fecha de revisión: 19/04/2024
Fecha de aceptación: 07/06/2024

Introduction

Gypsum ($CaSO_4 \cdot 2H_2O$) is the most abundant sulfate on Earth and one of the most common minerals in sedimentary environments, encompassing both marine and continental settings (Klein and Hurlbut, 1997). The importance of this evaporitic mineral has led to numerous investigations of its precipitation process, size distribution and morphology during the last few decades (*e.g.* Aref and Manaa, 2021). Particularly, the assessment of morphological varieties of gypsum crystals in continental sediments can offer valuable insights into the conditions of gypsum formation (Cody and Cody, 1988; Magee *et al*. 1995; Vogel *et al*. 2010). Cody and Cody (1988) linked the diversity of gypsum morphologies with changes in water salinity, temperature, type and amount of dissolved organic compounds and pH in laboratory conditions. Other studies correlated the morphological characteristics of gypsum with their occurrence in continental subaqueous and subaerial depositional environments (Magee *et al*., 1995), as well as with biological factors (Vogel *et al*., 2010).

During the late-Quaternary, gypsum precipitation from Ca^{+2}-SO_4^{-2}-rich waters occurred in some Andalusian lakes (García-Alix *et al*., 2022; Martegani *et al*., 2023; Gázquez *et al*., 2023). Here, gypsum formation is usually linked to water evaporation under temperate and arid climate, where Ca^{+2} and SO_4^{-2} are derived from dissolution of Triassic gypsum deposits (Valero-Garcés *et al*., 2014).

Fuente de Piedra (FdP) playa-lake (Málaga), the largest saline lake in Andalusia (Fig. 1), contains abundant gyp-

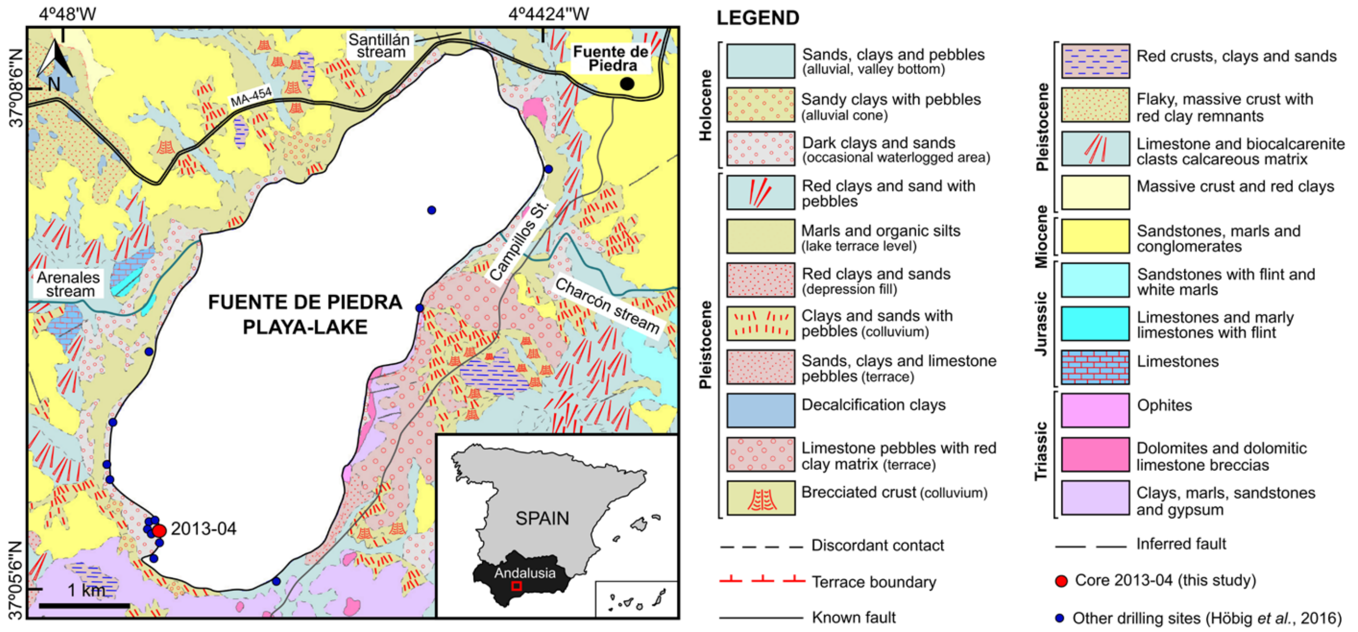

Fig. 1.- Location and lithology (Serrano García, 1982) of Fuente de Piedra playa-lake area. Core 2013-04 (this study) and other relevant drilling sites investigated by Höbig et al. (2016) are also shown. See color figure in the web.

