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Bouguer anomalies of the NW Iberian continental margin and the adjacent abyssal plains

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ABSTRACT
The NW Iberian continental margin has a complex structure, resulting from the succession of several rifting episodes close to a ridge triple junction, and a superimposed partial tectonic inversion stage. The wide-ranging physiography matches the diverse tectonic deformation domains related to its evolution. Each deformation domain has a distinctive gravity signal, so the detailed Bouguer anomaly map presented here is a good first approach to the regional study of the whole margin. Moreover, as the presented chart is a complete Bouguer anomaly map (including terrain corrections), its analysis and interpretation can be done in terms of density, geometry and depth variations below the seafloor. This map is mainly based on the dataset obtained during seven one-month surveys carried out in the frame of the Spanish Economic Exclusive Zone project, and also includes two 2 + 3/4D density models illustrating the deep structure of the margin.

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1. Introduction

The use of the potential field methods for the analysis of the structure and geodynamics of the Earth's interior is widespread (e.g. Hinze, Von Frese, & Saad, 2013 and references therein). The gravity method allows to infer density distribution in the Earth's interior, identifying lateral variations (with density contrasts) resulting in gravity anomalies (e.g. Hinze et al., 2013; Jacoby & Smilde, 2009). In general terms, we consider a gravity anomaly as the difference between the measured gravity acceleration and the expected measure at a determined location, calculated from a theoretical model of the density distribution in the Earth's interior (e.g. the Geodetic Reference System). In general, gravity anomalies can be related to mass excess (positive anomalies), such as dense rocks, basement highs, mantle rises, etc., or to mass deficit (negative anomalies), such as sedimentary basins, thicker crust, etc. Thus, gravity anomalies allow the discrimination between continental and oceanic crustal domains, and can be used as a first approach to the location of basins with potential hydrocarbon reservoirs and the identification of prospective ore deposits. Further advantage of this method is that it allows the construction of 2D and 3D density models of the geometry and lateral density variations in the subsurface, properly constrained by other geophysical information like seismic data, geological mapping or wells. At sea, where geological and geophysical exploration expenses make difficult to accomplish broad detailed studies, this kind of geophysical analysis allow a low-cost first approach to the general structure of a region.

The sector of the NW Iberian continental margin is connecting the hyperextended west Iberian margin with the partially inverted margin to the north. The west Iberian margin has been extensively studied since the 80's decade of the past century as an archetype of hyperextended margin (e.g. Boillot, Winterer, & Meyer, 1988; Péron-Pinvidic, Manatschal, & Osmundsen, 2013; Whitmarsh, Sawyer, & Klaus, 1996). Also, many studies have been carried out along the north Iberian margin in order to understand the mechanisms and magnitude of the Cenozoic partial inversion (e.g. Álvarez-Marrón et al., 1996; Fernández-Viejo, Gallastegui, Pulgar, & Gallart, 2011). However, despite this, the transition between the west (extensional) and the north (compressional) margins has been scarcely studied to date (Druet et al., 2018).

The first gravity mappings in the NW Iberian margin were accomplished by Bacon, Gray, and Matthews (1969) and Bacon and Gray (1970). They presented Free-air anomaly maps, identifying diverse relative minimum and maximum, related to localized structures of the margin. Later, in the frame of the Deep

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Sea Drilling Program, a new Free-air anomaly map was published by Groupe Galice (1979), where they differentiate the gravimetric signal of the main morphotectonic regions of the continental margin. Nevertheless, Free-air gravity anomaly maps have high bathymetry (and topography) dependence and, for this reason, it is not possible to achieve a direct interpretation from them if the relief isn't taken into account. Conversely, using Bouguer anomaly maps offshore is much more significant from a geological point of view, especially if terrain corrections are applied (Jacoby & Silde, 2009). Only then, the Bouguer gravimetric anomalies can be interpreted in terms of density, geometry and depth variations of the different anomaly sources below the water sheet (Ball, Eagles, Ebinger, McClay, & Totterdell, 2013; Carbó, Muñoz, Llanes, & Álvarez, 2003). Recently, Druet et al. (2018) made a detailed gravimetric analysis from the Bouguer anomaly data of the NW Iberian margin, including spectral analysis, Bouguer anomaly grid filtering, and gravity modeling.

