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Open Access Earth System Science Data Discussions

Reassessing the lithosphere: SeisDARE, an open access seismic data repository

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Abstract. Seismic reflection data (normal incidence and wide-angle) are unique assets for Solid Earth Science as they provide critical information about the physical properties and structure of the lithosphere, as well as about the shallow subsurface for exploration purposes. The resolution of these seismic data is highly appreciated, however they are logistically complex and expensive to acquire and their geographical coverage is limited. Therefore, it is essential to make the most of the data that has already been acquired. The collation and dissemination of seismic open access data is then key to promote accurate and innovative research and to enhance new interpretations of legacy data. This work presents the Seismic DAta REpository (SeisDARE), which is, to our knowledge, one of the first comprehensive open access online databases that stores seismic data registered with a permanent identifier (DOI). The datasets included here are openly accessible online and guarantee the FAIR (Findable, Accessible, Interoperable, Reusable) principles of data management, granting the inclusion of each dataset into a statistics referencing database so its impact can be measured. SeisDARE includes seismic data acquired in the last four decades in the Iberian Peninsula and Morocco. These areas have attracted the attention of international researchers in the fields of geology and geophysics due to the exceptional outcrops of the Variscan and Alpine orogens and wide foreland basins; the crustal structure of the offshore margins that resulted from a complex plate kinematic evolution; and the vast quantities of natural resources contained within. This database has been built thanks to a network of national and international institutions, promoting a multidisciplinary research, and is open for international data exchange and collaborations. As part of this international collaboration, and as a model for inclusion of other global seismic datasets, SeisDARE also hosts seismic data acquired in Hardeman County, Texas (USA), within the COCORP project (Consortium for Continental Reflection Profiling). SeisDARE aims to make easily accessible old and recently acquired seismic data and to establish a framework for future

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seismic data management plans. The SeisDARE is freely available at https://digital.csic.es/handle/10261/101879, bringing endless research and teaching opportunities to the scientific, industrial and educational communities.

1 Introduction

Controlled source seismology is a fundamental tool for Solid Earth Science, as it provides very valuable information about the physical properties and structure of the Earth's crust and upper mantle. Controlled source seismic experiments have been undertaken in all continents, oceans and tectonic settings since the mid-nineteenth century (Mintrop, 1947; Jacob et al., 2000), shedding light on our current understanding of the Earth's interior, from its composition and structure to its evolution. The outputs of these experiments, Deep Seismic Sounding (DSS) data, are generally expensive, logistically complex to acquire, and often result from a huge scientific effort involving national and international institutions. Therefore, it is imperative that legacy and new acquired data are easily available for future generations of geoscientists. Taking into account that data processing algorithms are constantly evolving, new or additional information can be extracted from these data.

Aware of the value of DSS data, Prodehl and Mooney (2012) provided a comprehensive, worldwide history of controlled source seismological studies acquired from 1850 to 2005, highlighting the enormous efforts made in the last 170 years to increase our knowledge of the subsurface. Since the 1970's, ambitious seismic reflection projects were developed worldwide, acquiring unique datasets that targeted key lithosphere structures. These datasets provided unprecedented images of the lithosphere, characterizing crustal discontinuities, major faults, geometry of orogenic belts, and other lithospheric features that had not been envisioned before. Some of these major seismic research programs that acquired DSS normal incidence and wide-angle data include: COCORP (USA); BIRPS (UK); ECORS (France); DEKORP (Germany); ESCI, IAM and ILIHA (Spain); HIRE and FIRE (Finland); ESRU and URSEIS (Russia); INDEPTH (Himalayas); LITHOPROBE (Canada); NFP 20 (Switzerland); and SINOPROBE (China).

In parallel, the hydrocarbon industry also added value using legacy seismic reflection data (Nicholls et al., 2015) by applying new processing approaches and techniques. Furthermore, reprocessing of high resolution seismic reflection data have also been used in exploration for mineral resources (Manzi et al., 2019; Donoso et al., 2020), civil engineering (Martí et al., 2008) and are also successful for the characterization of seismogenic zones and hazard assessment (Ercoli et al., 2020). Therefore, legacy data are extremely valuable for basic and applied earth sciences, and preserving and making data available constitutes an effort that should contribute to move science forward.

The international community has focused towards the preservation of the data and facilitating its access. Examples of these efforts include the SIGEOF database (Geological and Mining Institute of Spain) that hosts geophysical data of the Iberian Peninsula (http://info.igme.es/SIGEOF/), OpenFIRE (https://avaa.tdata.fi/web/fire, Finland), and the IRIS-PASSCAL consortia (https://ds.iris.edu/ds/nodes/dmc/, USA), which is probably one of the most active seismic related data repository. In

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addition, the International Geological Correlation Programme (IGCP) initiative (http://www.earthscrust.org.au/) has made widely available some of these unique seismic images.

Within the European research community there is a consistent vision of fostering global Open Science as a driver for enabling a new paradigm of transparent, data-driven science and accelerating innovation. This vision is becoming a reality thanks to a number of ambitious programs internationally supported. The European Open Science Cloud (https://www.eosc-portal.eu/) is driving towards a virtual environment with open and seamless services for storage, management, analysis and reuse of research data by federating existing scientific data infrastructures, currently dispersed across disciplines and European countries. In the same way, the European Strategy Forum on Research Infrastructures (ESFRI) is a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach. The ESFRI in Earth Sciences is the European Plate Observation System (EPOS, https://www.epos-ip.org/) that was initiated in 2002 to tackle a viable solution for the Solid Earth grand challenges. It is aligned with the Berlin Declaration for the Open Access to Knowledge in the Sciences and Humanities (2003) which stipulates that research data products need to be integrated and made accessible through open access schemes. EPOS aims to ensure a long-term plan to facilitate the integration of data and fosters worldwide interoperability of Earth Science services to a broad community of users for innovation in science, education and industry.

In close collaboration with EPOS, the Spanish National Research Council (CSIC) hosts the 'DIGITAL.CSIC' repository, where all kinds of scientific data are accessible following the international mandates of open access data and the FAIR principles of data management: findable, accessible, interoperable and reusable (Bernal, 2011; Wilkinson et al., 2016). As part of CSIC, Geosciences Barcelona (GEO3BCN, formerly Institute of Earth Sciences Jaume Almera-ICTJA) has participated in numerous geophysical projects carried out mainly in the Iberian Peninsula and Morocco during its more than 50 years' history. The unique geological characteristics of these areas (outstanding record of the Variscan orogen and Alpine mountain belts, wide foreland basins, good accessibility and outcrop conditions, etc.) make them an excellent resource to study the structure of the lithosphere, and the spatial and temporal evolution of tectonic extension, mountain building, plate tectonics and evolution of rifts (Daignières et al., 1981, 1982; Gallart et al., 1980, 1981; Choukroune and ECORS Team, 1989; Roca et al., 2011; Simancas et al., 2013; Martínez Poyatos et al., 2012; Macchiavelli et al., 2017; Ruiz et al., 2017; Cadenas et al., 2018; DeFelipe et al., 2018, 2019). These data jointly with multi-technique seismic acquisitions from other experiments have provided a full picture of the physical structure of the Mohorovičić discontinuity (Carbonell et al., 2014b; Díaz et al., 2016), the accommodation of shortening mechanisms at different crustal levels (Simancas et al., 2003, 2013), the structure of the Iberian margins and mountain ranges (Pedreira et al., 2003; Ayarza et al., 2004; Fernandez-Viejo et al., 2011; Ruiz et al., 2017), and the effect of Alpine reactivation in the Iberian Peninsula (Teixell et al., 2018; Andrés et al., 2019). In addition to those continental scale projects, an increased interest in the study of the shallow subsurface has emerged in the last decade in different areas of the Iberian Peninsula. These interests are related to natural resources exploration and exploitation, geo-energy and permanent storage applications, earthquake hazard assessment or infrastructure planning (Alcalde et al., 2013a, b; Martí et al., 2019).

