IESDB – The Iberian Evaporite Structure Database

Eloi González-Esvertit[1], Juan Alcalde[2], Enrique Gomez-Rivas[1,*]

[1] Departament de Mineralogia, Petrologia i Geologia Aplicada, Facultat de Ciències de la Terra, Universitat de Barcelona, c/ Martí i Franquès, s/n, 08028, Barcelona, Spain.
[2] Geosciences Barcelona, GEO3BCN-CSIC, c/ Lluís Solé i Sabarís, s/n, 08028, Barcelona, Spain.
[*] Corresponding author: e.gomez-rivas@ub.edu

Abstract. Evaporites flow in the solid state under relatively low differential stress, and have unique mechanical properties compared to other sedimentary rocks. Worldwide, they control the structural and stratigraphical architecture of many basins and orogens in ancient and active tectonic settings. Moreover, they host mineral deposits and play a key role in petroleum systems because they typically act as seals due to their low permeability, and their ability to flow results in the formation of structural hydrocarbon traps such as folds and faults in their encasing rocks. Additionally, evaporite structures can be used as subsurface storage sites for Geo-energy applications and nuclear waste. The systematic characterization of subsurface evaporite structures is thus key for the development of geoscience-based technologies to address societal challenges. Owing to their value, massive amounts of surface and subsurface information about (among others) the stratigraphy, structure, geochemistry, and petrophysical properties of evaporite structures and their surrounding rocks have been acquired by earth scientists, petroleum and mining exploration companies, and geological surveys. However, the data often appear segregated (*i.e.*, in the form of database fragments, scientific articles and unpublished reports), not systematically organized, and sometimes not fully accessible. This contribution presents the Iberian Evaporite Structure DataBase (IESDB), the first comprehensive assessment that focuses on evaporite structures carried out in any region of the world. The IESDB includes information and figures for 150 evaporite structures and their surrounding rocks inventoried in Spain and Portugal, and is sourced from other six thematic databases and more than 1,500 published and unpublished scientific documents. The database targets undeformed to slightly deformed evaporite successions, outcropping and buried diapirs, evaporite-cored anticlines, evaporite-detached thrusts, and allochthonous evaporite bodies. Collated data include information about the structure, stratigraphy, event chronology, surface and subsurface data availability, mining activity, and key bibliographic references. The IESDB follows the FAIR principles of database management (Findable, Accessible, Interoperable and Reusable) and is presented as an interactive webpage and an open-access database, where indexed structures can easily be selected from a map or browser and filtered by a search engine. The IESBD intends to be a useful resource for teaching (*i.e.*, pointing out examples of exceptional evaporite outcrops), academic and industry research (*i.e.*, identifying knowledge deficits on specific structures or tectonic settings), and for the sustainable exploration and appraisal of mineral resources and Geo-Energy applications (*i.e.*, representing a *terminus a quo* for site selection and suitability assessment). The framework provided by the IESDB is an opportunity to enhance the scientific research on Iberian evaporite structures in Spain and Portugal and to take advantage of

their scientific and economic potential to tackle important societal challenges faced by these countries. The IESDB is freely available at https://iesdb.eu and the datasets can be downloaded from *https://doi.org/10.20350/digitalCSIC/14586* (González-Esvertit et al., 2022).

1 Introduction

Evaporites are rocks that form by precipitation from a surface or near-surface saturated brine in hydrologies mainly controlled by solar evaporation (Warren, 2016), both in marine and continental sedimentary environments. They are key components of sedimentary basins and orogens and can control the stratigraphy and structure of many ancient and active extensional, contractional and strike-slip tectonic settings worldwide (Fig. 1). The mechanical properties of evaporite rocks are unique and differ from those of other sedimentary rocks, such as clastic and carbonate rocks. Evaporites have a unique rheology that allows them to flow in the solid state under relatively low differential stresses, thus behaving in a more viscous manner, whilst their incompressibility makes them one of the least dense materials of the Earth's crust (*e.g.*, Hudec and Jackson, 2007). As a result, evaporitic sequences help to constrain the evolution of sedimentary basins and mountain ranges (Fig. 1), frequently acting as detachments for thrusts and forming structures such as salt diapirs and walls, which typically produce folding and faulting of their encasing rocks. Evaporites tend to be impermeable at shallow depths and hence normally act as barriers to fluid flow. The combination of these particular petrophysical properties and the ability to form hydrocarbon traps in their surrounding rocks make evaporites key components of petroleum systems (Weijermars et al., 1993). Accordingly, they control the reservoir distribution and hydrocarbon migration in some of the world's major hydrocarbon provinces, such as the Persian Gulf, North Sea or Gulf of Mexico basins, among others (Warren, 2006; Hudec and Jackson, 2012; Jackson and Hudec, 2017 and the references thereof).

We use hereafter the term *evaporite structure* to refer to any outcropping or buried rock body mappable at the 1:25,000 scale, dominantly composed of evaporite minerals, and geographically limited by geological boundaries such as stratigraphic or diapiric contacts, faults or fold limbs. The principal evaporite minerals, corresponding to the sulphate and chloride groups, are among the most mined mineral commodities worldwide with an estimated production of over 140,000 million tonnes in 2019 (US Geological Survey, 2020). In addition, salt caverns built within evaporite structures are considered suitable environments for Geo-Energy applications, such as the storage of oil, natural gas, compressed air and hydrogen energy (Lux, 2009; Ozarslan, 2012; Wang et al., 2017), and are one of the key geological repositories of deep nuclear waste (*e.g.*, International Atomic Energy Agency, 2003).

Given the important applications of evaporite rocks for our society, the geological characterization, classification, and indexation of surface and subsurface evaporite structures are essential for the implementation of new geoscience-based technologies in the near future, especially aiming at the energy transition and climate change mitigation (Tarkowski and

Czapowski, 2018; Saucier, 2021; Duffy et al., 2023). In the Iberian Peninsula (hereby referred to as Iberia when including the Balearic Islands; Figs. 1, 2), a large number of evaporite structures have been historically recognized and studied (*e.g.*, see a review of gypsum resources in Escavy et al., 2012). Iberian evaporites range from Upper Palaeozoic to Quaternary in age and are mainly found as: (1) undeformed to slightly deformed sedimentary layers, (2) passive, active and reactivated diapirs, (3) evaporite-cored anticlines, (4) evaporite-detached thrusts and (5) allochthonous evaporite bodies. In addition, some deformed structures have evolved through different stages and types of growth and deformation, resulting in complex histories of stacked halokinetic movements. Examples of these complex evolutionary records in the Iberian Peninsula include the Aulet, Montiberri, Adons and Viu de Llevata evaporite structures in the Southern Pyrenees (Saura et al., 2016; Dalton, 2019) or the Bakio, Bermeo, Munguía and Gernika evaporite structures in the Basque Arc (Cámara, 2017; Soto et al., 2017).