1.1. Geological setting

The NW Iberian margin was originated by the northward propagation of the North Atlantic Ocean opening. Several rift pulses underwent in this margin from Late Jurassic (~150 M.a.) to Early Cretaceous times (~120 M.a.) (e.g. Murillas et al., 1990), including a westward rift axis jump (Manatschal & Bernoulli, 1999), in the vicinity of a triple ridge junction connecting the west and north Iberian margins. As a result of this staged rifting, there is an along-strike segmentation of the margin, as well as an across-strike succession of the different deformation domains related to the rift process (Druet et al., 2018). Since Late Cretaceous (~85 M.a.) to Oligocene-Miocene times (~23 M.a.), the Alpine compressional stress field led to a partial tectonic inversion of the north Iberian margin (De Vicente et al., 2008; Thinon, Fidalgo-González, Réhault, & Olivet, 2001; Tugend, Manatschal, & Kusznir, 2015). The effects of this later compressional episode clearly extend to the northern sector of the west margin (Grimaud et al., 1982; Murillas et al., 1990), partly overriding the former extensional deformation domain succession (Druet et al., 2018).

The result of the complex tectonic history of the margin is a wide-ranging physiography (Figure 1). This intricate orography matches the succession of the different tectonic deformation domains related to the evolution of the margin. In this connection, along the margin we can identify (Figure 1): (1) a marginal basin (the Galicia Interior Basin) whose origin is related to the former rift axis active during the first extensional episode (e.g. Murillas et al., 1990; Pérez-Gussinyé, Ranero, & Reston, 2003); (2) a seamounts region, that is a horst area between the Galicia Interior Basin aborted rift axis and the westward final rift axis location, and locally uplifted (to the north) under the later Alpine compressional regime (e.g. Druet et al., 2018 and references therein); (3) the named Deep Galicia Margin, where hyperextension and mantle exhumation occur (e.g. Whitmarsh, White, et al., 1996; Lymer et al., 2019); (4) a marginal platforms region to the northwest of Galicia, resulting from the tectonic inversion of former half-graben basins (Druet et al., 2018; Murillas et al., 1990); (5) the Iberia abyssal plain, surrounding the margin to the west, and (6) the Biscay abyssal plain, to the north and northwest. These deformation domains are related to different crustal thickness and crustal type distribution, having distinctive gravimetric signal along the margin (Druet et al., 2018). Thus, the detailed Bouguer anomaly chart that we present here is a good first approximation to address a regional study of the whole margin and to characterize its deep structure.

2. Data set and methods

2.1. Data acquisition and processing

The systematic oceanographic surveys carried out in the frame of the Spanish Exclusive Economic Zone Project (SEEZ) provide an unprecedented detailed mapping of the whole NW Iberian continental margin and its adjacent abyssal plains. The marine datasets we use here were obtained during seven one-month cruises, carried out between 2001 and 2009 (ZEEE2001, ZEEE2002, ZEEE2003, ZEEE2006, ZEEE2007, ZEEE2008, and ZEEE2009), onboard the R/V Hespérides. A total amount of 16,620 nautical miles were navigated with gravity data acquisition, with more than 400,000 valid data points obtained (Figure 2). As the main objective of the SEEZ surveys is to obtain multibeam swath bathymetry with 100% coverage of the seafloor, the survey lines are planned according to the multibeam requirements. As a result, the spatial distribution of the gravity measurements is not uniform, with an irregular spacing and variable orientation of the surveyed lines (Figure 2).

During the surveys, time and position information was acquired via a differential GPS, using two TRIMBLE 4000 DL systems. Heading and velocity data were provided by the vessel's navigation system. Gravity data were obtained with a Bell Aerospace Textron BGM-3 marine gravity meter, with ± 1 mGal accuracy, mounted on a gyro-stabilized platform damping ship's movements. At each marine survey, the gravity data were tied to the on land gravity network using the first-order absolute gravity bases from the Instituto Geográfico Nacional of Spain, using two terrestrial gravity meters: a Lacoste & Romberg (model G) and a Worden Master. During the tying works for the ZEEE2001, ZEEE2003 and ZEEE2003 cruises, both terrestrial gravity meters were used simultaneously.