Here, we report on the readily available database SeisDARE (Seismic DAta REpository), which compiles large geophysical projects developed in the Iberian Peninsula and Morocco. Part of the data comprised in this database were already stored in Geo DB (http://geodb.ictja.csic.es/#dades1). However, they lacked from a Digital Object Identifier (DOI), thus representing an intermediate step in making the datasets FAIR. SeisDARE goes beyond Geo DB by hosting a larger number of datasets, providing them with a DOI and linking them to its scientific literature by means of the Scholix facilities and the DataCite Event Data (Hirsch, 2019, https://search.datacite.org/).

The geoscientific data are the basis for the generation of meaningful geological knowledge (Pérez-Díaz et al., 2020). The idea behind SeisDARE is to treat the data as any scientific publication, making it as relevant as the publication itself (Carbonell et al., 2020; DeFelipe et al., 2020). The data are accessible at different processing stages, as raw data and/or processed forms. Raw data will fulfill the needs of researchers that would like to develop a new processing approach and the already processed data will provide images for scientists aiming to test alternative interpretations. The purpose of this paper is to provide a general overview of the geological setting of the experiments, a brief description of each dataset, and the link to the open access data. This database is the result of a fruitful national and international inter-institutional collaboration, aiming to enhance multidisciplinary research and to promote advanced research networks. Thus, we are actively working in keeping our database updated, gathering more datasets.

2 Outline of SeisDARE

The multidisciplinary GEO3BCN database is being constantly updated, and especially since last years, the efforts put into the dissemination of the data have yielded to a significant increase in the number of the collection views and downloads of all items (Figure 1). The number of view counts has steadily increased since the beginning of the records in 2015 to mid-2020, with an outstanding amount of views in August 2020. The number of downloads has strikingly increased since October 2019 onwards, reaching the highest value in April 2020. Additional statistics of each item views and downloads are also available and can be consulted straightforward in the statistics facilities of the repository.

Within the GEO3BCN database, SeisDARE contains 19 datasets of DSS (normal incidence, NI, and wide-angle, WA) and high resolution data (Table 1). Our database comprises the data files together with a comprehensive description of their general characteristics and the acquisition parameters. Furthermore, a list of authors and publications derived from the data are also provided. The data included are mainly in SEG-Y format, the most commonly used format for seismic data (https://seg.org/Publications/SEG-Technical-Standards). Additionally, each project is summarized in a file or index card, where the general information of the data, a location map of the seismic data, an image of the data as an example, references and funding agencies are provided. Figure 2 shows an example of the index card of the IBERSEIS-WA project. Ideally, all the content stored in the database is self-explanatory, so that the inexperienced users can handle the datasets straightforwardly.

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In general, the philosophy behind SeisDARE is entirely transferable to similar seismic datasets from other areas in the world. The promoters of SeisDARE are actively looking for engagement with other international institutions, either by offering to host their datasets or to serve as a model for the establishment of new similar platforms. This internationalization effort led to the establishment of a collaboration with the Consortium for Continental Reflection Profiling (COCORP), to host the Hardeman County (Texas) dataset. This kind of collaboration adds a great value to the database by expanding the range of geological settings sampled and strengthening the research network between different institutions worldwide.

3 Geological setting of the study areas

The Iberian Peninsula and Morocco have experienced a long and complex geological history since the Paleozoic, resulting in a rich variety of tectono-sedimentary domains. These include the Variscan terrains of the Iberian Massif, Pyrenean Axial Zone and Iberian Chain; broad Mesozoic basins; the Alpine mountain belts; and the Cenozoic foreland basins (Figure 3). In addition, Figure 4 shows the crustal models published based on six datasets belonging to SeisDARE, covering an almost complete section of the Iberian Peninsula (onshore and offshore) and Morocco.

The Variscan orogen resulted from the convergence of the Laurentia-Baltica and Gondwana continents, yielding to the creation of the supercontinent Pangea (e.g., Matte, 1991, 2001; Murphy and Nance, 1991; Simancas et al., 2003; Pérez-Cáceres et al., 2016). In the Iberian Peninsula, the Iberian Massif represents the main outcrop of the Variscan terrains and has been divided in six zones (Julivert, 1972; Figure 3). The West Asturian-Leonese Zone (WALZ) and the Cantabrian Zone (CZ), being the latter the external foreland zone (e.g., Martínez Catalán et al., 1997), are the northernmost zones. The Central Iberian (CIZ) is the largest zone which includes the entirely allochthonous Galicia Tras-Os-Montes Zone (GTOMZ) towards the northwest (Martínez Catalán et al., 1997; Arenas et al., 2007). South of the CIZ, the Ossa-Morena Zone (OMZ) is a highly deformed area of Upper Proterozoic-Lower Paleozoic rocks (Matte, 2001; Pérez-Cáceres et al., 2016, 2017). The southernmost zone of the Iberian Massif is the South Portuguese Zone (SPZ), another external zone that hosts the largest concentration of volcanic massive sulphide deposits worldwide, the Iberian Pyrite Belt (Tornos, 2006). The structure of the CZ, WALZ, CIZ, OMZ and SPZ has been studied through the ESCI-N, IBERSEIS and ALCUDIA experiments (Figures 4c and 4d). In these areas the Alpine inversion resulted mostly in localized faults and well-defined crustal imbrications, thus the data reflect a nearly complete crustal section of the late Variscan orogen. A main feature observed along the Iberian Massif is the poor coupling between the upper and lower crusts, resulting in different reflectivity patterns interpreted as the image of contrasting deformation mechanisms to accommodate shortening at both crustal levels (Simancas et al., 2003, 2013).

Throughout most of the Mesozoic, lithospheric extension in relation to the opening of the Atlantic Ocean and Bay of Biscay gave way to the formation of rift domains of hyperextended crust and exhumed mantle, and deep Cretaceous basins in the Pyrenean-Cantabrian realm (e.g., Ziegler, 1988; García-Mondéjar et al., 1996; Jammes et al., 2009; Pedreira et al., 2015; Tugend et al., 2014, 2015; DeFelipe et al., 2017; Ruiz et al., 2017). The mechanisms and geodynamic evolution of the Iberian

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Atlantic margin and Bay of Biscay were investigated with the pioneer IAM and ESCI-N projects, followed by the MARCONI initiative (e.g., Banda et al., 1995; Álvarez-Marrón et al., 1995a, b, 1996; Pulgar et al., 1995, 1996; Fernández-Viejo et al., 2011). These projects allowed mapping the offshore distribution of the North Pyrenean basins, to assess the lateral variations of the crust in the North Iberian Margin and to evaluate the inheritance of the extensional structures in the Alpine orogeny (Álvarez-Marrón et al., 1996; Fernández-Viejo et al., 1998; Ferrer et al., 2008; Roca et al., 2011).