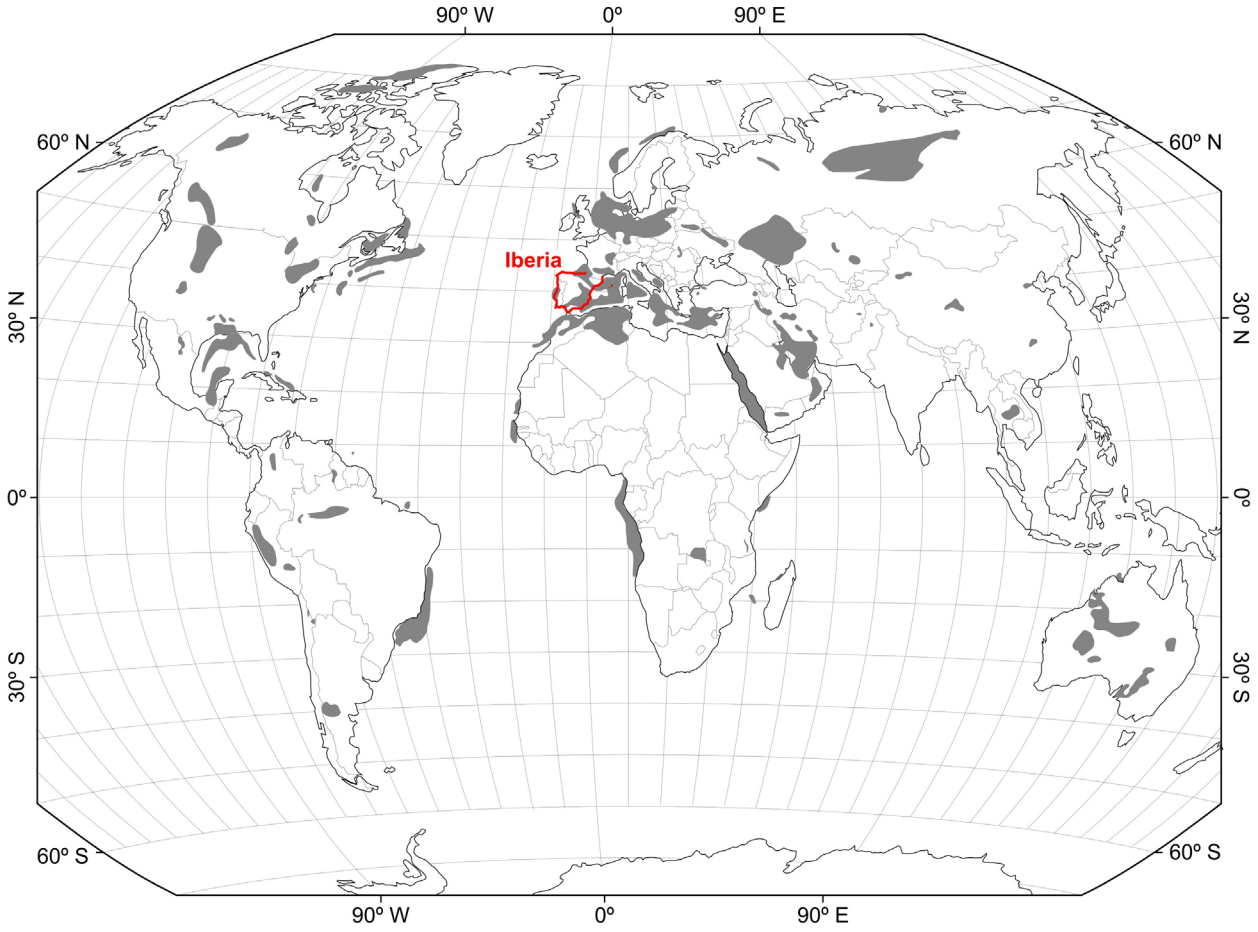


Figure 1. Global distribution of deformed evaporite basins, compiled from Hudec and Jackson (2007, 2012) and Warren (2010).

Iberian evaporite structures have mostly been studied individually and with a certain lack of regional correlation, and only a few review articles summarise their occurrence and significance from a basin- or orogen-scale perspective (Cámara, 2017; Cámara and Flinch, 2017; Martínez del Olmo et al., 2015). Moreover, no inventories or databases focused on evaporite structures are available in Iberia, nor, to the best of our knowledge in other worldwide regions, despite the existence of large amounts of valuable and open access, surface- and subsurface-derived, stratigraphic and structural data. In order to fill this gap, and to foster the use of evaporite resources for the energy transition (both as subsurface storage sites for Geo-Energy applications and as mineral resources), here we present the Iberian Evaporite Structure Database (IESDB), an overall comprehensive assessment of evaporite structures in Iberia. The IESDB includes information on the location, type, structure, stratigraphy, event chronology, seismic and well data availability and mining activity (historical and active) of 150 evaporite structures of Iberia and their surrounding rocks (Fig. 2). The database also includes a comprehensive literature review (more than 1,500 published and unpublished references), as well as a set of geological maps, sketches, and cross-sections (1,200 figures; 8 for each indexed evaporite structure). The IESDB is sourced from the past 50-year-long efforts of the scientific and industrial community in gathering data from evaporite structures. The database has been built and formatted with rigorous data-selection and data-ordering criterions, and is presented here as a freely available, open-to-feedback website (www.ub.edu/iesdb). The IESDB follows the FAIR principles of database management (Findable, Accessible, Interoperable and Reusable; Wilkinson et al., 2016) and can be operated as a Geographic Information System (GIS)-based interactive tool, allowing the user to navigate through the indexed evaporite structures by direct map selection or multi-criteria filtering.

The IESDB aims to provide the research and industrial communities with a user-friendly "evaporite radar" for any scientific, industrial, societal or teaching purpose. The IESDB aims to be a collaborative project where users can provide feedback on the information collected, propose new evaporite structures to be indexed or discuss the geological aspects of those already characterized. The database will be periodically updated as new data become available. Hence, more evaporite structures can be added in the IESDB as they are discovered, and new published data that provide re-interpretations or represent a significant knowledge widening of the already inventoried structures will also be integrated in the IESDB during the scheduled updates.

2 Geological setting

Iberia is located at the western end of the Himalayan-Alpine collision zone, a Cenozoic belt formed after the Paleotethys closure during the Alpine Orogeny (Rosenbaum et al., 2002). However, Iberia records older (nearly 600Ma) geodynamic events that make it a geologically diverse region (Fig. 2). The main events that affected this region can be broadly summarized as: (1) Early Cambrian to Early Permian compression, magmatism and metamorphism (Variscan Cycle; *e.g.*, Simancas, 2019 and references therein), (2) Mesozoic rifting and basin formation (early Alpine cycle; *e.g.*, Gómez et al., 2019 and references therein), and (3) Cenozoic compression and mountain range development by the inversion of Mesozoic rift

basins (Alpine Orogeny; *e.g.*, Rosenbaum et al., 2002; Vergés et al., 2019 and references therein). Since no Palaeozoic evaporites are present in Iberia, we hereafter focus on the Iberian geodynamics and evaporite rock evolution from the early Mesozoic to the Quaternary.