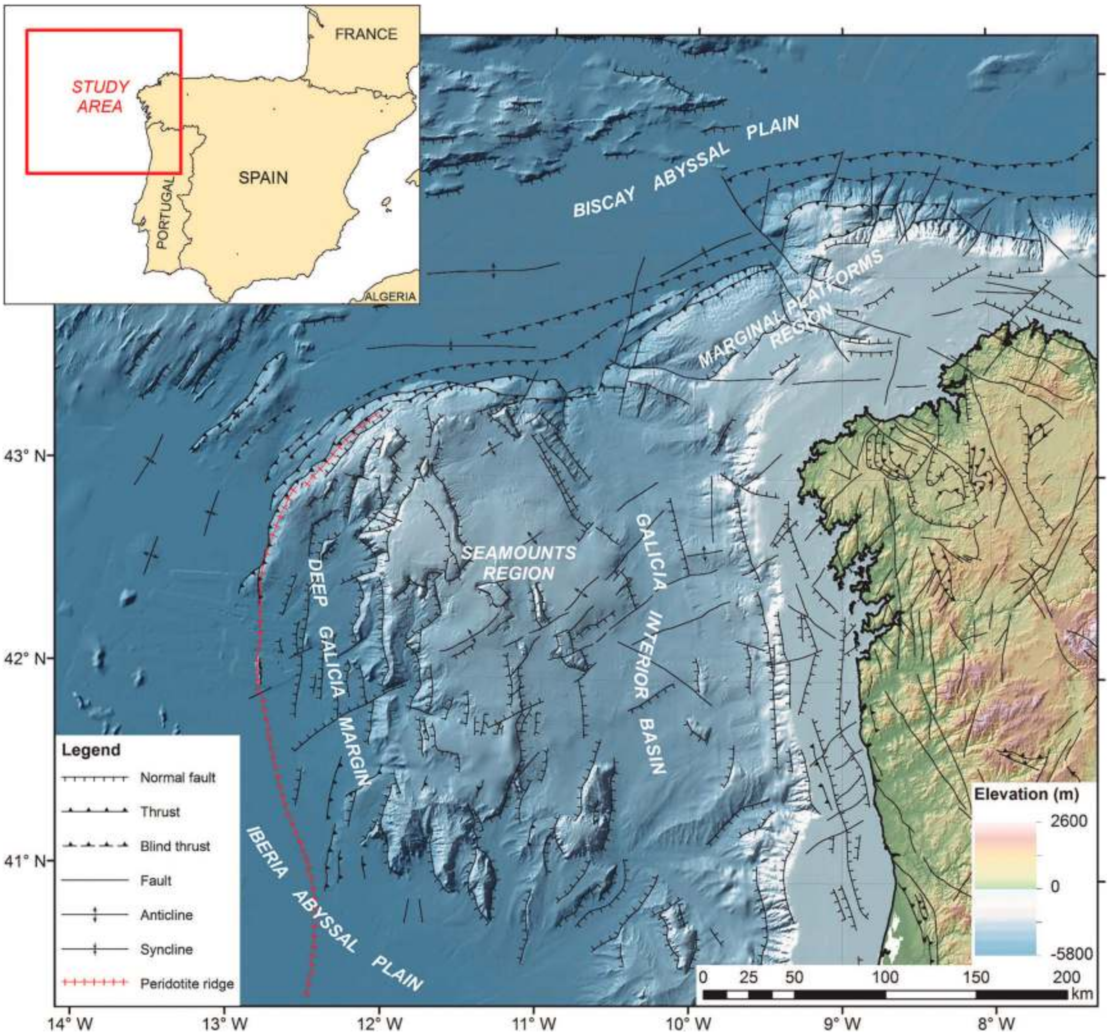

Figure 1. Structural sketch of NW Iberia, over the digital terrain elevation models from the EMODnet (offshore) and SRTM (onshore) open databases. Modified from Groupe Galice (1979), Boillot et al. (1988; 1995), Grimaud et al. (1982), Murillas et al. (1990), Malod, Murillas, Kornprobst, and Boillot (1993), Álvarez-Marrón et al. (1996), Ramírez et al. (2006), Vázquez et al. (2008), Druet (2018), and Druet et al. (2018). Inset: Location of the study area represented on the Main Map.