From the Late Cretaceous to the Miocene, the Alpine convergence resulted in the tectonic inversion of the Mesozoic basins and mountain building (e.g., Muñoz, 1992; Teixell, 1998; Rosenbaum et al., 2002a; Teixell et al., 2016, 2018; DeFelipe et al., 2018, 2019). Figure 4b shows the crustal structure of the Cantabrian Mountains, the North Iberian Margin and the Duero basin. Seismic imaging in this area allowed interpreting a crustal thickening under the highest peaks of the Cantabrian Mountains, with the Iberian crust subducting towards the north (Pulgar et al., 1996; Gallart et al., 1997a; Pedreira et al., 2003, 2015; Gallastegui et al., 2016). More recently, Teixell et al. (2018) suggested the southwards subduction of the Bay of Biscay crust along the MARCONI-1 profile, although of probable limited extent at this longitude. Towards the west, along the IAM-12 profile, the oceanic crust of the Bay of Biscay subducts towards the south (Teixell et al., 2018). This subduction also imaged in the ESCI-N3.2 and ESCI-N3.3 profiles as inclined subcrustal reflections and diffractions (Ayarza et al., 2004).

Towards the south of the Iberian Peninsula, the Gibraltar Arc System comprises the Betic Cordillera and the Rif, the westernmost belt of the Alpine chains (Figure 3). It is a broad arcuate collision zone separated by the Alborán Sea that resulted from the convergence between the Eurasian and African plates since the Miocene. This area represents a complex tectonic scenario with periods of compression overprinted by extensional episodes and dextral strike-slip movements of the Iberian subplate (*e.g.,* Sanz de Galdeano, 1990; Carbonell et al., 1997; Rosenbaum et al., 2002b; Platt et al., 2013). The RIFSIS and SIMA projects investigated these areas, sampling the African lithosphere down to the Moroccan Atlas. The topography of the latter is too high when considering the context of limited orogenic shortening featured in this area. Volcanism and intermediate depth seismicity support a model where isostasy is not enough to maintain the orogenic load, thus dynamic topography must have played a key role (Ayarza et al., 2005; Teixell et al., 2007). The RIFSIS and SIMA experiments shed some light into the P-wave velocity structure of the lithosphere and the Moho topography on this large area improving existing models (Ayarza et al., 2010; Gil et al., 2014; Figure 4e).

4 DSS datasets

This section describes the DSS datasets hosted in SeisDARE, ordered by year of acquisition, which were acquired in different parts of the Iberian Peninsula and Morocco (onshore and offshore). Each subsection provides a description of the individual datasets and the most relevant references associated.

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4.1 ILIHA

The pioneer ILIHA (Iberian LIthosphere Heterogeneity and Anisotropy) project was acquired in 1989 and consisted of a star-shape arrangement of six long-range wide-angle reflection profiles covering the entire Iberian Peninsula. It was designed to study the lateral heterogeneity and anisotropy of the deep levels of the lithosphere of the Variscan basement in the Iberian Peninsula. The results of this project suggested a layered lower lithosphere which layering may penetrate to at least 90 km depth, contrasting with the heterogeneity of the Variscan surface geology (Díaz et al., 1993, 1996). The dataset is available in Díaz et al. (2020).

4.2 ESCI

The ESCI project (*Estudios Sísmicos de la Corteza Ibérica*-Seismic Studies of the Iberian Crust) was conducted to obtain multichannel deep seismic reflection images in three areas of the Iberian Peninsula (Figure 3): the NW of the Iberian Peninsula (ESCI-N), the Gulf of Valencia (ESCI-Valencia Trough), and the Betic Cordillera (ESCI-Betics).

4.2.1 ESCI-N

ESCI-N comprises four multichannel seismic experiments, some of them including also wide-angle reflection datasets. ESCI-N1 is an onshore profile that runs E-W through the Variscan structure of the WALZ and the CZ. ESCI-N2, also onshore, runs with a N-S orientation and was aimed to image the Alpine structure of the Cantabrian Mountains. ESCI-N3 is made up of three seismic lines that follow a swerved line in a mainly E-W direction in the Galicia and west Asturian offshore. Finally, ESCI-N4 runs in a N-S direction offshore (Álvarez-Marrón et al., 1995a, b, 1996, 1997; Gutiérrez-Alonso, 1997).

Beneath the CZ, ESCI-N1 shows the presence of a basal gently west dipping detachment identified as the Cantabrian Zone basal detachment. Towards the WALZ, a stack of thrust sheets probably affecting Precambrian rocks is placed above a crustal-scale ramp dipping to the west (Pérez-Estaún et al., 1994, 1997; Gallastegui et al., 1997; Fernández-Viejo and Gallastegui, 2005). The ESCI-N3 depicted a Moho offset between the CIZ and the WALZ, and the southward subduction of the oceanic crust of the Bay of Biscay as a consequence of Alpine shortening (Martínez Catalán et al., 1995; Álvarez-Marrón et al., 1995a, b, 1996; Ayarza et al., 1998, 2004). Furthermore, ESCI-N2 and ESCI-N4 revealed a crustal thickening beneath the highest summits of the Cantabrian Mountains interpreted as the northwards subduction of the Iberian crust under this mountain range (Pulgar et al., 1995, 1996; Fernández-Viejo and Gallastegui, 2005). The dataset is available in Pérez-Estaún et al. (2019).

4.2.2 ESCI Valencia Trough

The Valencia Trough is a NE-SW trending Cenozoic basin in the western Mediterranean Sea bounded by the Betic Cordillera to the southwest, the Iberian Chain to the west and the Pyrenees to the north (Figure 3). Different geodynamic models were proposed for the Valencia Trough during the 1980s and early 1990s, but there was a lack of agreement on its crustal structure

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and geodynamic evolution. Therefore, ESCI Valencia Trough was conducted to shed light on the structure of the western Mediterranean, providing for the first time a continuous image of this area. This experiment revealed that beneath the Valencia Trough, the crust is of continental type and strongly attenuated. The Moho is located at 17-18 km depth, thus being the strongest thinning reported so far in comparable passive margins (Gallart et al., 1994, 1997b). The dataset is available in Gallart et al. (1993).

4.2.3 ESCI Betics

The ESCI Betics dataset consists of two profiles in the southeast of Spain through the Betic Cordillera (Figure 3). The ESCI Betics 1 is a NW-SE oriented profile of 90 km that crosses the Guadalquivir basin, the external part of the Betic Cordillera and the Neogene-Quaternary basin at the limit with the internal zone. The ESCI Betics 2 profile runs across the emerged part of the Alborán domain with a NNE-SSW orientation for 106 km (Carbonell et al., 1997; Vegas et al., 1997). The main aim of this project was to image the structure of the crust, as well as to investigate the development of collisional structures, the response to extensional stresses in regions of recently thinned crust, and the correlation between the crustal structure and the distribution of seismicity in a tectonically active area (García-Dueñas et al., 1994). It provided the first complete structural transect of the northern flank of the Gibraltar Arc and the Alpine metamorphic complexes of the Betic Cordillera. The dataset is available in García-Dueñas et al. (1991).

