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ORIGINAL ARTICLE

Petrophysical properties in the Iberian Range and surrounding areas (NE Spain): 1-density

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ABSTRACT
We introduce the first map of density data in Northeastern Spain which can help in the interpretation of gravimetric surveying. The background map is a simplified version of the Geode continuous geological cartography (scale 1:200.000) of the Iberian Range and Ebro basin. These maps are synthetic and homogeneous maps based on previous 1:50,000 scale geological maps (MAGNA). The map uses the ETRS89 datum and UTM coordinates (30T northern zone) and covers an area of 140,000 sq km. The compiled data shown in the map come from previous papers of the region (≈ 700 points) as well as from more than 800 additional points developed in the course of an exploratory project focused on the underground characterization of a potential CO_2 reservoir in the so-called 'Linking Zone'. The new data accomplish some basic criteria; they are accurately georeferenced and lithology, stratigraphic age and other technical details about the measurements (e.g. means and error) and methods are fully displayed.

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Potential fields; petrophysics; density; gravimetry; Iberian Range; Ebro basin

1. Introduction

Potential field geophysics can help in reconstructing the subsurface geometry of geological bodies provided that there are contrasts of some physical properties in the involved rocks (Clark, 1983, 1997; Henkel, 1976; Paterson & Reeves, 1985). Gravity and magnetization measurements (ground and airborne) depend on the location, size and shape of the geological bodies underneath as well as their petrophysical properties. Therefore, as the final target of geophysical modeling is to achieve an accurate subsurface reconstruction (Jessel, 2001), the petrophysical properties of the rocks play a key role. The density (ρ) measured in samples from outcropping rock bodies or from boreholes will have an impact in the gravimetric measurements, especially if this variable is contrasted with the surrounding masses. Similar influence can be expected from the susceptibility (κ) on the magnetic signal. Here, the magnetic remanence (NRM), if significant, may seriously modify the Earth's induction field, but this only happens with very limited rock types.

Unfortunately, the petrophysical information (ρ, κ and NRM) is very often poorly described in scientific papers or technical reports. In fact, it is usually scattered, scarce and many times opaque. Sometimes, it is introduced as frequency diagrams (by age or lithology) and therefore, many details and the raw information are missing. Petrophysical information can also be included in technical reports, usually from the oil and mining industries (well reports), but frequently, these files have restricted or difficult access. For all these reasons, many researchers working on potential field geophysics use standard data from handbooks (Carmichael, 1982; Kobranova, 1990).

More recently, some papers have established rules and protocols and/or have compiled petrophysical properties in certain regions (e.g. García-Lobón, Rey-Moral, Arias-Llorente, Cueto-Pascual, & Gómez-Paccard, 2003; García-Lobón, Rey-Moral, & Ayala 2006; Hemant & Maus, 2005; Rybakov, Goldshmidt, Rotstein, Fleischer, & Goldberg, 1999; Yang, Gao, Gu, Dagva, & Tserenpil, 2013). These databases, when the data are properly published (georeferenced, fully described, etc.), can be very useful in future studies since the petrophysical information can be reused and improved (especially if the data sets are maintained on a web server). The Geological and Mining Institute of Spain (IGME) has already established some basic criteria, and methodological workflows to build these databases (Plata Torres, 2009).

In this paper, we introduce the first cartographic compilation of density data from Northeastern Spain