The Mesozoic evolution of Iberia was governed by widespread rifting periods along its northern, eastern and western margins, ending with the continental break-up along the Bay of Biscay, Lingurian-Thetys and Atlantic plate boundaries, respectively (Salas and Casas, 1993; Casas-Sainz and de Vicente, 2009; Vergés et al., 2019). As a result, shallow to deep marine sedimentary basins formed at the main rifting zones (Fig. 2a): These are: (1) the intracratonic Iberian basin, represented nowadays by the Iberian Range, Maestrat basin, Cameros Massif and Catalan Coastal Ranges (Salas and Casas, 1993; Vergés and Fernàndez, 2006), (2) the Basque–Cantabrian–Aquitanian–Pyrenean basin, which currently forms the Basque-Cantabrian basin and the Pyrenees (Vergés and Fernàndez, 2006; Soto et al., 2008; López-Gómez et al., 2019), (3) the Atlantic Margin rift basins, represented onshore by the Lusitanian basin (Rasmussen et al., 1998), and (4) the Atlantic–Lingurian-Tethys linkage zone, which currently forms the external Prebetic and Subbetic cordilleras within the Betic System (García-Hernández et al., 1980; Peper and Cloetingh, 1992) and the Algarve basin (Ramos et al., 2016; 2020).

Mesozoic evaporites played an important role during the Mesozoic extension and Cenozoic compression periods. Lower Mesozoic evaporites can be found within the epicontinental Triassic rocks of the Buntsadstein, Muschelkalk and Keuper facies (Ortí et al., 2017). The uppermost Buntsadstein "Röt" and the Intermediate Muschelkalk "M2" evaporites are scarce and restricted to the NE of Iberia (Virgili et al., 1977; Marzo, 1980; Jurado, 1990; López-Gómez et al., 1993) (Fig. 2c, d), whilst the Upper Triassic Keuper facies are the most abundant Mesozoic evaporite deposits and can be found in all the Mesozoic basins (Ortí et al., 2017) (Fig. 2). Jurassic evaporites (mainly Upper Rhaetian-Hettangian) include the Anhydrite Member (Ortí, 1987; Ortí et al., 2017) along northern and eastern Iberia (Fig. 2c, d, f), the Dagorda Formation (Rasmussen et al., 1998; Wilson et al., 1989) in the Lusitanian basin and the Hettangian Evaporites (Ramos et al., 2016, 2020) in the Algarve basin (Fig. 2b). Cretaceous evaporites are scarce and geographically restricted (Segura et al., 2006; Escavy et al., 2012; Quijada et al., 2013), so, to our knowledge, no stratigraphic correlations between units have been reported to date.

Mesozoic evaporite deformation mainly happened in the form of Upper Triassic-Lower Jurassic salt mobilization and diapiric raise between the Early Jurassic and the Late Cretaceous in all the Iberian Mesozoic basins (Vergés et al., 2019). Diapirs with a nearly circular outcrop geometry are found within the Basque-Cantabrian (Cámara, 2017; Roca et al., 2021) and Algarve (Ramos et al., 2016, 2017) basins (Fig. 2b, f), whilst halokinetic structures and stratal geometries have been overprinted during the Alpine compression in other Iberian domains (*e.g.*, Escosa et al., 2018; Burrel and Teixell, 2021) (Fig. 2c, d, e). Thus, most of the evaporite structures nowadays correspond to anticline cores, detachment horizons and allochthonous evaporite bodies (McClay et al., 2004; Martínez del Olmo et al., 2015; Vergés et al., 2020).

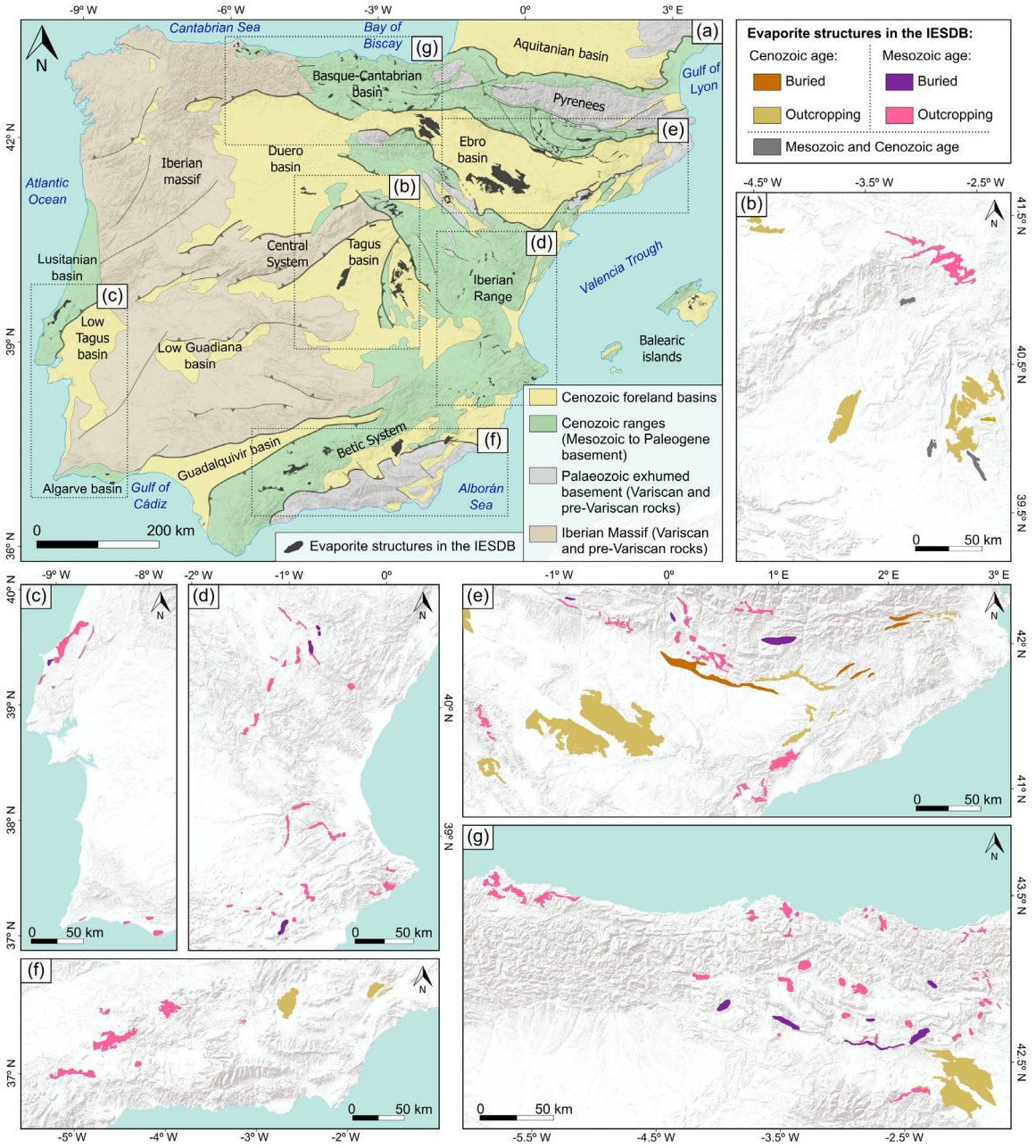


Figure 2. (a) Simplified tectonic map of Iberia, after the geological and structural maps of Andeweg, (2002), Casas-Sainz and de Vicente (2009), Vergés et al. (2019) and Vergés and Fernàndez (2006). Detail of the evaporite structures indexed in the IESDB (*n*=150) is provided in: Central Iberia (b), the Lusitanian and Algarve basins (c), the Iberian Range and the eastern Betic System (d), the central and western Betic System (e) and the Basque-Cantabrian basin (f). Base maps modified from ESRI®.

