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Statistical analysis of the oceanic magnetic anomaly data

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ABSTRACT

The study of the statistical properties of ocean magnetic anomalies could be very important to obtain new understanding on plate tectonics, especially about the past properties of the lithospheric oceanic plates. Here we analyse in terms of statistical distributions the ocean magnetic anomaly data at the global scale covering the crustal oceanic ages from the present to 180 Ma. Our results show that the marine magnetic anomaly data follow the Laplace statistical distribution. This behaviour is observed at global scale and for any time interval within the last 180 Ma. In addition, the statistical parameters of the Laplace distribution are used to define some properties of the crustal oceanic magnetic field, focusing our investigation on the Cretaceous Normal Superchron. Finally, we also provide a physical explanation of this statistical distribution of marine magnetic anomaly data using a test with synthetic data.

1. Introduction

Plate tectonics has been one of the major revolutions in Science (e.g. Condie, 1997). Its discovery and development have allowed the researchers to get a greater understanding of the Earth's interior, in particular, how its outer parts, the outermost rigid lithosphere, and the underneath ductile asthenosphere, interact each other in a complex way, causing mostly horizontal and vertical movements of the lithospheric plates (e.g. Turcotte and Schubert, 2002). We can classify the lithospheric plates in oceanic and continental, or transitional. Additional understanding of plate tectonics has come from the study of the ancient Earth's magnetic field (e.g. Merrill et al., 1996). It is also expected that an in-depth study of the oceanic magnetic anomalies could be of great help in revealing additional properties of the lithospheric plates, and in general of the plate tectonics.

The lithospheric magnetic field is due to the magnetic sources in the lithosphere, which are confined to a magnetized ca 10–50 km-thick layer, depending also on the Curie isotherm. We use the term "lithospheric" for this kind of magnetic field, instead of simply "crustal", because of the possibility of a magnetic field produced in the upper mantle (Langel and Hinze, 1998), so following the nomenclature accepted by the geomagnetic/paleomagnetic community referring to these magnetic anomalies or geomagnetic models based on these data as lithospheric magnetic anomaly (Schubert, 2007) or lithospheric models (e.g. Maus, 2010), respectively. The magnetization of the lithospheric rocks presents two different origins: a) the induced and viscous magnetizations with temporal variations similar to those of the main geomagnetic field (with a possible temporal delay), and b) the remanent magnetization caused during the geological formation of the lithosphere or produced by other physical and chemical phenomena. The latter magnetization is relatively stable on geological times.

During recent years, numerous studies have been developed to analyse in detail the magnetic lithospheric data generating different theoretical lithospheric magnetization models (e.g., Gubbins et al., 2011; Masterton et al., 2013), spherical harmonic field models (e.g., the NGDC-720 global model by Maus, 2010), magnetic anomaly maps (e.g., EMAG2 by Maus et al., 2009) or magnetic anomaly compilations (e.g., Quesnel et al., 2009). However, although many studies have dealt with the statistical properties of the lithospheric magnetic field (e.g. Jackson, 1990, 1994; Maus et al., 1997; Voorhies, 1998; Voorhies et al., 2002; Thébault and Vervelidou, 2015; O'Brien et al., 1999; Korte et al., 2002) much less attention has been paid to the Laplacian characteristics of the

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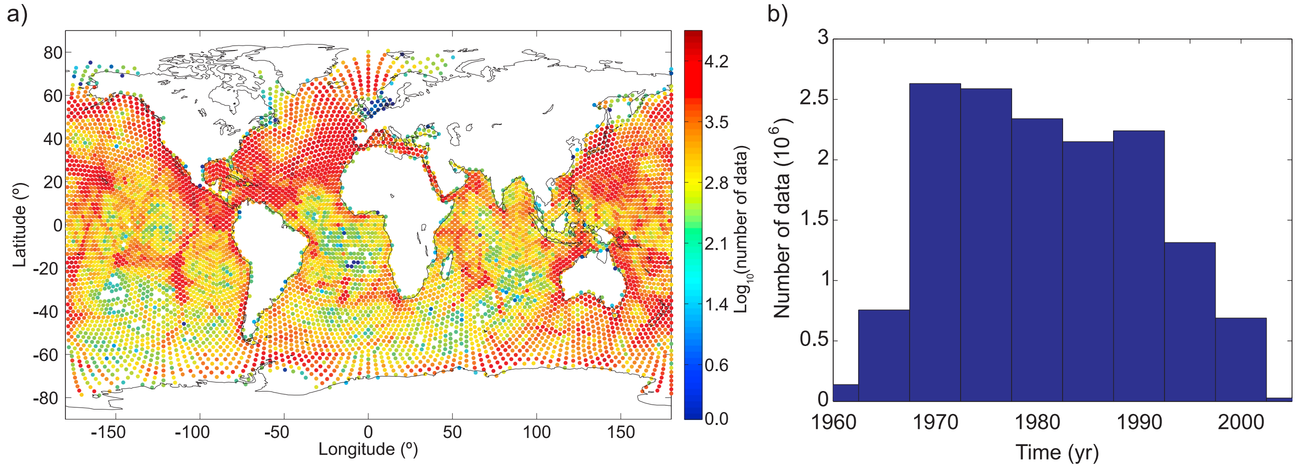