Fig. 1.- Ubicación y litología (Serrano García, 1982) del área de la laguna de Fuente de Piedra. También se muestran el testigo 2013-04 (este estudio) y otros sitios de perforación relevantes investigados por Höbig et al. (2016). Ver figura en color en la web.

sum-rich sediments throughout its sedimentary sequence. These sediments have been investigated previously for paleoclimate reconstructions (Höbig *et al.*, 2016). These authors identified several lithofacies (denoted as from 1 to 5; Fig. 2) in sediment cores collected along the shore and the centre of the lake (Fig. 1). Core 2013-04, which is used in the present study, was collected from the southwestern shoreline and consist of fine-grained sediments, predominantly clays and carbonate muds, interspersed with evaporites. Lithofacies classification, conducted by Höbig *et al.* (2016) based on macro- and microscopic observation and geochemical data, enabled a preliminary reconstruction of the paleohydrological history of FdP paleo-lake during the late-Quaternary (30 cal. ka BP; calibrated kiloyears before present). Lithofacies 1 is not present in this core. Lithofacies 2 is mainly composed of massive clays with relatively elevated organic content, while lithofacies 3a and 3b essentially consist of beds of calcitic and dolomitic mud with some gypsum crystals. Lithofacies 4 and 5 are characterized by a dolomitic mud composition and present several gypsum morphologies. The distinction between them lies in the higher occurrence of subangular to subrounded gypsum and the absence of subaerial traits in lithofacies 5.

The great abundance of gypsum with different morphologies in the FdP sediments offers an opportunity to investigate whether changes in hydrological conditions of the lake resulted in changes in the typology of this mineral. In the present study, we characterize the gypsum crystal morphology in sediments from FdP playa-lake and establish a comparison with the lake level reconstruction of Höbig *et al.* (2016).

Geological and Climate settings

FdP playa-lake is the largest (13.5 km^2) of the many lakes in southern Spain (Fig. 1). It is currently an ephemeral lake, with an average depth of <1 m (Rodríguez-Rodríguez, 2002). Climate of the study site is Mediterranean, with mild, wet winters and hot, dry summers. It is characterized by a pronounced seasonality in precipitation, mainly concentrated during spring and autumn (Bolle, 2003). In FdP playa-lake area, mean annual precipitation is about 500 mm.

The FdP playa-lake is located in the Betics fold-and-thrust belt, in an area interpreted as a canopy of Triassic evaporites (Fig. 1; Flich and Soto, 2022). Playa-lakes inception and evolution are controlled by karstification process of the underlying Triassic evaporites (Gutierrez *et al.*, 2002) and/or tectonic processes active for the last 2 My (Rodríguez-Rodríguez *et al.*, 2016).

Mean values of lake water conductivity and salinity are 29.5 mS/cm and 17.6 g/l, but can reach values up to 156 mS/cm and 56 g/l, respectively (Rodríguez-Rodríguez, 2002).

Materials and methods

We investigated 250 gypsum-rich sediment samples from core 2013-04 (14 m depth), collected from the southwestern lakeshore of FdP playa-lake in 2013 (Fig. 1) using a vibracorer. This core is stored in the sediment repository of the RWTH Aachen University, Germany, and was previously investigated by Höbig *et al.* (2016). The samples were selected based on the presence of gypsum crystals and examined under a microscope to determine gypsum crystal morphologies following the classification by Cody and Cody (1988).

The different morphologies were categorized and then compared with the lake level reconstruction provided by Höbig *et al.* (2016). Note that in our study we do not refer our observations to ages but rather to depths. This is due to the imprecision of the current chronological model for core 2013-04, likely caused by reworked organic matter in the catchment area and the effects of hard water (see Höbig *et al.*, 2016).