4.3 IAM

The IAM (Iberian Atlantic Margin) project comprised 20 offshore reflection seismic profiles covering a total length of ~3,800 km. This project was set to study the deep continental and oceanic crusts in different parts of the Iberian Atlantic margin, thus sampling the north, west and south Iberian margins (Banda et al., 1995; Figure 3). The full dataset is available in Torné et al. (2018).

The IAM-12 crosses the North Iberian Margin with a N-S orientation from near the coastline to the central Bay of Biscay (Fernández-Viejo et al., 1998), revealing for the first time its crustal structure and the nature of its crust. The sedimentary infill of the abyssal plain is probably underlain by an oceanic basement (Álvarez-Marrón et al., 1997). The Moho is imaged as a subhorizontal reflection package located on land at 23-26 km (Córdoba et al., 1987) that features a rapid shallowing up to 15 km depth in the abyssal plain.

The West Iberian Margin is structurally divided in four zones: oceanic crust, peridotite ridge, transition zone and thinned continental crust. The crust decreases its thickness progressively to the west towards an oceanic crust of 6.5-7 km thick (Pickup et al., 1996; Sutra and Manatschal, 2012; Sutra et al., 2013). The peridotite ridge is a basement high that coincides with the eastward boundary of the seafloor-spreading magnetic anomalies (Dean et al., 2000). The transition zone has been interpreted as a tectonically exposed upper mantle extensively serpentinized that continues laterally to the continental crust.

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The Southern Iberian Margin has undergone a complex tectonic history through a sequence of Mesozoic rifting and collisional events associated with the Africa-Eurasia plate convergence (González et al., 1996). This area corresponds to the Azores-Gibraltar seismic zone and comprises two regions: the Gorringe Bank and the Gulf of Cádiz. The Gorringe Bank is characterized by an irregular topography and a large amplitude gravity anomaly (Souriau, 1984; Gràcia et al., 2003; Cunha et al., 2010). It consists of mafic and ultramafic plutonic and extrusive rocks covered by Aptian to Pliocene sediments (Tortella et al., 1997; Jiménez-Munt et al., 2010). On the other hand, the basement of the Gulf of Cádiz is a continental crust that thins progressively from east to west (González-Fernández et al., 2001). The transition from the continental crust of the Gulf of Cádiz to the transitional/oceanic crust of the Gorringe Bank, is imaged as a series of E-W oriented thrusts, folds and diapirs formed during the Cenozoic convergence (Tortella et al., 1997).

4.4 MARCONI

The deep seismic survey MARCONI (North-Iberian COntinental MARgin) was carried out to understand the processes that governed the evolution of the Bay of Biscay and to establish the lithospheric structure of its southeastern part (Gallart et al., 2004). It included the acquisition of eleven multichannel deep seismic reflection profiles with a total length of 2,000 km (Fernández-Viejo et al., 2011; Figure 3). This project imaged the sedimentary architecture in this part of the Bay of Biscay where no boreholes or direct geological data were available. The results of the MARCONI project confirmed the existence of compressive N-directed structures resulted from the Alpine orogeny developed at the foot of the continental slope, as well as the existence of NNE-SSW oriented transfer zones. Furthermore, it helped to identify the Cretaceous rift domains. The crust is interpreted to be transitional from continental to oceanic and highly thinned in contrast with the oceanic-type crust towards the west of 6°W, where the lateral termination of the seafloor spreading center is deduced from magnetic anomalies (Ferrer et al., 2008; Fernández-Viejo et al., 2011; Roca et al., 2011; Ruiz et al., 2017). The dataset is available in Gallart et al. (2019).

4.5 IBERSEIS

In the SW of the Spain, a NI profile and two WA seismic profiles were acquired in 2001 and 2003 respectively to image the southernmost part of the Iberian Massif in the framework of the IBERSEIS project (Figure 3).

4.5.1 IBERSEIS-NI

IBERSEIS-NI is a 303 km long NE-SW oriented deep seismic reflection profile designed to image the south of the Iberian Massif (Simancas et al., 2003, 2006) sampling three major tectonic domains: the SPZ, the OMZ and the southernmost part of the CIZ (Figures 3 and 4c). The high-resolution image obtained matched existing field cross-sections, suggesting the existence of left-lateral strike-slip displacements of Carboniferous age in the boundaries of the OMZ. The profile also provides an image of the boundary between the OMZ and the SPZ, which is formed by a complex accretionary prism of sediments and oceanic basalts. The limit between the OMZ and the CIZ is assembled as an accretionary wedge of high-pressure metamorphic rocks.

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Fold-and-thrust belts in the upper crust merge downwards in a decoupling horizon between the upper and the lower crust. In the OMZ and CIZ, a 175 km long thick band of relatively high amplitude, the Iberian Reflective Body (IRB), is interpreted as a layered mafic/ultramafic body intruded along a mid-crustal decollement. In all the transect, a horizontal Moho reflection at.10.5 s suggests a 30-33 km thick crust (Simancas et al., 2003; Carbonell et al., 2004; Simancas et al., 2006). The full dataset is available in Pérez-Estaún et al. (2001).

4.5.2 IBERSEIS-WA

The IBERSEIS-WA profile was acquired with the aim of providing constraints on the physical properties of the lithosphere beyond the results obtained in the IBERSEIS-NI profile. The IBERSEIS-WA project consisted of two transects running subparallel in a NE-SW to ENE-WSW direction. Transect A coincides with the trace of the IBERSEIS-NI profile and transect B was located farther to the east. Both transects join at their northern end. The main results of this project provided for the first time the P- and S-wave velocity models of the crust and upper mantle in this region. These experiments allowed modeling the density (Palomeras et al. 2011a) and the Poisson's ratio (Palomeras et al., 2011b), which provided an additional petrological description to estimate the crustal composition. Furthermore, it allowed locating the crust and mantle boundary at a depth of 31-33 km and to identify a subcrustal discontinuity at 66-70 km (Palomeras et al., 2009), later interpreted as the Hales discontinuity or gradient zone (Ayarza et al., 2010). The dataset is available in Palomeras et al. (2003).

4.6 ALCUDIA

The ALCUDIA dataset consists of two experiments, NI and WA, acquired in 2007 and 2012, respectively. These two experiments sample the CIZ from the boundary with the OMZ to the Spanish Central System in approximately NE-SW direction. It constitutes the northward prolongation of the previously acquired IBERSEIS seismic profiles (Figures 3 and 4c).

4.6.1 ALCUDIA-NI

ALCUDIA-NI is a 230 km long NE-SW profile that imaged the lithospheric architecture of the Variscan orogen from the northern boundary of OMZ to the Tajo basin (Martínez Poyatos et al., 2012). The processed ALCUDIA-NI seismic profile shows a Moho discontinuity at 10 s TWT (two-way time, *ca*. 30 km depth) that overlies a mantle where subhorizontal reflectivity was identified between 14 and 19 s TWT. The most prominent feature is a lower crust tectonic wedge in the southern segment of the transect, causing a local crustal thickening. The interpreted structures, as deduced from surface geology and the seismic image, show that deformation was distributed homogeneously in the upper crust, whereas it was concentrated in wedge/thrust structures at specific sectors in the lower crust (Martínez Poyatos et al., 2012; Simancas et al., 2013). The dataset is available in Pérez-Estaún et al. (2007).

