Introduction

Carbonate rocks present complex structures and geometries due to their biological origin and intrinsic susceptibility to environmental changes (Choquette and Pray, 1970). A major challenge is to determine permeability associated with fractures and carbonate facies. In naturally fractured carbonate reservoirs, permeability mainly depends on the heterogeneity and connectivity of open fractures at different scales. However, additional depositional and diagenetic features such as the presence of Porites and local karstification play an important role on the development of permeability. An adequate characterisation of these parameters is key to the creation of accurate reservoir models of carbonate systems, namely in oil and gas exploration, geothermal reservoir characterisation, hydrogeology and environmental studies, mining and tunnelling, as well as carbon sequestration projects.

A regional multi-scale analysis of structural and depositional features is undertaken in this work across a section of the exposed Messinian Fringing Reef Unit of Cariatiz in SE Spain (Fig. 1). Seven structural and depositional fabric types are analysed at different scales of observation: (i) centimetre-length open fractures (joints); (ii) centimetre-length mineral filled fractures (veins); (iii) vertical metre-length fractures; (iv) hundred-metre length fracture swarms; (v) karsts; (vi) vertical Porites; and (vii) pseudo-bedding surfaces (Fig. 2). The presence of these fabric types contributes to an increase in the permeability of the host rock when open. Conversely, they can create barriers to fluid flow when closed or cemented (Laubach, 2003; Strijker et al., 2012). The identification of these features when compiling reservoir models can decrease uncertainty in the assessment of their economic value (Lønøy, 2006).

Figure 1. a) Location of the study area in SE Spain. b) Regional map of the Sorbas Basin showing the area of interest within the Messinian Reef Unit. Modified after Reolid et al. (2014). c) LiDAR map with the slope attribute showing the large fracture swarms parallel to the platform margin. Specific locations in Fig. 2 are shown on the map.

Geological setting

The study area is located on the northern margin of the Sorbas Basin. This Neogene basin is 700 m thick, with strata ranging from Middle Miocene to Quaternary in age. It is oriented E-W and bordered by the Sierra de los Filabres to the north and the Sierras Alhamilla and Cabrera to the south (Braga and Martín, 1996; Reolid et al., 2014; Nooitgedacht et al., 2018) (Fig. 1b). The focus of this study is the Cariatiz Messinian Fringing Reef Unit, which was deposited between 6.04 Ma and 5.87 Ma.
(Sánchez-Almazo et al., 2007). This unit comprises six facies that comprise, from the inner platform to the basin, the following types: (i) lagoon; (ii) reef framework; (iii) reef talus slope (uppermost slope); (iv) proximal slope (middle slope); (v) distal slope (lowermost slope); and (vi) fan delta (Riding et al., 1991; Braga and Martín, 1996). The platform is tilted 3° to the SW due to very moderate regional uplift during its development (Braga et al., 2003). Clinoform bodies representing different reef growth phases are observed within the reef framework and reef slope facies, arranged into depositional wedges thinning downslope and basinward (Reolid et al., 2014). The reef framework consists of pinnacle morphologies formed by columnar Porites connected by vertical and laminar coral growth as well as stromatolitic crusts. The reef slope consists of reef framework blocks and coral breccia with Halimeda. Sea level changes are reported as the governing mechanism controlling productivity, reef slope geometry, and stacking patterns of the clinoform bodies during the development of the Cariatiz Messinian Fringing Reef (Kendall and Schlager, 1981; Reolid et al., 2014). Syn-depositional erosion influenced the geometry of the platform. A subaerial exposure event during the Messinian produced an erosional surface marking the top of the carbonate platform (Martín et al., 1997).

Data and methods

Fieldwork included mapping and identification of structural (faults, fractures and karsts) and depositional (facies) features across our study area at Cariatiz. Extensive rock exposures provide an opportunity to acquire a large three-dimensional data set of fractures and depositional features across several orders of magnitude. Field data was used in conjunction with LiDAR maps to describe the latter features at varied scales. A LiDAR map was used to identify large features with a length of tens to hundreds of metres. The Instituto Geográfico Nacional (IGN) and the Centro Nacional de Información (CNIG) of Spain provided the LiDAR data (Fig. 1c). The density of points for the data acquisition was 0.5 points/m² with a grid size of 5 m. ArcGIS 10.5 was used to visualise and interpret the LiDAR map on 2D and 3D. A slope attribute was computed to highlight the major structural features at Cariatiz (Fig. 1c).

Results and discussion

This study investigates the different types of fractures and depositional fabrics that can develop on flat-topped carbonate platforms such as the Messinian Fringing Reef Unit of Cariatiz. We recognise five types of structural features in Cariatiz (Fig. 2). The first type are centimetre-length open fractures or joints (Fig. 2c). These joints are present across the Reef Unit and have a wide distribution with no clear dominant orientation. Trace-lengths range from 1 cm to 150 cm with variable apertures. The second type are veins with a calcite infill and revealing similar geometries to joints (Fig. 2d). A third fracture type is recognised from a section parallel to the platform margin (Fig. 2a). These are vertical fractures oriented perpendicular to the platform margin. They present trace-lengths with tens of metres that offset depositional facies boundaries, initiating at the reef crest (Fig. 2a). The fourth fracture type are large fracture swarms that are tens to hundreds of metres long. They are 20 m to 50 m wide and are composed of clusters with closely spaced fractures (Figs. 1c and 2b). Fracture swarms display a clear orientation parallel to the platform margin, which is better observed from LiDAR maps (Fig. 1c). The last structural feature observed in the field are karsts (Fig. 2a, e). Karsts are diagenetic features predominantly related to vertical fractures, creating centimetre and metre length caves due to rock dissolution by acidic (CO₂-rich) meteoric waters.

Two depositional features are observed in Cariatiz. A system of vertical Porites is the main component of the Reef Unit, together with microbial boundstones (Fig. 2e). These Porites develop vertical lineations and moldic porosity which combined with fractures can increase permeability. Cariatiz is a massive rock unit with no apparent bedding. However, the presence of chaotic and curved pseudo-bedding surfaces are noted throughout the study area (Fig. 2f). These surfaces create block compartments within the Cariatiz Fringing Reef Unit. The combination of structural and depositional features observed in Cariatiz can affect the permeability of carbonate units. All these features can serve as fluid pathways, with the exception of cemented veins capable of forming barriers to fluid flow.
Figure 2. Types of structural and depositional fabrics. a) Outcropping section of the Cariatz Fringing Reef Unit showing large vertical fractures and karsts. b) Fracture swarms. c) Open fractures (joints). d) Closed fractures (veins). e) Vertical Porites and a small karst cave. f) Pseudo-bedding surfaces.

Conclusions

Carbonate platforms like Cariatz presents complex structural and depositional features that can affect permeability. From this study we identified five structural and two depositional features: (i) centimetre length open fractures (joints); (ii) centimetre-length closed fractures (veins); (iii) metre-length vertical fractures; (iv) tens to hundred metre-length fracture swarms; (v) karsts; (vi) vertical Porites; and (vii) pseudo-bedding surfaces. All of them increase the relative permeability of the studied Cariatz Fringing Reef Unit, apart from calcite-filled fractures (veins) creating barriers to fluid flow.
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