Cenozoic geodynamics in Iberia were governed by contractional tectonics as a result of the convergence between the European, Iberian and African plates since the late Santonian-early Campanian (Puigdefàbregas and Souquet, 1986; Macchiavelli et al., 2017; Vergés et al., 2019). Asynchronous deformation occurred along the Iberian margins and within intraplate domains. This caused the inversion of Mesozoic rift basins giving rise to the Cenozoic ranges and foreland basins that shape the current geological configuration and landscape of Iberia. The origin and evolution of the Cenozoic ranges at the plate boundaries (*i.e.*, the Pyrenees and the Betic System; Fig. 2d, e) and within the plate interior (*i.e.*, the Iberian Range; Fig. 2c) were controlled by the distribution of evaporite deposits of Mesozoic to Paleogene age. These rocks acted as detachment levels during thrust development (Vergés and Fernàndez, 2006; Muñoz et al., 2018). In summary, evaporite successions were deposited from the early Mesozoic to the Paleogene, have been involved in different tectonic processes and are nowadays deformed. On the contrary, Neogene to Quaternary evaporites within the Cenozoic foreland basins have practically been unaffected by deformation.

As a result of uplifting during the Cenozoic, most of the large Cenozoic basins of Iberia evolved from exorheic to endorheic drainage conditions during the Paleogene and Neogene, except for the Guadalquivir basin that remained connected to the Atlantic Ocean. This stage produced intense evaporation and favoured evaporite deposition, mostly in the Duero, Ebro and High Tagus foreland basins (Escavy et al., 2012) (Fig. 2a, d, f). Furthermore, the (minor and more restricted) Neogene to Quaternary basins of the Betic System were also isolated from the Atlantic ocean and the Mediterranean sea since the late Miocene, giving rise to a diachronic formation of evaporites followed by a complete disconnection and basin continentalization. (Fig. 2e) (Galdeano and Vera, 1992; Playà et al., 2000; Galindo-Zaldívar et al., 2019; García-Veigas et al., 2020, and references thereof). The Baza basin, the largest Neogene–Quaternary intramountain basin of the eastern Betic Chain, evolved from endorheic to exorheic after being captured by the drainage network of the Guadalquivir River since the latest middle Pleistocene (Gibert et al., 2007; García-Tortosa et al., 2008).

3 The Iberian Evaporite Structures Database

The IESDB includes a complete review of 150 evaporite structures and their surrounding rocks that crop out or are buried onshore Iberia, including undeformed to slightly deformed successions, evaporite-cored anticlines, diapirs, evaporite-detached thrusts and allochthonous evaporite bodies (Fig. 2). The structure of the IESDB is based on a process of selection, compilation and classification of the evaporite structures and their geological information. Thus, and considering that this workflow could be adapted and applied for inventorying other geological structures and replicated in other regions of the world, an overview of the IESDB structure is presented in this section, together with their building process and final datasets.

3.1 Outline

To ensure that the database includes only relevant entries, the evaporite structures included in the IESDB were selected according with the following criteria: (1) they are located onshore Iberia; (2) when cropping out, they should have a minimum exposed area of 0.5km^2; (3) when buried, seismic and/or well data should be available and they should have a minimum horizontal intersection area of 1.5km^2 at 0.5km depth; (4) the structure or deposit should be mentioned at least in ten peer-reviewed articles; (5) the stratigraphy and structure of the evaporite deposit and, when applicable, the overburden, halokinetic or post-kinematic sequences should be directly addressed in at least one peer-reviewed article or industry or government report. Each inventoried structure includes written and visual information about the geometry, stratigraphy, and structural evolution of the evaporites and their surrounding rocks together with (when possible) the evaporite flow driving mechanisms and their approximate age.

The database can be accessed and interoperated by two different procedures: (1) bulk download of the raw datasets, where information is categorized according to its type and nature (see sub-section 3.3), or (2) through the dynamic and open-access IESDB webpage (Fig. 3), where information is classified in 150 unique web sections that correspond to the indexed evaporite structures. The latter method has been conceived as interactive and user-friendly. This means that the indexed evaporite structures can be easily selected on a map (Fig. 3c), or can be browsed through a search engine by the following classification criterions: structure type, deformed/undeformed, geological setting, cropping out/buried, evaporite unit/s name, evaporite unit/s age, evaporite unit/s origin, salt structure classification according to the schemes of Jackson and Talbot (1991) and Hudec and Jackson (2007), and age of evaporite flow (Fig. 3b). The IESDB webpage structure is inspired by E-commerce management tools to treat the inventoried structures as "online products for sale", so each evaporite structure has a unique web section where written and illustrated information is displayed over several sub-sections, following a common layout (Fig. 3a). A *Guide* section is also provided in the IESDB webpage, and includes guidelines for interoperating the database, as well as information about the origin and meaning of the different types of data related to the evaporite structures.

The IESDB aims to be a dynamic project open to collaboration and with constant improvement and expansion. We encourage users to contact the database managers and submit new information or suggest corrections to expand and improve the database. New evaporite structures can be added as new research articles or public reports are published to provide new surface or subsurface information. Moreover, new data and re-interpretations that concern the already inventoried structures, as well as feedback provided by users via a contact page, will be considered to implement the data updates.