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4.6.2 ALCUDIA-WA

The ALCUDIA-WA experiment aimed to constrain the lithospheric structure and resolve the physical properties of the crust and upper mantle in the CIZ. This profile has led to a well-constrained, 280 km long and 50 km deep P-wave velocity model. Its major contribution was to confirm the existence of an incipient crustal thickening in the Tajo Basin area, close to the south of the Spanish Central System (Ehsan et al., 2015). The dataset is available in Pérez-Estaún et al. (2012).

4.7 SIMA

SIMA (Seismic Imaging of the Moroccan Atlas) is a wide-angle reflection seismic experiment that runs through the Rif, Middle and High Atlas and the Sahara craton of Morocco. This project provided the velocity structure of the crust and the geometry of the Moho boundary. Final models image the Atlas limited crustal root, which is defined by the northward imbrication of the Sahara crust underneath the Atlas itself. The limited extension of the crustal root, further supports the need of dynamic topography models to explain the current Atlas topography (Ayarza et al., 2014). In addition, the low P-wave velocities obtained in the lower crust and mantle of the Middle and High Atlas were assigned to the existence of high temperatures and partial melts at these levels, probably a consequence of the Tertiary-to-present magmatic activity of the Atlas region due to mantle upwelling. These lower P-wave velocities might indicate slightly lower densities that could modify the existing gravity models (Ayarza et al., 2005). The SIMA dataset can be consulted in Ayarza et al. (2010).

4.8 RIFSIS

The RIFSIS wide-angle reflection seismic experiment consists of two E-W and N-S oriented profiles, 330 km and 430 km long respectively. This acquisition geometry was designed to target the significant low Bouguer anomaly associated with this mountain range (Hildengrand et al., 1998). This project also aimed to improve the geodynamic models of the Gibraltar Arc (Gil et al., 2014). Jointly, RIFSIS and SIMA provided a 700 km-long profile from the southernmost Iberian Peninsula to the northern Sahara Desert (Carbonell et al., 2013, 2014a). The RIFSIS dataset can be consulted in Gallart et al. (2011).

4.9 CIMDEF

The most recent wide-angle reflection experiment in the Iberian Peninsula was acquired as part of the CIMDEF project (Andrés et al., 2019). This project aimed to obtain a P-wave velocity model of the CIZ, including that of the Spanish Central System and the western part of the Duero basin. This profile was meant to fill the data gap between the ALCUDIA and IBERSEIS profiles in the south and the ESCI-N profiles in the north (Figure 3). The dataset was acquired along two time periods: the seismic survey carried out in 2017 consisted of two profiles, NNW-SSE and E-W oriented of *ca.* 275 and 135 km length respectively. The survey carried out in 2019 consists of a NW-SE 340 km long profile. This dataset, embargoed until 01/01/2024, is available in Ayarza and Carbonell (2019).

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5 High resolution seismic dataset

In the 2010s, high resolution reflection seismic experiments were focused on shallow subsurface targets. These high resolution experiments were acquired with different objectives, including reservoir characterization for carbon capture and storage (CCS), nuclear waste storage, mineral resource exploration and seismic hazard assessments. These experiments involved imaging with both controlled and natural seismic sources, and allowed obtaining images and velocity models of the subsurface, from approximately 50 to 2,000 m depth.

5.1 HONTOMÍN

To characterize the first Spanish research facility for geological storage of CO_2, a 3D reflection seismic experiment was carried out in Hontomín (Burgos, Spain, Figure 3). This area is located in the southwestern part of the Basque-Cantabrian basin (Figure 3), which developed as a thick Mesozoic basin, tectonically inverted during the Alpine orogeny (e.g., DeFelipe et al., 2018, 2019). This experiment targeted a saline aquifer located at 1450 m depth within Lower Jurassic carbonates with a main seal formed by interlayered Lower to Middle Jurassic marl and limestone. The 3D geological structure consists of an asymmetric dome crosscut by a relatively complex fault system (Alcalde et al., 2013a, b, 2014). This study set the basis for the first CSS pilot plant in Spain. The dataset, embargoed until 01/04/2022, is available in Alcalde et al. (2010).

5.2 VICANAS

The increased need of facilities for temporary and long-term storage of radioactive waste has encouraged new geological and geophysical projects to characterize the structure of suitable settings. Within the framework of the VICANAS project, four reflection seismic profiles and a 3D high-resolution seismic tomography survey were acquired in the Loranca Basin (Cuenca, Spain, Figure 3). The 2D seismic reflection profiles were intended to characterize the shallow subsurface (up to 1,000 m) at regional level, focusing on faults and fracture networks that could potentially affect the stability of the waste disposal site. The high resolution seismic tomography survey provided a full 3D P-wave seismic velocity image of an area of 500 x 500 m (Marzán et al., 2016; Martí et al., 2019). This experiment was specially designed to image the upper 100 m that directly interacts with the ongoing construction works. The seismic tomography results combined with geophysical measurements from boreholes and 2D electrical resistivity tomography profiles, provided a detailed mapping of the different lithology contacts that build up the sedimentary sequence filled up to 200 m of fluvial and lacustrine facies sediments (Álvarez-Marrón et al., 2014; Martí et al., 2019; Marzán et al., 2019). Within the scope of this project, Marzán et al. (submitted) reinterpreted the 3D high resolution seismic dataset to provide a more consistent 3D Vp model by integrating the resistivity model with well-log data. To jointly interpret these data, the authors developed a machine learning scheme that resulted in a 3D lithological model of a high degree of correlation with the known geology. The 2D reflection seismic dataset is available in Marzán et al. (2013) and the 3D high resolution tomography is available in Marzán et al. (2015).

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5.3 INTERGEO

The INTERGEO dataset aims to characterize the seismogenic behaviour of active faults in strike-slip tectonic contexts. The case study of this project is the Alhama de Murcia Fault (AMF), located in the Betic Cordillera (SE Spain; Figure 3). This fault was responsible of one of the most destructive recent earthquakes in Spain (9 fatalities, 300 injuries and serious damages), occurred in May 2011 in Lorca, with Mw 5.2 (Martínez-Díaz et al., 2012). This earthquake was triggered by a rupture area of 3×4 km along the AMF in a transpressive context. Thus, in order to image the complex structure in depth of the southwestern part of the AMF, six NW-SE oriented reflection seismic profiles were successfully acquired. The seismic reflection profiles and travel time tomography allowed identifying and characterize the contact between the Miocene-Pliocene detrital sediments and the basement and the internal structure of the AMF and its different branches (Gascón Padrón, 2016; Ardanaz et al., 2018). The dataset is available in Martí et al. (2015).

5.4 SOTIEL

Within the Raw Materials Program, the European Institute of Technology has encouraged the development of cost-effective, sustainable and safe research and innovation solutions for mineral exploration. Within this framework, the SIT4ME project has implemented seismic mineral exploration methods at a reduced cost, analysing the efficiency and capabilities of controlled source (e.g., reflection imaging techniques) and natural source (e.g., ambient noise interferometry) methods in mining areas. For this purpose, a multi-method seismic dataset was acquired in the Sotiel-Coronada mine in the Iberian Pyrite Belt (SPZ) to image a massive sulphide ore body intruded in volcanic and siliciclastic rocks at a depth of 300-500 m (Alcalde et al., 2019). This dataset, embargoed until 01/04/2022, is available in Alcalde et al. (2018).