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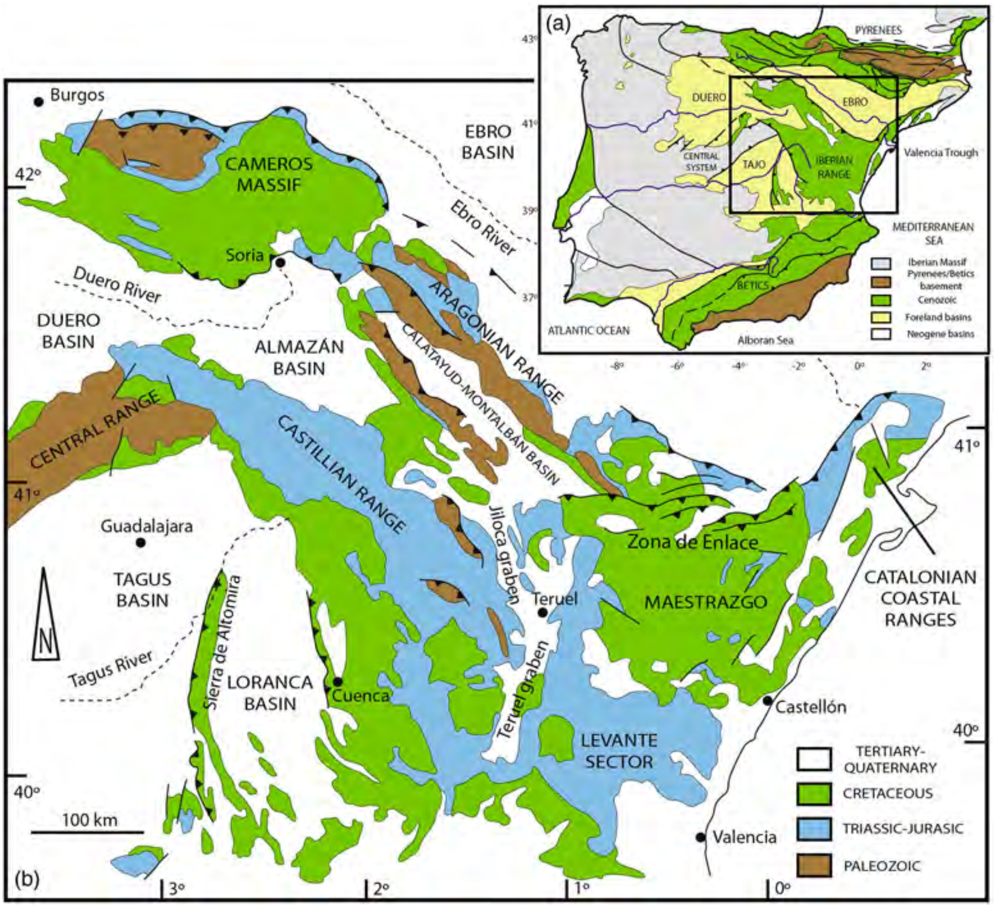

Figure 1. (a) Geological map of the Iberian Peninsula (modified from Rodríguez-Fernández, 2004 by Vergés & Fernàndez, 2006) with location of the Iberian Range. (b) Detailed map of the Iberian Range displaying the main geological units (modified from Liesa & Simón, 2009).

(Figure 1). It is planned to produce an equivalent database on magnetic properties (susceptibility and natural remanence). For the moment, we launch a pilot database centered in the Iberian Range but comprising also surrounding areas; large portions of the Ebro, Duero and Tagus Cenozoic basins as well as part of the Spanish Central Massif (Figure 1). The main goal is to bring together all previously published information (which implies a major effort in data homogenization) and to add new data derived from the exploration of a potential CO_2 reservoir where extensive potential field geophysics and petrophysics have been undertaken. This potential reservoir (PE-GE-06 in Pueyo et al., 2010) is located in the so-called Linking Zone (Guimerà 1984) between the Iberian Ranges and the Catalonian Coastal Ranges. Although the scope of the paper only focuses on the Iberian Range and surrounding areas, the compiled database can be used in many other regions of Spain since the Mesozoic and Cenozoic stratigraphic sequences (and related petrophysics) are very similar.

2. Data sets and methods

2.1. *Sources of the data*

Petrophysical data in the Iberian Range come from a limited number of papers. It is worth mentioning that some papers dealing with gravimetric surveying had not performed their own density measurements (Casas et al., 2000; Ernstson & Fiebag, 1992) and had used standard data or data from the literature (e.g. Carmichael, 1982). Similar problems affect large-scale interpretations of the gravimetric network (Fernández-Lozano et al., 2011; Gómez-Ortiz, Tejero, Ruiz, Babín-Vich, & González-Casado, 2005; Hernández-Moraleda & Bethencourt-Fernández, 2013; Mezcua, Gil, & Benarroch, 1996; Vergés & Fernàndez, 2006; and among others) partially because the scale and goals of these works allow the adoption of generic data from the literature.