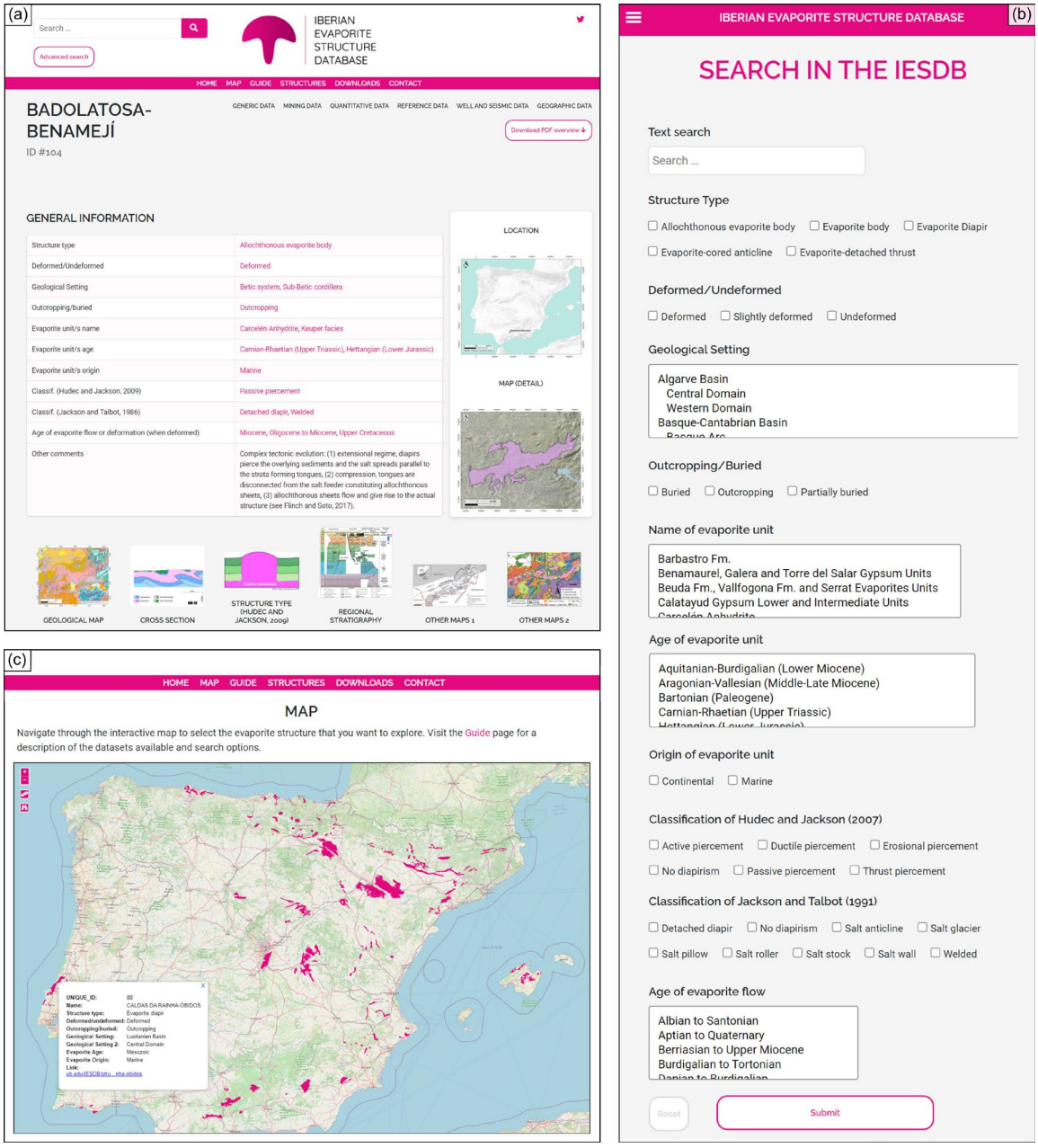


Figure 3. Screenshots of the IESDB webpage (https://ub.edu/iesdb). (a) Unique web section of the Badolatosa-Benamejí evaporite structure (ID #104) (web version). (b) Filtering criteria included in the IESDB advanced search engine (mobile version). (c) Interactive map with all the evaporite structures included in the IESDB; by clicking at one evaporite structure, the user will visualize a pop-up overview of the information and the corresponding link to the unique web section of the selected structure. Base map in (c) modified from © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

3.2 Data sources

The IESDB is sourced from over 1,500 classified references and six thematic open-access databases. Classified references include, among others, published articles and conference abstracts, books, book chapters, PhD theses and published and unpublished industry and government reports. Geological maps and cross-sections provided by IGME (Instituto Geológico y Minero de España, Spain Geological Survey; http://info.igme.es/cartografiadigital/geologica/Magna50.aspx), LNEG (Laboratorio Nacional de Energia e Geologia, Portugal Geological Survey; https://geoportal.lneg.pt/mapa/) and ICGC (Institut Cartogràfic I Geològic de Catalunya, Catalonia Geological Survey; https://www.icgc.cat/Administracio-i-empresa/Descarregues/Cartografia-geologica-i-geotematica) have also been used as source layers for data mining. The location and geometry of the available seismic and well data for each structure was obtained from the SeisDARE database (DeFelipe et al., 2020), together with the *GEODE* map series (IGME; https://info.igme.es/cartografiadigital/geologica/Geode.aspx), the *SIGEOF* database (IGME; https://info.igme.es/SIGEOF/) and the *Well Data Catalogue* (IGME; https://info.igme.es/Litoteca/), and integrated in a GIS-based environment. Mining inventories included in the *Spanish National Mining Cadastre* (*Ministerio para la Transición Ecológica y el Reto Demográfico, Spanish Government; https://energia.gob.es/mineria/Paginas/catastro.aspx*) and in the *Panorama Minero* inventory (IGME; *http://www.igme.es/PanoramaMinero/PMLin.htm)* have also been used to obtain the mining-related information of each structure. A detailed overview of the references related to each inventoried evaporite structures is provided as one of the IESDB datasets (see sub-section 3.3), and as a web sub-section in the IESDB webpage. In the latter case, hyperlinks to each listed reference are included in the IESDB webpage aiming to facilitate data query from the original data sources.

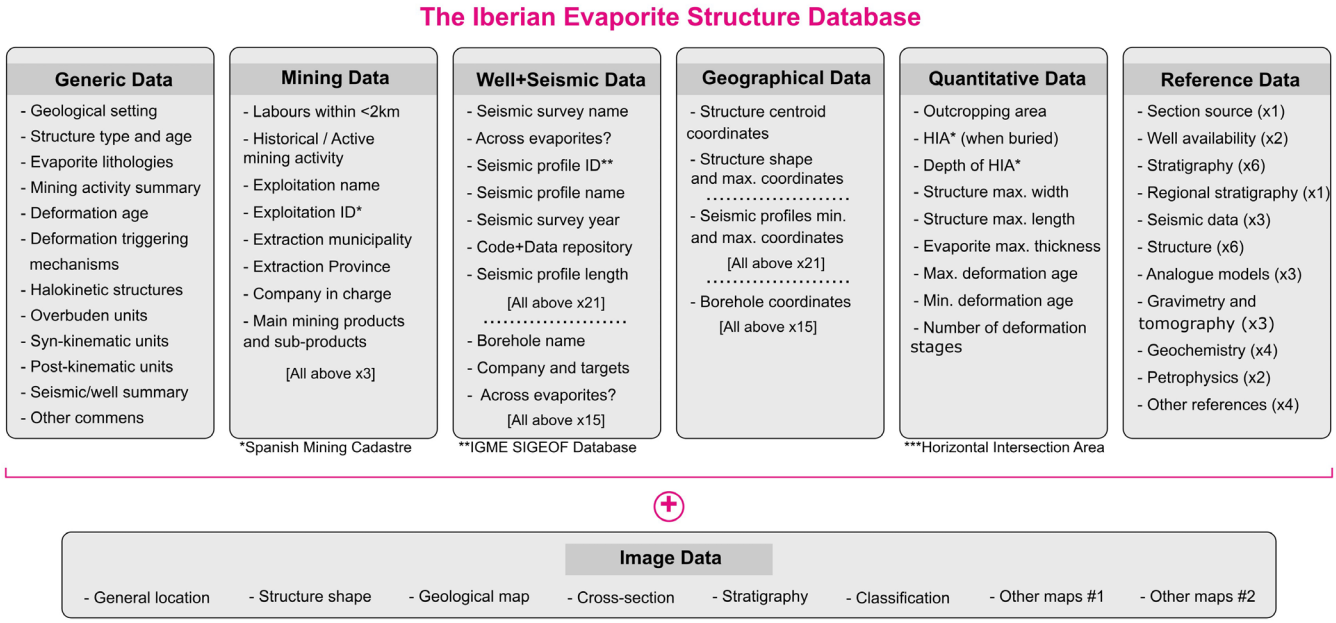
3.3 Database structure

Up to 454 information fields for each evaporite structure were manually filled by means of classification and curation of the information found in the data sources (see sub-section 3.2). The information fields were classified in seven datasets according to the type of information that they contain (Fig. 4): Generic Data (31 fields), Mining Data (20 fields), Well and seismic Data (228 fields), Geographic Data (120 fields), Quantitative Data (9 fields), Reference Data (38 fields) and Image Data (8 fields). The structures are correlated over these datasets through a unique ID that has been randomly assigned to them.