Meanwhile, for the ZEEE2006, ZEEE2007, ZEEE2008 and ZEEE2009 cruises, only the Worden Master terrestrial gravity meter was used for this issue. Depending on the origin and arrival ports, the first-order absolute gravity bases used were those located in La Coruña, Vigo, Santander and Cartagena, following the procedure described by Carbó et al. (2003). The error estimations during the tying works were always below 0.5 mGal.

Dataset reduction was executed with the GRS67. The Eötvos effect was corrected taking into account the navigation data (date, time, speed, course …) during the marine gravity acquisition. Solid Earth-tide effects, due to the moon and sun tidal accelerations, were corrected using Longman's formulations (Longman, 1959). For the water slab correction, we have followed Nettleton's procedure (Nettleton, 1976), using 1.03 g/cm^3 for the water density. The gravity effect related to the sea-bottom relief must be corrected also, especially in areas with large bathymetric variations, so that the final Bouguer anomaly reflects the density distribution at the sea bottom, without the bathymetry variations influence. The sea-bottom correction was applied using the dedicated software LANZADAF (Carbó et al., 2003). Sea-bottom correction was carried out up to a distance of 22 km from the gravity measure, using a 2 km-gridded digital terrain model (Sandwell, Müller, Smith, Garcia, & Francis, 2014). In order to correct herringbone effects and intersection errors related to the systematic acquisition during the oceanographic surveys, a statistical leveling correction was also applied using the Geophysics Leveling extension of the Geosoft Oasis Montaj^{TM} software. Here on, it should be noted that when we use the term 'Bouguer anomaly' we refer to a complete Bouguer anomaly, as sea-bottom and topographic corrections have been included.

Where no ship gravity data are available offshore, we have used the satellite altimetry-derived Global Gravity Model data (Sandwell et al., 2014). The parameters used to reduce satellite derived data have been those used in the corrections made to marine data. In order to compare the accuracy of the marine and satellite altimetry derived datasets, and to evaluate the resolution