The compilation of density data performed in this work derived from nine papers (≈700 measurements, Table 1) focused on six areas, as well as the outcrop samples taken during an ongoing large-scale gravimetric survey in the 'Linking Zone' (>800 measurements, Table 1), the region where the Iberian Range and the Catalan Coastal Range converge (Guimerà & Alvaro, 1990). Additionally, we also display the location of oil exploration wells where density logs are available (see available databases in www.igme.es). It is worth noting that significant effort was performed by the IGME to retrieve this information, scattered or inaccessible to the public.

Table 1. Sources of density data in the Iberian Range.

Area	# measurements and observations		References
Cameros-1	9	Density and sonic logs from Aldehuela and Demanda wells	Rivero et al. (1996)
Almazán	58	Density and sonic logs from El Gredal-1, Olmos and La Seca wells	Rey-Moral (2001) and Rey-Moral et al. (2003, 2004)
Duero basin and Castillian branch	75	Density and sonic logs from Olmos and La Seca wells. Additional surface measurements	Gómez-Ortiz, Tejero, and Babín (2003)
Cameros-2	510	All measurements from outcrop samples	del Río et al., (2013)
Herrera	39	All measurements from outcrop samples	Calvín et al. (2012, 2014)
Zona de Enlace-1	118	All measurements from outcrop samples	This work (Oliva-Urcia, Rodríguez-Pintó, and Pérez-Ortiz)
Zona de Enlace-2	356	All measurements from outcrop samples	This work (Izquierdo-Llavall)
Zona de Enlace-2	353	All measurements from outcrop samples	This work (Rodríguez-Pintó)
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Indeed, the first density data available in the Iberian Ranges come from two wells located in the westernmost sector; Demanda-1 and Aldehuela-1 (Rivero, Guimerà, & Casas, 1996, see location in The Map and well details in Lanaja, 1987) in the Demanda and Cameros ranges, respectively. Technical details are limited, the data were derived from sonic and density logs, and only a few data averages are shown in that paper without clarifying if they are means or individual measurements. The first data from outcrops and from another well (El Gredal-1; SHELL, 1982) also come from the western sector of the Iberian Range: the Cameros hills and the Almazán Basin (Rey-Moral, Gómez-Ortiz, & Tejero-López, 2003; Rey-Moral, Gómez-Ortiz, Sánchez-Serrano, & Tejero-López, 2004). These data where acquired as part of a PhD (Rey-Moral, 2001).

Additional data from the western Duero Basin, the Castilian branch of the Iberian Range as well as the Variscan basement (Spanish Central System) can be found in the work of Gómez-Ortiz, Tejero, and Babín (2003), Gómez-Ortiz, Tejero, Ruiz, et al. (2005) and Gómez-Ortiz, Tejero-López, Babín-Vich, and Rivas-Ponce (2005). Again, part of the data were obtained from two other wells; Olmos and La Seca but another 75 measurements came from samples taken in outcrops distributed in a large geographic region and a large stratigraphic pile. Unfortunately, the raw data are missing in the paper and only averages per geological period are displayed in the publication. Recently, the first massive density study in the Iberian Range was published and focused on the Cameros Basin (del Río et al., 2013). These authors studied more than a thousand samples, but the raw data and their locations were not published with accuracy. However, most of the sampling localities were recovered from this paper (purple dots in the Map). Calvín, Casas, and Villalaín (2012) and Calvín, Casas, Villalaín, and Tierz (2014) have introduced the first data from the central sector of the Iberian Range (Loscos area) including the first density data from volcanic rocks.