The quality and quantity of the information fields of each structure depends on its type, actual knowledge, and geoscientific interest. Thus, there are evaporite structures with complete information in all the datasets, whilst some information types may be missing for other structures depending on data availability. We established the Information Filling Percentage (IFP) to address the completeness of database fields for each evaporite structure. The IFP is calculated by normalising the fields that contain information with respect to the total number of fields for each dataset (Figs. 4, 5). The IFP of all the inventoried structures is over 75% for the reference-dependant datasets, whilst it is more variable for the Mining, Well and Seismic and (partially) Geographic datasets. This is because these latter fields depend totally or partially on the

performance and availability of borehole and seismic surveys (Fig. 5). We describe below the nature and type of information that is included in each of the IESDB datasets.

Figure 4. Datasets included in the Iberian Evaporite Structures Database (IESDB).



3.2.1 Generic Data

Generic Data (median IFP of 89%; Fig. 5) includes, for each inventoried structure, general information about the regional geological framework and of the structure and stratigraphy of the evaporites and their surrounding rocks (Fig. 4). Data corresponding to the evaporite units refers to the formation/facies names, the depositional environment, the lithological composition, the type of evaporite structure (according to Jackson and Talbot, 1991, and Hudec and Jackson, 2007) and the evaporite flow characteristics, including the age and number of deformation stages, their triggering mechanisms, and their halokinetic structures. The structural and stratigraphic information of the surrounding rocks includes the name, age and lithological composition of the stratigraphic formation/facies, which are categorized according to whether they are post-evaporite sedimentation and pre-kinematic (*e.g.*, overburden sequences), syn-kinematic or post-kinematic.

Names of boreholes and seismic profiles that crosscut or are within 5 and 3 km of each structure, respectively, are also provided in the Generic Data, but their information is further detailed in the *Well and Seismic* and *Geographical Data* datasets described below. Historical and active mining activities in the inventoried structures include information about the exploitation methods, start and end dates of mining, and the products or sub-products that have been or are being extracted. Finally, a miscellaneous section is included to gather other relevant information about the inventoried structures. This includes

the relationships between neighbouring subsurface evaporite bodies, details about their deformation history, or interpretations of their structural evolution according to different studies.

3.2.2 Mining Data

Mining Data (median IFP of 41 %; Fig. 5) contains more detailed information about the mining exploitation activities in the inventoried structures (Fig. 4). A 2 km multi-ring buffer (constant distance) around the inventoried structures was used to obtain information of the open-pit mining activities above them as well as of the underground galleries that exploited the evaporites in the subsurface. Mining companies typically acquire and compile information on the structural, stratigraphic, and geochemical characteristics of the products and sub-products they exploit. Therefore, the names of the companies that own the concessions of active mines are also presented, together with the exploitation ID indexed in the *Spanish National Mining Cadastre* (*Ministerio para la Transición Ecológica y el Reto Demográfico, Spanish Government;* https://energia.gob.es/mineria/Paginas/catastro.aspx).

3.2.3 Well and Seismic Data

Borehole and seismic data are key information sources of the subsurface stratigraphy and structure of the inventoried structures and their surroundings. Thus, *Well and Seismic Data* (median IFP of 27 %; Fig. 5) holds expanded information about boreholes and seismic profiles located within a 5 and 3 km multi-ring buffer (constant distance) around the evaporite structures, respectively (Fig. 4). An important part of this dataset is extracted from the aforementioned IGME and SeisDARE databases (see sub-section 3.2), whereas other (private access) information was obtained from published articles and industry and government reports. The seismic line information includes the ID and name of the profiles and the name and year of the seismic acquisition campaign. Additionally, the availability of each profile in SEG-Y format in *SIGEOF* catalogue (IGME), or in *SeisDARE* database (DeFelipe et al., 2020) is also provided. Well information includes the name of the boreholes and the company that executed them, together with the targets of their execution (*i.e.*, subsurface substances or structures).

3.2.4 Geographical Data

Geographical Data (median IFP of 31 %; Fig. 5) contains geographical information (in *EPSG:4326 - WGS 84* coordinates) of the datasets described above (Fig. 4). Evaporite structures are positioned with respect to the central, minimum and maximum latitude and longitude coordinates of their shape. Boreholes related to the indexed structures are listed point data and referenced by their X and Y coordinates, whilst seismic lines also include their minimum and maximum latitude and longitude values. An ESRI® shapefile file that includes the georeferenced shape of the inventoried evaporites is available at IESDB website for direct download and visualization in a GIS-based environment.

3.2.5 Quantitative Data

Quantitative Data (median IFP of 99 %; Fig. 5) includes a summary of the geometry and event chronology for each structure (Fig. 4). For the geometrical characterization, outcropping or (when buried) horizontal intersection areas of the evaporite structures are included, as well as their maximum thickness and maximum width and length values. The chronology of deformation episodes is only addressed for the deformed structures, and comprises the maximum and minimum age of evaporite deformation (*i.e.*, folding, thrusting or diapirism), as well as the number of deformation phases or diapiric growth stages.

3.2.6 Reference Data

Reference Data (median IFP of 76 %; Fig. 5) provides an extensive literature review of each evaporite structure indexed in the IESDB (Fig. 4). References consist of more than 1,500 conference abstracts, scientific articles, books, book chapters, PhD theses and unpublished industry and government reports, all of them cited with APA format edition and linked to their online versions with hyperlinks (*i.e.*, Digital Object Identifiers or, when not available, generic URLs). Some sources address the evaporite structures regionally and multidisciplinary, while others only focus on individual geological features. Thus, references are categorized by their main knowledge area and some of them fit in two or more study fields. Altogether, 14 geoscience-related disciplines that include up to 38 references for each evaporite structure have been established to offer an overall literature assessment. Selected disciplines or categories, with the respective number of references that they include, are the following: Cross-section source (1), Available well data (2), Stratigraphy (6), Regional stratigraphy (1), Available seismic data (3), Structure (6), Analogue modelling (3), Gravimetry and/or tomography (3), Geochemistry (4), Petrophysics and/or palaeomagnetism (2), *MAGNA50* map series (IGME) sheet number (1), Other maps (2) and Other references (4).

3.2.7 Image Data

Image Data (median IFP of 100 % and therefore not included in Fig. 5) contains newly created and previously published figures of the inventoried evaporite structures (Fig. 4). Newly created figures include (1) a general location map of each structure, (2) a detailed map of their outcropping or (when buried) horizontal intersection shape and (3) a cross section showing their subsurface structure. Additionally, a simplified sketch of the structure type according to the Hudec and Jackson (2007) classification is included for the deformed evaporites (when applicable). The already published figures consist of (1) a stratigraphic correlation panel or column that represent the regional stratigraphy of evaporites and surrounding rocks (referenced in the "Regional stratigraphy" category of the Reference Data), (2) a portion of the IGME, LNEG or ICGC geological map and (3) two geological maps from literature (referenced in the "Other maps 1 & 2" categories of the Reference Data), the first at basin scale (*i.e.*, focused on regional geology of the evaporite structure) and the second at the most detailed scale available. The rightsholder copyright permissions have been checked for all the already published figures reproduced in the IESDB website, and hence the availability, accuracy and scale of the figures are restricted to those that are published open-

access and that provide permission to be reproduced. This fact also prevented from sharing the most up-to-date illustrated data on some of the structures, and therefore the reproduced figures show in some cases less details than the IESDB could (and would like to) offer.