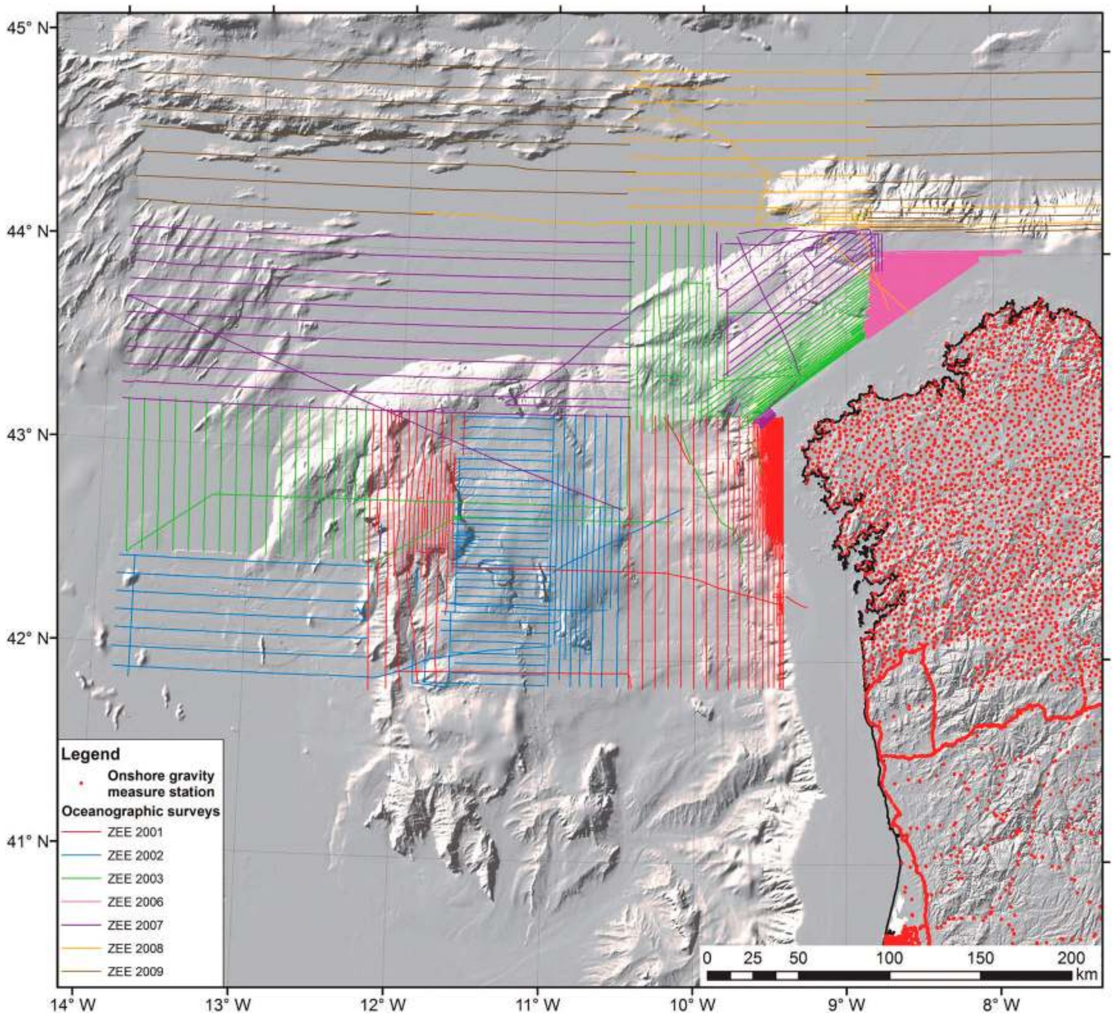

Figure 2. Ship navigation lines with gravity data acquisition during the different surveys, and on land station locations, over the shaded relief model obtained from EMODnet (offshore) and SRTM (onshore) open datasets. Modified from Druet et al. (2018).

improvement when using marine gravity data, a coherency analysis was performed (Druet et al., 2018). It showed that, for wavelengths lower than 20 km, the coherence between both datasets diminish, and satellite altimetry derived dataset loose in accuracy.

In order to prepare the complete map off the NW Iberian margin, we have included onshore gravimetric data from the Instituto Geográfico Nacional of Spain, the Empresa Nacional de Residuos Radiactivos of Spain, the Bureau Gravimétrique International, and the Instituto Geológico y Minero de España databases (Ayala et al., 2016; Álvarez, 2002) (Figure 2). Finally, ship, on land, and satellite-derived data were jointly processed and included in a georeferenced database. The final regular grid was calculated with the continuous curvature splines in tension method (Smith & Wessel, 1990) using GMT software (Wessel, Smith, Scharroo, Luis, & Wobbe, 2013), with a tension parameter of 0.25 and 2 min interval regular grid. The map presented here covers an area of 306,000 km^2 between parallels 40° 17′ N and 45° 11′ N and meridians 7° 13′ W and 14° 29′ W.

Additionally, in order to facilitate the Bouguer anomaly map interpretation, two 2 + 3/4D density models have been performed from Bouguer anomaly profiles. They are partially constrained by refraction and reflection seismic data (Clark, Sawyer, Austin, Christeson, & Nakamura, 2007; Druet et al., 2018; Ercilla et al., 2008; González, Córdoba, & Vales, 1999; Murillas et al., 1990; Sibuet et al., 1995; Reston, Krawczyk, & Klaeschen, 1996; Whitmarsh, White, et al., 1996). These density distribution models have been calculated using the Geosoft GM-SYS profile modeling software. For the conversion from seismic velocities to densities, we have used the empiric relationship curves by Ludwig, Nafe, and Drake (1970), Barton (1986), Christensen and Mooney (1995) and Brocher (2005).

2.2. Data plot

The Bouguer anomaly map of the NW Iberian continental margin and the adjacent abyssal plains (see Main Map) is a composite sheet made of three maps (a main map, and two auxiliary maps), and two 2 + 3/4D gravity models representative of the deep structure of the margin.