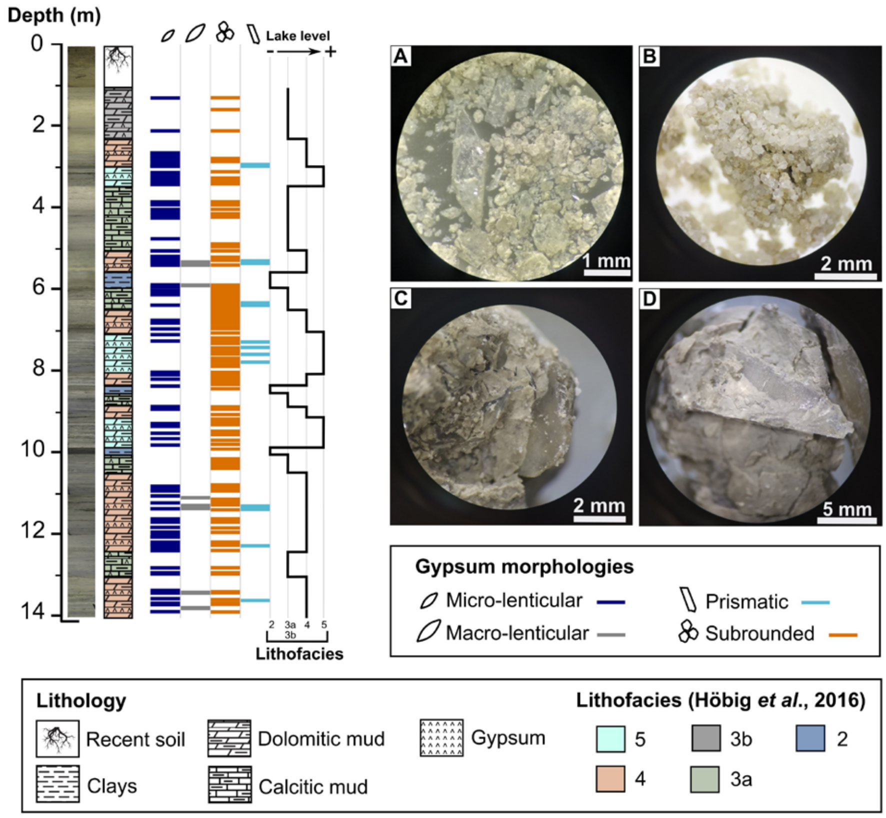

Fig. 2.- Gypsum morphologies identified in core 2013-04 of Fuente de Piedra playa-lake, based on the classification of Cody and Cody (1988): prismatic crystals (A), subrounded sand-size gypsum grains (B), micro-lenticular crystals (C) and macro-lenticular crystals (D). Lithological features, lithofacies and lake level reconstruction interpreted by Höbig et al. (2016) are displayed for comparison. See color figure in the web.

Fig. 2.- Morfologías de yeso identificadas en el testigo 2013-04 de la Laguna de Fuente de Piedra basadas en la clasificación de Cody y Cody (1988): cristales prismáticos (A), granos de yeso subredondeados de tamaño de arena (B), cristales mirolenticulares (C) y cristales macrolenticulares (D). A modo de comparación se muestran las características litológicas, las litofacies y la reconstrucción del nivel del lago interpretadas por Höbig et al. (2016). Ver figura en color en la web.

Results and discussion

The gypsum crystals in core 2013-04 are whitish to beige in color, with no visible impurities (*i.e.*, clay minerals) in most cases. They typically occur as mm- to cm-thick layers or as isolated crystals embedded in finer clayey material. Based on the macro- and microscopic observations, gypsum crystals were divided into different morphological varieties: (1) mm to cm-sized prismatic crystals, (2) subrounded sand-size gypsum grains, previously interpreted as "detrital" or reworked gypsum by Höbig *et al.* (2016) and (3) single or twinned micro-lenticular and (4) macro-lenticular crystals (mm to cm-scale, respectively) (Fig. 2).

The abundance of each gypsum morphology varies significantly along the core (Fig. 2). Prismatic crystals (Fig 2A) are exclusively observed in lithofacies 4 and 5. In general, prismatic crystals form preferentially in the water column of saline lakes (Mees *et al*., 2012). They develop in environments with relatively stable conditions, low concentrations of dissolved organic compounds and grow primarily independent of temperature (Cody and Cody, 1988). Höbig *et al*. (2016) interpreted the occurrence of carbonate muds and the absence of subaerial features as a relatively deep environment during lithofacies 5, when FdP probably was a permanent lake. These conditions, attributed to stages of lake highstands, align with the requirements for prismatic crystal precipitation. Therefore, their occurrence in lithofacies 5 support this interpretation.