6 Enlarging borders in DSS data sharing: COCORP Hardeman County, Texas

The Consortium of Continental Reflection Profiling (COCORP, http://www.geo.cornell.edu/geology/cocorp/COCORP.html) was a research group that pioneered seismic reflection profiling of the crust and upper mantle. COCORP worked during the 1970s and 1980s in the acquisition of more than 8,000 km of seismic profiling in the USA (Brown et al., 1987) and stimulated major deep seismic exploration programs in over 20 countries, such as ECORS in France, DEKORP in Germany or LITHOPROBE in Canada. COCORP demonstrated how seismic reflection information on the geological basement can contribute addressing questions in resource exploration (Brown, 1990). In its first experiment COCORP acquired 37 km of CMP stacked seismic reflection profiles in Hardeman County, Texas (Oliver et al., 1976; Schilt et al., 1981). These data imaged the Cambrian to Permian sedimentary rocks lying unconformably over a Precambrian basement intruded by relatively homogeneous igneous plutons (Oliver et al., 1976). Prominent upper basement layering first imaged in Hardeman County was later found to underlie much of the east central USA, perhaps representing major igneous intrusions on a continental scale (Kim and Brown, 2019). Furthermore, the COCORP Hardeman County proved the viability of using the VIBROSEIS

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technique to characterize the geological structure of the deep crust, resulting nowadays in a widespread technology of acquisition (Finlayson, 1975). The dataset of COCORP Hardeman County can be accessed in Oliver and Kaufman (1975).

7 Data availability

The SeisDARE is freely available at: https://digital.csic.es/handle/10261/101879 (last access: September 2020).

8 Conclusions and final considerations

Seismic reflection data (normal incidence and wide-angle) allow a high resolution characterization of the lithosphere, and set constraints on the structure and nature of the deep and shallow subsurface. The controlled source seismic data are useful not only in basic science but also in applied science, like in resource exploration and natural hazard assessment. DSS data are expensive and logistically complex to acquire, and often require a huge scientific effort involving several national and international research groups. The reproducibility of scientific results is dependent on the availability of data, which reinforces the paradigm of transparent and open access data-driven science as well as fosters innovation. Legacy data can be useful by itself or by applying the latest innovative processing techniques to generate new meaningful outputs. SeisDARE has been developed to facilitate the preservation and reuse of the existing data by future generations of geoscientists by hosting seismic data in the online institutional repository DIGITAL.CSIC. The SeisDARE database accomplishes the international mandates of open access data and the FAIR principles of data management. It is the result of a close collaboration between national and international institutions and encourages new networks to make seismic data easily available. Currently, SeisDARE contains 19 seismic datasets of DSS and high resolution data acquired since the 1980s in the Iberian Peninsula and Morocco. In addition, as a result of this internationalization effort we established a collaboration with the scientists that led the Consortium for Continental Reflection Profiling (COCORP) to host the pioneering Hardeman County dataset. All these datasets aimed to characterize different geological settings, ranging from the continental scale Variscan and Alpine orogens and the offshore Iberian Margins to exploration scale studies. The SeisDARE is being constantly updated and can be accessible via a web browser. It is free and open, bringing endless research and teaching opportunities to the scientific, industrial and educational communities.

Author contribution

IDF, JA, MI, DM, MR, IM, JD, PA, IP, JLFT, RR and RC worked on the data acquisition, compilation, collation and dissemination of the datasets. CM and IB provided the facilities to upload the datasets into DIGITAL.CSIC. LB provided with additional data to enlarge our database. IDF prepared the manuscript with contributions from all co-authors.

Competing interest

The authors declare that they have no conflict of interest.

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830 **Table 1: Seismic campaigns comprised in SeisDARE (DSS: deep seismic sounding; HR: high resolution). The location of the seismic datasets is shown in Figure 3.**

Dataset	Year	Seismic data	Onshore/offshore	Research target	Section
ILIHA	1989	DSS Wide-Angle	Onshore	Iberian Massif	4.1
ESCI	1991-1993	DSS Normal Incidence	Onshore and offshore	Iberian Massif Bay of Biscay Cantabrian Mountains Valencia Trough Betic Cordillera	4.2
IAM	1993	DSS Normal incidence	Offshore	Iberian Atlantic Margin	4.3
MARCONI	2003	DSS Normal Incidence	Offshore	Bay of Biscay	4.4
IBERSEIS	2001 and 2003	DSS Normal Incidence and Wide-Angle	Onshore	Iberian Massif (South Portuguese Zone, Ossa-Morena Zone and Central Iberian Zone)	4.5
ALCUDIA	2007 and 2012	DSS Normal Incidence and Wide-Angle	Onshore	Iberian Massif (Ossa-Morena Zone and Central Iberian Zone)	4.6
SIMA	2010	DSS Wide-Angle	Onshore	Rif Cordillera and Atlas Mountains	4.7
RIFSIS	2011	DSS Wide-Angle	Onshore	Rif Cordillera	4.8
CIMDEF	2017 and 2019	DSS Wide-Angle	Onshore	Duero basin, Central Iberian Zone and Tajo basin	4.9
HONTOMÍN	2010	HR Normal Incidence	Onshore	CO_2 storage site characterization	5.1
VICANAS	2014	HR Normal Incidence	Onshore	Nuclear waste disposal site characterization	5.2
INTERGEO	2015	HR Normal Incidence	Onshore	Quaternary seismicity in the Alhama de Murcia Fault	5.3
SOTIEL	2018	HR Normal Incidence	Onshore	Mining exploration in the Iberian Pyrite Belt	5.4

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COCORP Hardeman County	1975	DSS Normal Incidence	Onshore	Hardeman County (Texas, USA)	6