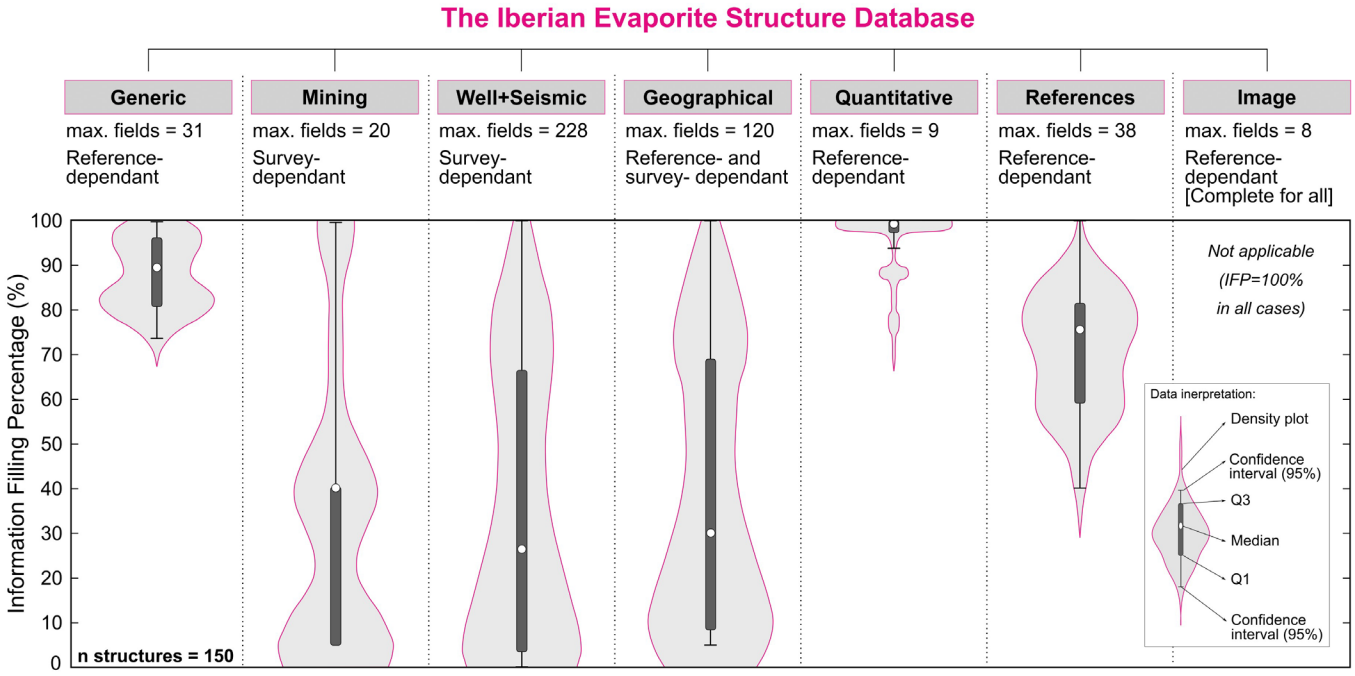


Figure 5. Datasets included in IESDB with their respective statistics on the percentage of filled fields (Information Filling Percentage, IFP). IFP is calculated for each structure by normalizing to 100% the fields which contain information relative to the total fields of each dataset. Note that the survey-dependant datasets show a significatively higher variability when compared with the reference-dependant datasets.

3.2.8 Summarized Index Cards

Besides the seven datasets described above, a downloadable pdf-format "index card" has been created to provide a comprehensive overview of each evaporite structure (Fig. 6). These *Summarized Index Cards* are conceived as a summary of the stratigraphic and structural properties, subsurface data availability, and main references of each evaporite structure. They follow a common layout and include four figures from the Image Data (see sub-section 3.2.7) corresponding to the location, shape, geological map and cross-section of the evaporite structure they represent. The *Summarized Index Cards* can be downloaded separately from the unique web section of each evaporite structure, or jointly from the data repository as a complete dataset.