Finally, as part of a structural and geophysics study, hundreds of new data have been acquired in the eastern sector where the Iberian Ranges and the Catalan Coastal Ranges join: the Linking Zone. There, a large potential CO_2 reservoir is under investigation. A combined geophysical (potential fields) and structural (balanced cross-sections) study is in progress to tackle the 3D characterization of the reservoir. The uncertainty in the gravimetric modeling, due to insufficient petrophysical sampling (≈100 samples), motivated us to perform more ambitious petrophysical exploration. In total, we have achieved more than 800 new density data (sampled outcrops in the field, see location in the Main Map). The final goal of these efforts was to reduce the uncertainty in the 2D modeling of the gravimetric signal in combination with balanced cross-sections (Ayala et al., 2015; Izquierdo-Llavall et al., 2015).

2.2. *Methodology*

Density measurements in the IGME laboratories are performed by cutting the samples into regular cubes weighing between 0.3 and 0.6 kg. Then, they are weighed in air and water (Archimedes principle). The samples come from, at least, 2 kg of rock (usually between 4 and 5 kg) collected in the outcrop (García-Lobón et al., 2014; Plata Torres, 2009). The rock sampling strategy is intended to be representative of as much part of the geological unit as possible. Usually, between one and two cubes are obtained in each outcrop. A pseudo-log is built grouping the samples by age and lithology, in order to assess the variability of the physical properties within the geological domains along the stratigraphic sequences. Concerning borehole data, for example, in the Gredal well (SHELL, 1982), measurements were taken (Rey-Moral, 2001) every 25 m of the borehole providing a mean density for each geological unit down to the 1669 m at the end of the core (end of the well). In general, the availability of density logs improves the knowledge of the in depth density variation which reduces the uncertainties related to the geophysical modeling.

On the other hand, published density data from del Río et al., (2013) and Calvín et al. (2012, 2014) and most of the new density data gathered in this study were obtained in the laboratories of the Geotransfer Research Group of the University of Zaragoza. The

Table 2. Mean density data and other statistical parameters along different geological periods. Minimum (min) and maximum (max) numerical geological ages obtained from Gradstein and Ogg (2004).

Age	Min age	Max age		#	Min	Max	Sum	Mean	Median	RMS	Std Dev	Variance	Std Error	Skewness	Kurtosis
Quaternary	0	1	🟨	12	1,52	2,59	24	**1,99**	1,93	2,030	0,410	0,169	0,118	0,236	-1,496
Neogene	1	23	🟨	151	1,28	2,69	355	**2,35**	2,39	2,361	0,249	0,062	0,020	−1,161	1,652
Paleogene	23	65	🟧	174	1,63	2,73	420	**2,41**	2,45	2,419	0,178	0,032	0,013	−0,876	1,518
Tertiary	23	65		337	1,28	2,73	798	**2,37**	2,41	2,380	0,236	0,056	0,013	−1,345	2,376
Upper Cretaceous	65	100	🟩	62	2,27	2,72	162	**2,61**	2,66	2,615	0,109	0,012	0,014	−1,692	2,068
Lower Cretaceous	100	145	🟩	473	1,46	3,45	1195	**2,53**	2,60	2,535	0,205	0,042	0,009	−0,791	3,277
Cretaceous	65	100		535	1,46	3,45	1357	**2,54**	2,60	2,544	0,198	0,039	0,009	−0,903	3,561
Jurassic	145	200	🟦	116	1,55	2,80	305	**2,63**	2,67	2,631	0,157	0,025	0,015	−3,963	20,412
Keuper	200	229	🟪	70	1,54	2,90	159	**2,27**	2,21	2,294	0,335	0,112	0,040	0,083	−0,930
Muschelkalk	229	237	🟪	133	1,51	2,96	321	**2,41**	2,48	2,432	0,310	0,096	0,027	−0,480	−0,716
Buntsandstien	237	251	🟥	43	1,91	2,60	101	**2,34**	2,35	2,344	0,171	0,029	0,026	−0,626	−0,330
Triassic	200	251		246	1,51	2,96	580	**2,36**	2,34	2,378	0,304	0,092	0,019	−0,282	−0,710
Carboniferous-Permian	251	360	🟥	73	2,38	2,94	193	**2,64**	2,64	2,640	0,101	0,010	0,012	0,100	0,547
Silurian-Devonian	360	445	🟫	48	2,17	3,02	125	**2,61**	2,63	2,614	0,151	0,023	0,022	−0,479	2,605
Cambrian-Ordovician	445	545	🟩	115	2,37	3,50	309	**2,69**	2,69	2,693	0,109	0,012	0,010	3,239	24,832
Paleozoic	251	545		236	2,17	3,50	627	**2,66**	2,65	2,661	0,121	0,015	0,008	0,832	11,233
All data	0	545		1470	1,28	3,50	3668	**2,50**	2,57	2,507	0,244	0,060	0,006	−1,115	2,068