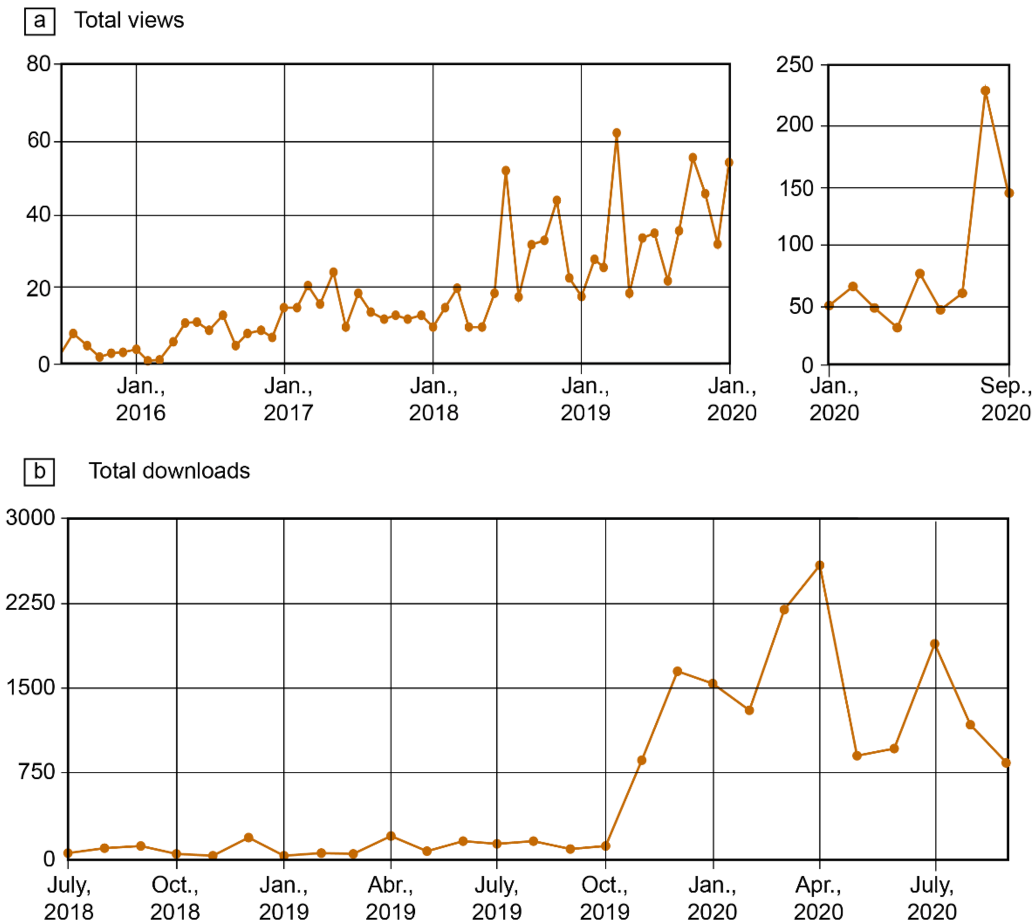

Figure 1: a) Total views (note the change of the vertical scale from January 2020 onwards) and b) total downloads of all datasets from the GEO3BCN database (https://digital.csic.es/handle/10261/101879, last access September 2020).

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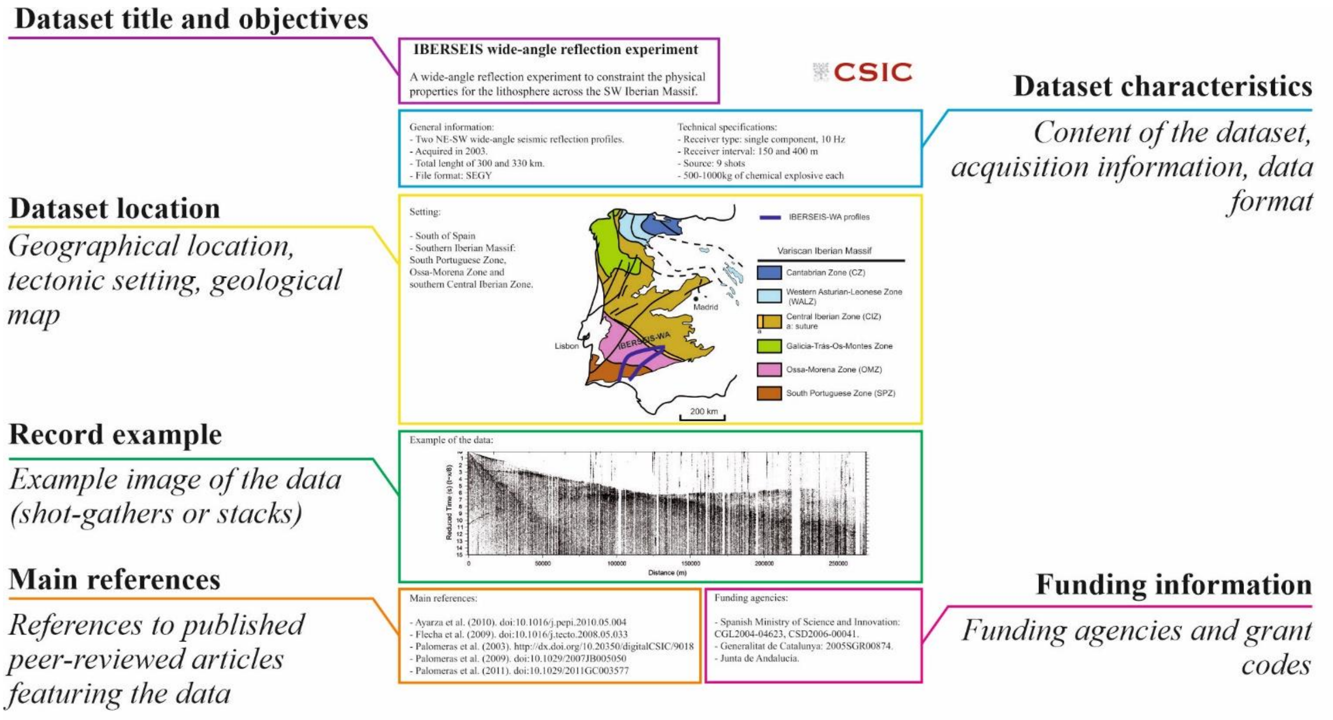

Figure 2: Example of the index card containing the IBERSEIS-WA project (section 4.5.2) information.

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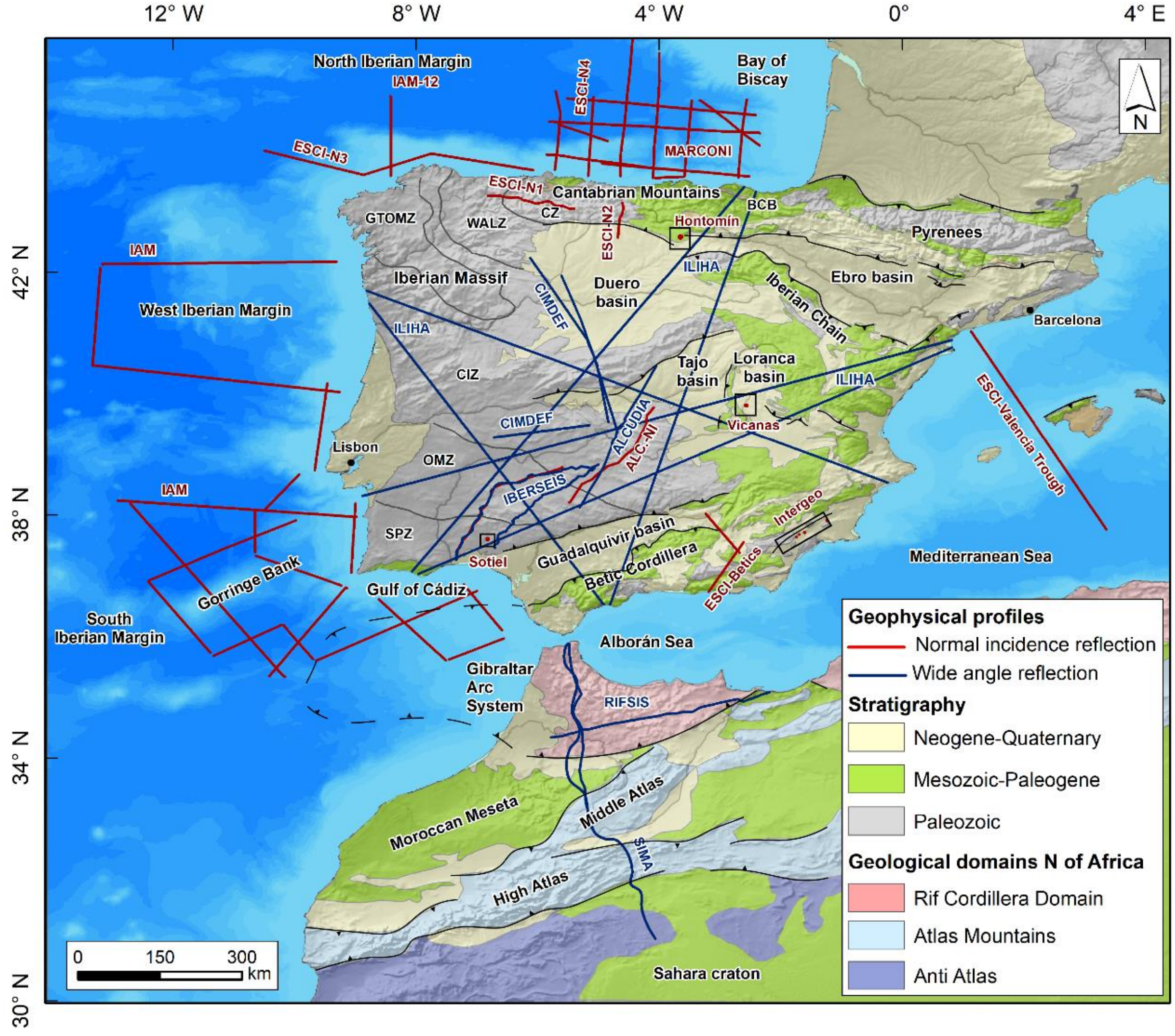