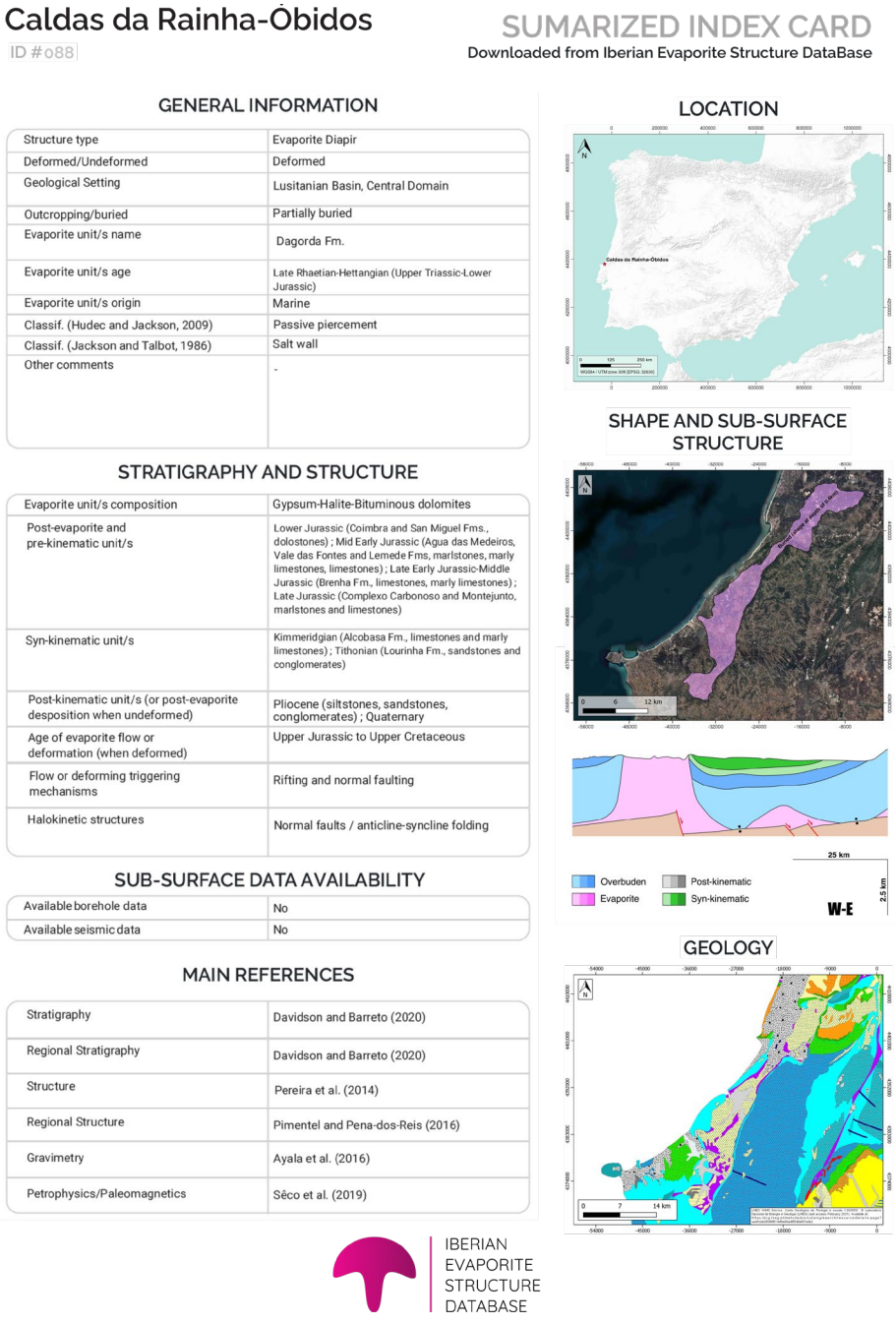


Figure 6. Example of the Index Cards included in IESDB for each indexed evaporite structure. They include a summarized and illustrated overview of the general information, structure, stratigraphy, subsurface data availability and main literature references. Base maps modified from ESRI®; geological map modified from Laboratório Nacional de Energia e Geologia (LNEG), Government of Portugal.

4 The IESDB applications on geology, geo-resources, and geo-energy

Evaporites have unique properties that make them stand out from other sedimentary rocks (*e.g.*, Hudec and Jackson, 2007; Jackson and Hudec, 2017). Their ability to flow in the solid state under relatively low differential stress makes their study key for understanding the formation of sedimentary basins and orogens, and to characterise their role in controlling deformation processes at multiple scales (salt tectonics). Exceptionally well-exposed evaporites in Iberia allow to study and interpret their halokinetic structures and growth strata (*e.g.*, Rubinat et al., 2013 at the Bicorp-Quesa diapir in the Eastern Prebetic zone and Roca et al., 2021 at the Bakio diapir in the Basque-Cantabrian basin), whilst an array of detailed (and often untapped) subsurface information constitutes an opportunity for understanding the extent and geometry of subsurface evaporite bodies and their relationship with the regional structure and stratigraphy (as demonstrated, *e.g.*, in the regional reviews of Martínez del Olmo et al., 2015 in the Prebetic Cordillera and of Carrillo et al., 2017 in the southeastern Pyrenees). The surface and subsurface stratigraphical, structural, and geophysical data for each evaporite structure is provided in the IESDB, so the website can be used as a search engine to find examples of, among others, the types and timing of salt mobilization processes or the halokinetic sequences in the salt encasing rocks. The IESDB is thus a powerful tool for screening structures with geological features of interest, a resource for detecting missing information and set research goals, and a geoscience teaching tool that allows looking for examples to illustrate stratigraphic and tectonic processes in which evaporites are involved.

In addition, properties of evaporites and their capacity to act as geological traps for hydrocarbons and other fluids has fostered their use in different geo-energy applications. Salt caverns are widely used as seasonal and long-lasting reservoirs for hydrocarbon products (e.g. oil crude and natural gas), and in some cases have been considered as potential repositories for nuclear waste (*e.g.*, Ozarslan, 2012; Wang et al., 2017; Warren, 2017). Furthermore, they have been proposed as suitable sites for renewable energy storage (e.g. in the form of green hydrogen and compressed air energy storage). Thus, understanding the deformation kinematics, flow history and actual geometry of evaporite structures is crucial not only for the exploration and production of hydrocarbons, but also for the future development of cleaner energy storage activities, required to secure the energy transition to zero-carbon. Onshore buried evaporite structures from the Southern Pyrenees, Basque-Cantabrian basin, Pre-Betic cordillera and Lusitanian basin (all of them indexed in the IESDB; Fig. 2) have been already proposed as suitable candidate sites for underground energy storage (Carneiro et al., 2019; Caglayan et al., 2020; Martínez del Olmo, 2021). It is worth noting that Spain ranks third in the European national storage potential classification, after Germany and Poland (Caglayan et al., 2020), and evaporite structures are fundamental for this.

Other studies also appraised the suitability of some of the evaporite structures indexed in the IESDB to be used as seals for CO_2 geological storage facilities (Sun et al., 2021), particularly in the Lusitanian basin (Pereira et al., 2014, 2021), the Betic System (Urquiza, 2012) and the Basque-Cantabrian basin (Llamas et al., 2017) (Fig. 2). Finally, evaporite structures have also been postulated as suitable hosts for low- to high-level nuclear waste repositories, initially by the US Committee of Waste

Disposal (Heroy, 1957) and more recently by other organizations (e.g., International Atomic Energy Agency, 2003). The site election for development of this facilities must be, however, based on multiple criterions to ensure their safety and durability (e.g. Warren, 2017). For example, numerous of projects lead by ENRESA, a public and non-profit organization responsible for the management of radioactive waste in Spain, were funded between 1986 and 1997 to study evaporite formations as potential hosts for deep nuclear waste storage. Given the wide range of applications that they offer, knowledge on the geologic features of evaporite structures will thus be crucial in the near future for energy storage, climate change mitigation and waste management, and the overall assessment provided in the IESDB represents an initiative that could be replicated in other, evaporite-rich world regions (Fig. 1).

5 Data availability

The IESDB database is freely available at https://iesdb.eu (last access: November 2022). Datasets and Summarized Index Cards can be downloaded from the DIGITAL.CSIC data repository at https://doi.org/10.20350/digitalCSIC/14586 (González-Esvertit et al., 2022) (last access: November 2022).

6 Conclusions and final remarks

Evaporite rocks have attracted great scientific and industrial interest during the last century. Earth scientists and hydrocarbon and mining companies have studied evaporite structures worldwide aiming to understand, among others, their origin, significance and influence on basin and orogen architecture. Surface and subsurface geoscientific information derived from these aims remain useful nowadays, but often untapped because of its access issues, segregation, and scarce data dissemination. The IESDB includes a painstaking compilation of 150 evaporite structures and their surrounding rocks from Iberia, and is sourced from an extensive database and literature review of scientific articles, published maps and reports. This database represents a comprehensive multidisciplinary review of Iberian evaporites, as well as the first overall assessment of evaporite structures carried out in any region of the world. The IESDB is presented as an open access, user-friendly and open to feedback webpage where the inventoried structures can be selected from a map or sorted out by multi-criteria filtering, and the workflow used to build it could be replicated in other world regions for the indexation of evaporite or other types of geologic structures. The database stores systematically-organized information about the structure, stratigraphy, event chronology, seismic and well data availability, and mining activity (historical and active) of 150 evaporite structures. The compilation and assessment provided in IESDB will serve as a starting point for improving the regional and local geological understanding of the inventoried structures, and also can act as an “evaporite radar” for the identification of suitable sites for energy, carbon or nuclear waste storage facilities.

Author contribution

JA and EGR conceptualized the original idea, indexation criterions and data compilation methods. EGE collected, filtered and organized the data and images with contributions from all co-authors. JA managed the data upload to the DIGITAL.CSIC data repository and the DOI assignation. EGR provided the project funding and managed the website hosting at the Universitat de Barcelona servers. EGE, JA and EGR designed the webpage and carried out the data uploading. EGE drafted the manuscript with contributions from all co-authors.

Competing interest

The authors declare that they have no conflict of interest.

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