Note: Mean density values (bold character) in cgs units (g/cm^3). #: Number of data, Min and Max: minimum and maximum values observed, Sum: Addition of all considered data.

double weighing method was also used: the samples were first weighed in air (Wa) and then weighed while suspended in water (Ww, hydrostatic weighing) using a precision mass balance. From these two measurements, the density of the sample (ρ_S) was computed as

$$\rho_s = \mathrm{Wa}/(\mathrm{Wa} - \mathrm{Ww})\rho_w$$

Selected samples weighed between 10 and 60 g and had an average volume of 12 cm^3. High-porosity samples were first coated with paraffin wax to keep them dry during the hydrostatic weighing (Figure 2(b) and 2(c)). The weight of the paraffin wax was subtracted for the density calculation.

3. Map of density measurements (and database) in the Iberian Range

3.1. *Map technical information*

The geological map used to project the density data comes from the integration and simplification of the GEODE maps of the Iberian Range and the Ebro Basin (López-Olmedo et al., 2011; Robador-Moreno et al., 2011 respectively). GEODE is the Spanish acronym for the continuous geological map (1:50,000 scale); these maps are derived from the preceding 1:50,000 geological maps (known as MAGNA maps). There are 28 GEODE zones or geological provinces. For every one, a new key was set up after performing a detailed analysis of units, stratigraphy and chronology of all contained MAGNA sheets. The geographic information is projected in UTM coordinates (30T zone) and uses the ETRS89 datum. Digital sources and web visualizers of these maps can be found in the IGME web servers (http://cuarzo.igme.es/sigeco/ or in http://cuarzo.igme.es/geoveo2/).

3.2. *Density data*

Concerning the density data, the sampled outcrops together with the density data from wells cover almost the entire stratigraphic sequence (Figures 4 and 5) of the Iberian Range, from the Paleozoic basement to the Meso-Cenozoic cover units (Triassic, Jurassic, Cretaceous and Cenozoic sedimentary rocks). Although the Cretaceous rocks have a larger weight in the distribution (because of the Cameros basin studies), the rest of the periods have a similar representativeness, with the only exception being the Jurassic, which is slightly under sampled (Figure 3 and Table 2). On the other hand, the central sector of the Iberian Ranges is, by far, the poorest sampled area. Most of the data come from the western (Cameros-Demanda) and eastern (Linking Zone) sectors. However, this fact should not involve a bias in the defined properties because sedimentary units cropping out in the central sector of

Figure 2. (a) Some rock hand-samples after the second petrophysical survey (this work). (b and c) Measurements of the density in the laboratory at the University of Zaragoza.

the range are similar in lithology (although many of them are underrepresented because of stratigraphic hiatuses) to the more densely sampled sectors (Figure 3). Future studies should try to balance this disequilibrium.

Individual density values in the different stratigraphic units range from 1.28 g/cm^3 (Neogene conglomerates) to 3.5 g/cm^3 (Devonian, Fe-rich sedimentary quartzites) (see supplemental Table 3). The highest density values were obtained for Paleozoic metasedimentary and volcanic rocks, although some high values (>2.80 g/cm^3) were also observed in the Muschelkalk dolostones. The lower density values (<1.90 g/cm^3) were measured in the Upper Triassic layers, mainly formed by gypsum, shales and marls (Keuper facies), but also in Neogene conglomerates and Quaternary deposits.