Fig. 1. a) Spatial and b) temporal distributions (in terms of data acquisition) of the marine magnetic anomaly data. The number of data in a) is given for each cell in which the ocean surface has been divided (see text for more details).

statistical distribution of the magnetic anomaly data that we will explore in this work. Walker and Jackson (2000) analysed the histograms of marine magnetic anomalies and proposed that they exhibit a clear Laplace distribution, but they did not provide a physical explanation for this statistical behaviour of marine magnetic anomalies. In nature, a Laplace behaviour of the statistical distribution is rare and unexpected, since the Gaussian distributions are more ubiquitous, especially in geophysics, such as, for instance, time series of the electric or magnetic field, velocities of turbulent fluid flows, the Gauss coefficients of the main geomagnetic field, etc. The classical explanation given for the universality of the so-called “normal distribution law” is an appeal to the Central Limit Theorem (CLT, e.g. Rice 2006), which shows that a quantity made up of the sum of a large number of independent random variables, all drawn from the same distribution, will tend to be normally distributed, no matter what the distribution of the individual contributors to the sum is. In the view of the CLT, as a first plausible hypothesis, one could see the marine magnetic anomalies as comprising the sum of random fields due to elements of magnetization in the crust, so a normal distribution should be expected. Conversely, this is not the case and the reasons behind that will be the focus of our present work.

2. Marine magnetic anomaly data

In our study we use the marine magnetic anomaly data set of Quesnel et al. (2009). This dataset is based on the magnetic anomaly compilation GEODAS DVD Version 5.0.10 (Metzger and Campagnoli, 2007) that contains more than 14 million geomagnetic field data measured in a total of 2411 marine routes, from 1953 to 2003 (Quesnel et al., 2009). The original database corresponds to the total strength geomagnetic field, i.e. the intensity of the geomagnetic field as a sum of all the internal and external contributions observed at the sea level. In order to isolate the oceanic lithospheric contribution, it is necessary to apply different corrections. The main and external field contributions were removed using the CM4 model (Sabaka et al., 2004) for those cruises carried out between 1960 and July 2002, and the CHAOS model (Olsen et al., 2006) for the cruises after 2002.5. The IGRF-10 model (Macmillan and Maus, 2005) was used to estimate the core field in 5 cruises prior to 1960 (no correction for external fields was made). The procedure of data reduction includes an adjustment of long-wavelength magnetic anomalies using the National Geophysical Data Center (NGDC)-720 model (Maus, 2010). After checking and cleaning the data by removing spikes and spurious values, a line levelling method was applied to reduce inconsistencies between surveys undertaken at different epochs. A complete description about the cleaning and extraction operations of the oceanic magnetic anomaly data can be found in Quesnel et al. (2009). After applying the different steps of this data processing, the final number of magnetic anomaly data points was 14,878,074.

Fig. 1 shows the spatial and temporal distribution of these data. The spatially heterogeneous distribution (Fig. 1a) indicates how the largest number of the marine routes comes from the basins of the Northern Atlantic and Pacific Oceans, whereas the Southern Pacific and Atlantic, and the Indian Oceans show the lowest density of data. However, the coastal areas and regions with relevant tectonic features, such as oceanic ridges, are generally well covered.

3. Laplace distribution of marine magnetic anomalies

In order to analyse the behaviour of the marine magnetic anomaly data, we have plotted the histogram showing the distribution of magnetic anomaly intensity values in Fig. 2a and the corresponding cumulative distribution in Fig. 2b. The former histogram reveals a clear symmetric distribution of the data with most of the magnetic anomaly values between ± 500 nT. A first overall statistical study provides a mean value μ of -2.75 nT and a standard deviation $\sigma = 150.60$ nT (variance $\sigma^2 = 22679.97\ \text{nT}^2$). Other classical statistical parameters are the median value (-5.5 nT) and the mode (-6.9 nT). The fact that mean, median and mode values differ significantly is a first indication of some departure from an ideal Gaussian distribution. Using these statistical values and the total number of data, we have also calculated and plotted in Fig. 2a and b the theoretical curves of different kinds of statistical distributions. In particular, according to the shape of the obtained histogram and cumulative distribution we have compared three different theoretical statistical distributions with our results: the Gaussian, the Laplace (or double exponential) and the Cauchy (also known as Lorentz or Cauchy-Lorentz) distributions (e.g. Walck, 2007).

The theoretical curves of the Gaussian distribution were calculated using the mean and standard deviation of the real data. The histogram and the cumulative distribution clearly do not follow the theoretical Gaussian distributions: the actual marine anomaly data present a narrower distribution around the mean than the Gaussian one. This is also evident in the comparison between the cumulative distributions especially between -250 nT and 250 nT (Fig. 2b).

On the other hand, the magnetic anomaly histogram is both wider and lower than predicted by a Cauchy distribution (see Fig. 2a). The corresponding Cauchy curves were calculated using the median value and the half-width at half-maximum value of the real distribution. The same inconsistency is found in the cumulative distributions given in Fig. 2b where the theoretical cumulative distribution does not fit well the real values lower than -100 nT and higher than 100 nT.