Regarding lithofacies 4, Höbig *et al.* (2016) inferred a hydrologically dynamic environment, characterized by alternating periods of relatively calm deep conditions, marked by carbonate mud precipitation and clay flocculation (similar to lithofacies 5), periods of turbulent conditions caused by water agitation and periods of relatively lower water levels due to more arid conditions. The prismatic crystals found in lithofacies 4, therefore, probably formed during the deep water stages.

Subrounded gypsum grains (Fig. 2B) are consistently found throughout the entire core. In most cases, they coincide with lithofacies 4 and can be associated with the periods of agitations pointed out by Höbig *et al.* (2016). This morphology suggests post-depositional sediment reworking within the playa-lake, potentially induced by waves and currents. Aref and Manaa (2021) also interpreted similar subangular to subrounded grains ("clastic gypsum") as being formed through extensive transportation by flood currents and/or wind action. Further studies on the reworked gypsum grains of FdP playa-lake are necessary to determine the relationship between the duration of the reworking period and the transport distance to other parts of the basin.

Lenticular gypsum is the most common morphology in sediments in subaerial settings, but it can also form sub-aqueously in certain environments (*e.g.*, Aref, 1998). Therefore, this morphological type provides limited environmental information (Cody and Cody, 1988; Mees *et al*., 2012). Micro-lenticular crystals of gypsum (Fig. 2C) are present in all the lithofacies, corresponding to both high and low lake levels. Macro-lenticular crystals (Fig. 2D), on the other hand, are less common and appear in few intervals of lithofacies 4. This could be related to the drier periods described by Höbig *et al.* (2016) within lithofacies 4, identified by the presence of gypsum embedded in the clayey sediments and the occurrence of subaerial traits. The salinity increase during relatively long periods could have led to a decrease in nucleation density, resulting in coarser gypsum crystals (Cody and Cody, 1988).

Gypsum is generally absent during lowstand periods (lithofacies 2). Höbig *et al.* (2016) interpreted this lithofacies as pond deposits, characterized by fluctuating water levels and higher organic content compared to other lithofacies. This may suggest that lake water was undersaturated in gypsum, likely due to less interaction of the lake with saline groundwater beneath, as suggested for other playa-lakes (Mediavilla *et al*., 2020). Furthermore, the presence of higher levels of dissolved organic compounds, possibly derived from the decomposition of vegetal remains (*e.g.* humic acids) present in the pond deposits, could have acted as inhibitors agents and may have reduced the rate and/or quantity of gypsum precipitation (Cody and Cody, 1988; Cao *et al.*, 2022).

Conclusions

The results of this study show the utility of gypsum morphology assessment to understand the environmental variations in playa-lakes. In the sedimentary sequence of Fuente de Piedra playa-lake, diverse morphologies of gypsum crystals were described and associated with different lake level stages. Consistent with earlier investigations, our results demonstrate that adding gypsum morphologies to the lithological and hydrological characterization of lakes, can help to further enhance our understanding of paleoenvironmental changes.

Author contributions

L.M. characterized the gypsum samples and drafted the preliminary version of the manuscript. F.G. obtained funds for this study and supervised the analyses. M.R.R., A.J.B., and C.V. participated in the conceptualization of the study. K.R. collected the cores from the lake and was involved in sample preparation. All the authors contributed to the writing of the manuscript.

Acknowledgments

This study was funded by the PALEOQUANT project (P18-RT-871; of the Andalusian Regional Government and FEDER Regional Development Funds) and the GYPCLIMATE project (PID2021-123980OA-I00, Ministry of Economy and Competitiveness of Spain and FEDER European Regional Development Funds). L.M. was funded by the FPU21/06924 grant of the Spanish Ministerio de Educación y Formación Profesional. Dr. F.G acknowledges the Ramón y Cajal fellowship, RYC2020-029811-I and the grant PPIT-UAL, Junta de Andalucía-FEDER 2022-2026 (RyC-PPI2021-01). C.V. was funded by the Marie Curie-Sklodowska post-doctoral fellowship (#101063961).

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