Intermediate mean density values were defined for (1) the Cenozoic continental deposits that vary from conglomerates, sandstones and shales to lacustrine limestones and gypsum, (2) the Upper Cretaceous calcareous beds, (3) the Lower Cretaceous continental and marine sequences, (4) the Jurassic limestones and marls and (5) the Lower Triassic red sandstones and shales (Buntsandstein facies) and Middle Triassic dolostones (Muschelkalk facies) (Figure 5). Density histograms (Figure 4) show a higher clustering of data (see standard deviation in supplemental Table 3) in lithologically homogeneous units such as the Jurassic and Upper Cretaceous limestones. In contrast, bimodal or slightly scattered distributions were obtained for lithologically heterogeneous units such as the Muschelkalk (which is formed by two dolostone sequences with an interbedded unit made of gypsum and shales) and the Keuper (formed by gypsum, shales, marls and occasionally dolostones).

From the compiled data, a slight increase in density with age of rocks can be inferred, with an exception for the Triassic, whose average is well below the rest of units. It is also interesting to note the difference between the mean and the median, especially in units with a significant number of samples. The asymmetry of the histograms points to an influence of alteration, either by epidiagenesis or by weathering, thus indicating

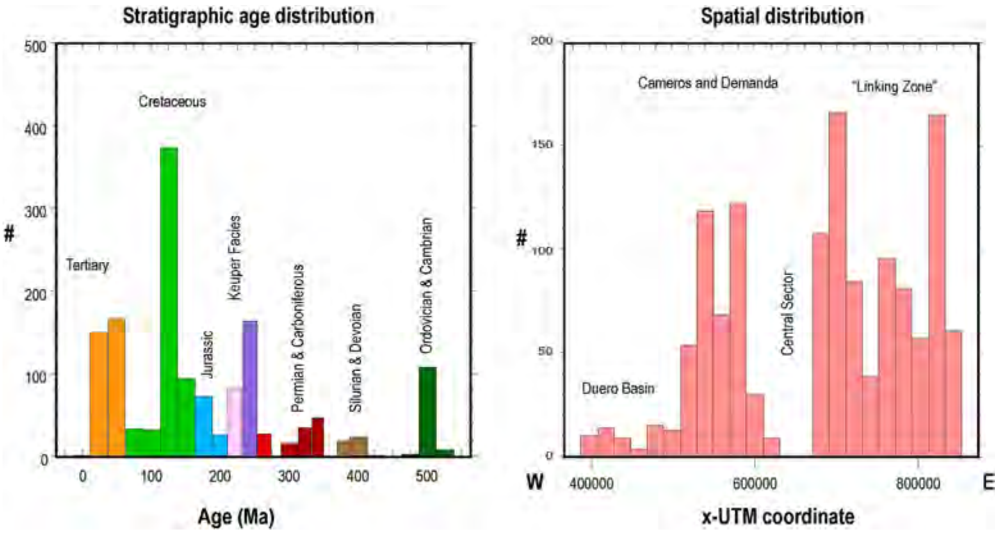

Figure 3. Geological age and spatial distributions of the Iberian Ranges database and map.