Figure 3: Geological map of the Iberian Peninsula and north of Africa with the seismic profiles provided in the SeisDARE. The geological units are simplified from the IGME Geological Map of the Iberian Peninsula 1:1.000.000 (Rodríguez Fernández et al., 2014). BCB: Basque-Cantabrian basin; CZ: Cantabrian Zone; WALZ: West Asturian Leonese Zone; GTOMZ: Galicia-Tras-Os-Montes Zone; CIZ: Central Iberian Zone; OMZ: Ossa Morena Zone; SPZ: South Portuguese Zone.

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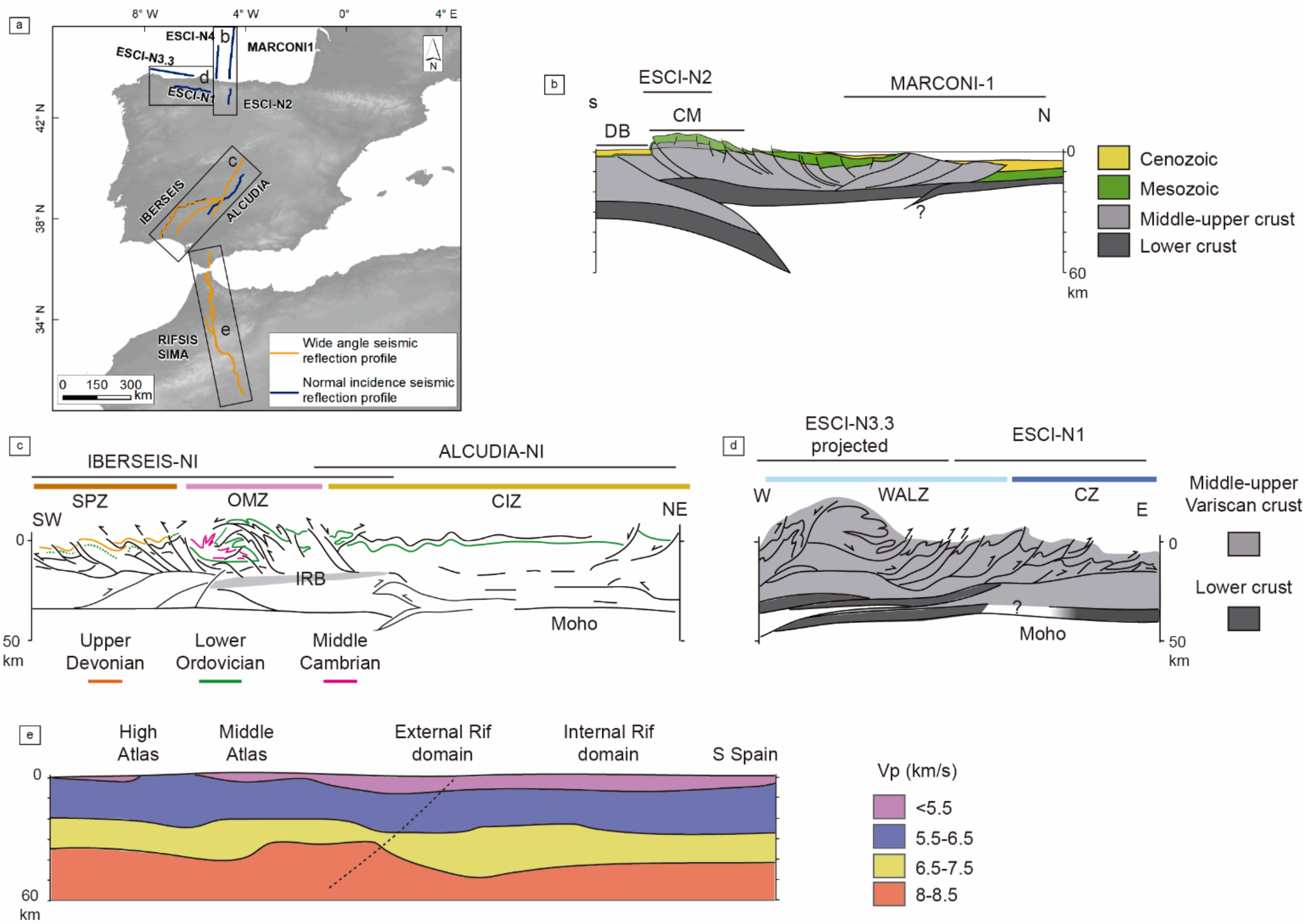

Figure 4: a) map of the Iberian Peninsula and north of Africa with the location of the ESCI-N, MARCONI 1, IBERSEIS, ALCUDIA, RIFSIS and SIMA projects; b) crustal structure of the Cantabrian Mountains (CM), Duero basin (DB), and Bay of Biscay based on ESCI-N and MARCONI data (after Pedreira et al., 2015; Gallastegui et al., 2016; Teixell et al., 2018); c) crustal structure of the southern Iberian Massif (SPZ: South Portuguese Zone; OMZ: Ossa Morena Zone; and CIZ: Central Iberian Zone; IRB: Iberian Reflective Body) revealed by the IBERSEIS and ALCUDIA projects (after Simancas et al., 2013); d) crustal structure of the northern Iberian Massif revealed by the ESCI-N1 and N3.3 profiles (after Ayarza et al., 1998; Fernández-Viejo and Gallastegui, 2005; Simancas et al., 2013); and e) P-wave velocity model obtain from the wide-angle reflection data of RIFSIS and SIMA (simplified from Ayarza et al., 2014; Gil et al., 2014).