The main map represents the Bouguer anomaly at a 1:750,000 scale, color shaded with an artificial illumination from an azimuth of 315° and an elevation of 45°. The first of the two complementary maps (Figure 2) shows the track lines with gravity data acquisition during the marine surveys, and the onshore gravity stations, over a composite digital terrain model constructed from the European Marine Observation and Data Network (EMODnet, offshore) and Shuttle Radar Topography Mission (SRTM, onshore) open databases. Besides, the second auxiliary map shows the Bouguer anomaly grid (colored) over the same shaded relief, with the tectonic interpretation of the main features (see tectonic interpretation on Figure 1).

The first gravity model, A-A′ (see location on the main Bouguer anomaly map), crosscuts the west Iberian margin from West to East, and is representative of the deep structure of this hyperextended margin (Druet et al., 2018). The second one, B-B′ (see location on the main Bouguer anomaly map) is a North to South model crossing the margin from the Biscay abyssal plain north of the seamounts region, showing the partial tectonic inversion in this area, to the hyperextended margin of south the Iberia abyssal plain (Druet et al., 2018).

3. Brief Bouguer anomaly map description and interpretation

Bouguer anomaly values range from −105 mGal (onshore) to 385 mGal (offshore, on the Iberia abyssal plain region). On the whole, there is a progressive rise of the Bouguer anomaly values to the north and to the west, that is to say, from the continental crust region to the oceanic crust regions of the Iberia abyssal plain and the Biscay abyssal plain (commonly over 300 mGal). The 100 mGal contour approximately matches the continental shelf break. Along the Galicia Interior Basin, a relative Bouguer anomaly high is found (up to 250 mGal), linked to the thinned continental crust and the related mantle rise in this region (Druet et al., 2018; Pérez-Gussinyé et al., 2003), where extensional tectonics focused during the first rifting stages (Murillas et al., 1990). Westwards, the seamounts region is linked to a relative minimum of less than 150 mGal, due to its relatively thicker continental crust. The transition to the domains of Deep Galicia Margin and the Iberia abyssal plain, where necking and hyperextension domains are well developed, is marked by steep Bouguer anomaly gradients ranging from 2.8 to 3.6 mGal/km. Conversely, the transition to the Biscay abyssal plain oceanic domain is staggered and complex, with Bouguer anomaly gradients ranging from 0.7 to 1.2 mGal/m, due to the effects of the compressional tectonics in this area (Druet et al., 2018; Grimaud et al., 1982). These compressional tectonics effects include oceanic crust thrusting at the foot of the slope to the N and NW of the seamounts region, the generation of foredeep basins, and the partial tectonic inversion of half-graben basins in the marginal platforms region.

4. Conclusions

The new Bouguer anomaly map of the NW Iberian continental margin and the adjacent abyssal plains presented here is built upon an improved gravity database, bringing together marine, on land, and satellite-derived gravity measurements. The map is represented at a 1:750,000 scale, using a 2 min-interval squared regular grid.

This Bouguer anomaly map covers a high geological interest area, with the best accuracy ever attained to date. A great advantage of gravity anomaly maps as this one is the continuous nature of the information that they show. This allow mapping geological domains and regions at different scales, including deformational domains as those occurring along the hyperextended and partially tectonically inverted NW Iberian continental margin.

The use of this new Bouguer anomaly map enables geoscientists from academia, research institutions and industry to perform a first approach to interest zones, following the evident relationship between the main deformation domains in the margin and the observed Bouguer anomaly.

Software

Marine gravity data were corrected using the dedicated software LANZADAF (Carbó et al., 2003) and Oasis Montaj^{TM} from Geosoft. The marine dataset was merged with the onshore and satellite-derived data to calculate a final regular grid using GMT software (Wessel et al., 2013). The three maps showed on the final chart (Main Map and complementary ones) were constructed using ArcGIS, with a customized rainbow color-coded scale to represent Bouguer anomaly values. Gravity modeling was accomplished using Geosoft GM-SYS software. The final layout was performed with CorelDraw.

Data availability statement

NW_Iberia_BouguerAnomaly_2019.tif is a downloadable geotiff file of the Bouguer anomaly (mGal) information, with a 2′ × 2′ cell spacing in a UTM 29N projection (WGS84 datum).

Geolocation information

The map and dataset presented are located between parallels 40° 17′ N and 45° 11′ N and meridians 7° 13′ W and 14° 29′ W.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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