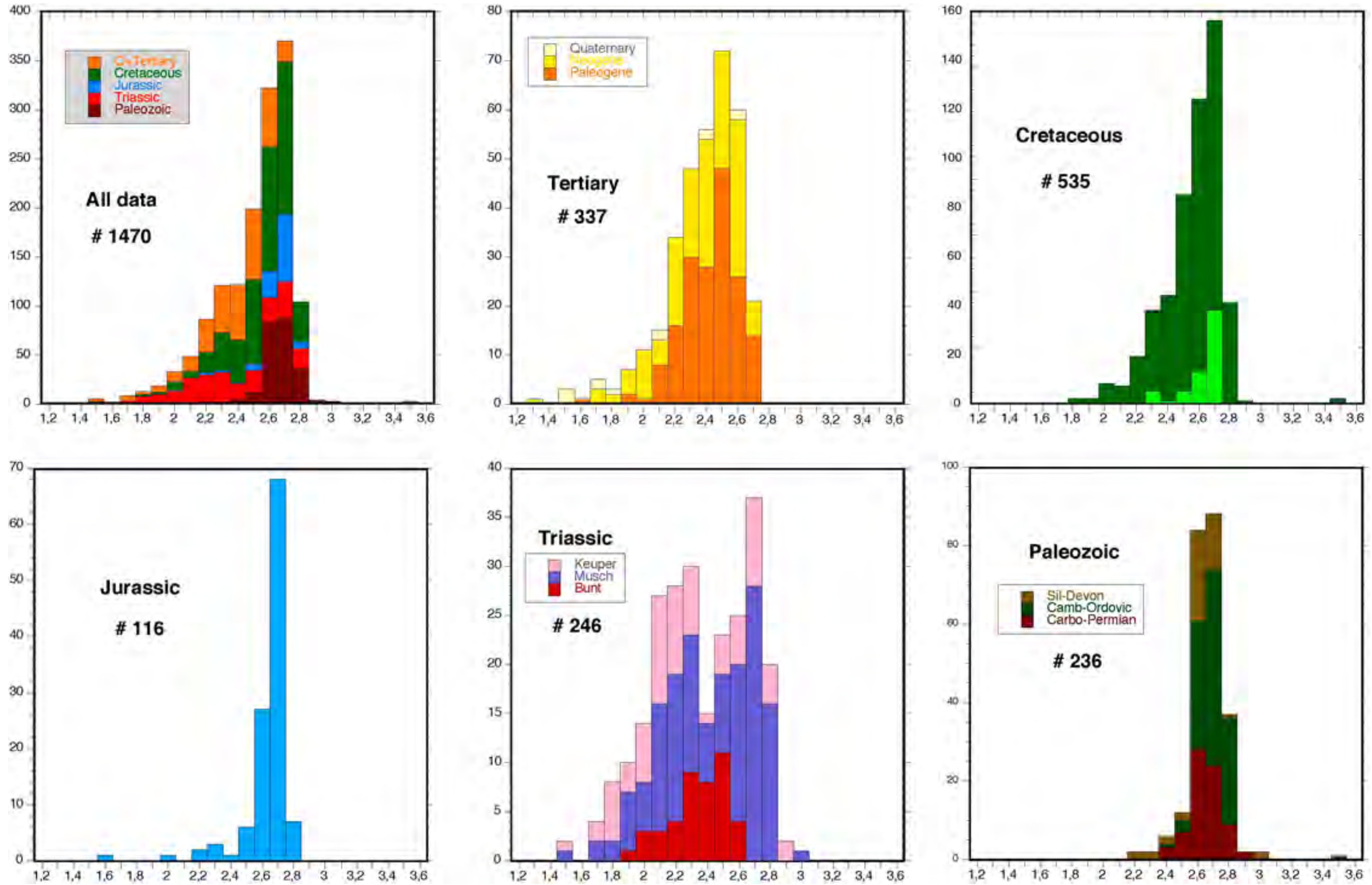

Figure 4. Density Histograms for different ages in the Iberian Range. Abscissa is the density in cgs units (g/cm^3) and ordinate is the number of samples. The Paleozoic is mainly formed by shales, sandstones and limestones, and includes abundant andesitic bodies. The Triassic is divided into three main units: the Buntsandstein sandstones and shales, the Muschelkalk facies, formed by two dolomitic sequences with an interbedded unit made of gypsum and shales, and the ductile Keuper layers, composed by red shales, gypsum and varicolored marls. The Jurassic and Upper Cretaceous consist of homogeneous sequences of marine limestones and dolostones, whereas the Lower Cretaceous includes both continental and marine deposits (shales, marls, limestones and sandstones). The Cenozoic is formed by continental units, which range from alluvial deposits (conglomerates, sandstones and shales) to lacustrine limestones and gypsum.

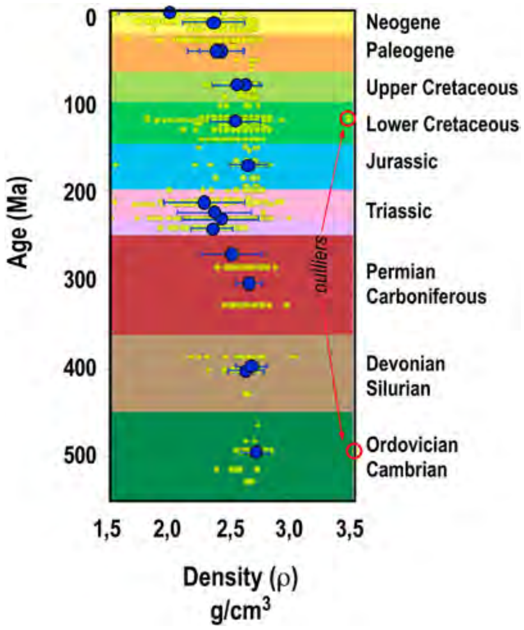

Figure 5. Pseudo-log of individual density data (and mean values with the corresponding uncertainty) versus the geological time scale (boundaries after Gradstein & Ogg, 2004).

that the median can be more representative of the properties of rocks at depth. The density contrast between the slightly denser Paleozoic basement, the bimodal Upper and Middle Triassic, the Mesozoic sedimentary sequences and the Cenozoic continental deposits account for residual gravimetric anomalies, usually ranging between 8 and –8 mGal, in the Iberian Range. In the Linking Zone, basement uplifts are generally related to positive gravity anomalies, whereas negative gravity anomalies are usually observed in areas where the Mesozoic and Cenozoic sedimentary units are thicker.

4. Conclusions

Aiming to produce a map displaying the location of measured density values (samples from outcrops or exploration wells), we have compiled numerous petrophysical data (only density in this map) from the Iberian Range and surrounding areas. These data were scattered in several scientific papers and technical reports. We have homogenized the information, redefining with the greatest accuracy possible the geopositioning of sampling points and re-processing part of data to serve robust and reliable density data. In addition, we have synthesized hundreds of data to provide averages with smaller uncertainty and histograms that will be useful for future studies (e.g. for potential field geophysics; gravimetry).

We suggest, for forthcoming published gravity or petrophysical data, that special attention should be given in the accurate geopositioning of the samples specifying projection system, coordinates and datum. The density data should be shown in full detail, including methodology, number of measurements per site, geological ages, lithologic and stratigraphic information, and so on; complete tables should be published together with the papers or reports (and preferably as supplementary online material). In this way, future online databases could be improved and the petrophysical stratigraphy more accurate.

As a final recommendation, we propose the potential use of paleomagnetic or AMS (magnetic susceptibility) samples to improve the petrophysical databases. Although the volume of these standard samples (≈ 10 cm^3) is smaller than petrophysical standards, the number of samples taken at the same outcrop (≈ 10–20) balances and guarantees the calculation of a reliable average. The main advantage is the easy calculation of density, since the standard paleomagnetic (or AMS) samples are cylinders with known dimensions (Ø2.5 cm * 2.04 cm height). An additional advantage is to calculate for every sample the three main petrophysical variables: density, magnetic susceptibility and remanent magnetization.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Software

The background geological map was produced using Esri ArcGIS. The original map leyend (from GEODE maps) was considerably simplified to produce the final background map (only a few stratigraphic horizons were chosen). Later on, a georeferenced jpg version of the map (ETRS89-UTM 30T zone) was used as the background layer in Quantum GIS; additional layers were added including wells and surface density data.

Supplemental data

Supplemental data for this article can be accessed at 10.1080/17445647.2015.1084545

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