DERIVATION OF LOCAL CRUSTAL MAGNETIZATION USING MULTIPLE ALTITUDE MAGNETIC DATA

Quesnel, Y., B. Langlais, and C. Sotin

Université de Nantes, Nantes Atlantique Universités, CNRS, Laboratoire de Planétologie et Géodynamique, UMR 6112, Faculté des Sciences et des Techniques, 2, rue de la Houssinière, BP 92208, Nantes, F-44000 France, Email: yoann.quesnel@univ-nantes.fr

ABSTRACT

The new ESA Swarm mission will measure the magnetic field of the Earth with an unprecedented accuracy. In particular, the different satellites will allow a better characterization of the magnetic field of lithospheric origin. It will be possible to investigate the nature of the lithospheric magnetization. Here we present a method that is well suited for that purpose. Forward and inverse schemes are used together. The *a priori* parameters for the inverse part are those estimated by the direct approach. The method is demonstrated to be accurate, by applying it on areomagnetic measurements that were acquired above the well-studied Champtoceaux Nappe. The application to Swarm satellite altitude predicted measurements shows that deep-seated magnetic sources as close as 170 km will be distinguished.

1. INTRODUCTION

One of the scientific objectives of the Swarm mission is to improve the characterization of the magnetic field of lithospheric origin. This will allow the properties of the lithosphere to be investigated, in terms of magnetization and depth to the Curie isotherm. The relationship between lithospheric magnetic anomalies and magnetic sources is non-unique. Here forward and inverse methods are compared and used to estimate the location and magnetization of magnetized sources. In the first part, the method is described. The pertinence of the approach is demonstrated by applying it to areomagnetic measurements; 'magnetic' results are compared to other geophysical information. The third part is devoted to predicted Swarm altitude measurements.

2. METHOD

Inverse methods usually assume either fixed source location or magnetization direction. Furthermore, they are generally applied to isolated dipolar magnetic anomalies. Here we propose an inverse method which solves for the location and direction of the sources together. Several contiguous sources may be studied at the same time.

First, simple forward models such as uniformly magnetized spheres [1], prisms [2] or cylinders [3] are used. Systematic exploration of the parameter space is made to determine what are the best location and magnetization parameters of these simple geometry sources. These parameters then serve as *a priori* inputs in the inversion process. This is based on a generalized non-linear inversion algorithm [4]. *A priori* standard deviations are associated with the parameters. This is an iterative process. The best model is determined with respect with the χ^2 that is computed at each iteration. *A posteriori* tests on misfits are performed. Possible outliers are removed, followed by a new inversion.

3. APPLICATION TO AEROMAGNETIC DATA

Aeromagnetic survey at 120 m over the Hercynian metamorphic complex of Champtoceaux (Nantes, Western France) were carried in 1998 by the BRGM (french gelogical survey) [5]. Observational, seismic and gravity data are also available to constrain the geology [6-8]. This will allow our results to be compared.

3.1. Synthetic case

In order to prove the robustness of the inverse method, several tests are first performed with synthetic data. Forward models are used to predict synthetic magnetic anomalies at 3 km. One, two or three sources are considered, between 0 and 15 km initial depth. Contiguous sources may be assigned comparable or very different magnetization. These sources are used to predict synthetic magnetic measurements along profiles or onto regular grids. A 7 nT gaussian noise is added or not.

Many *a priori* parameters and associated standard deviations are tested. For instance, we explore *a priori* depths for the most magnetized dipole, between 0 and 20 km, with associated standard deviations set to 0.1, 1 or 10 km. We show on Fig. 1 the final depth vs. initial one, for different a priori depths, and for a standard deviation equal to 0.1 km, in the case of clean data onto a regular grid. Less than 50% of the final depths are within 0.5 km of the initial ones. A 10-km standard deviation is also tested (Fig. 2). In this case, more than 80% of final depths are within 0.5 km of the initial ones. Similar tests are performed for one or two additional sources. In this case, the depth of the other bodies is set to 8 km. Associated *a priori* standard deviations are 0.01 or 1 km. These two additional sources do not alter the estimates of the depth of the first dipole.

These tests underline the need for reasonable *a priori* parameters and standard deviations. These have to be large enough to accommodate possible discrepancies between true and *a priori* parameters.

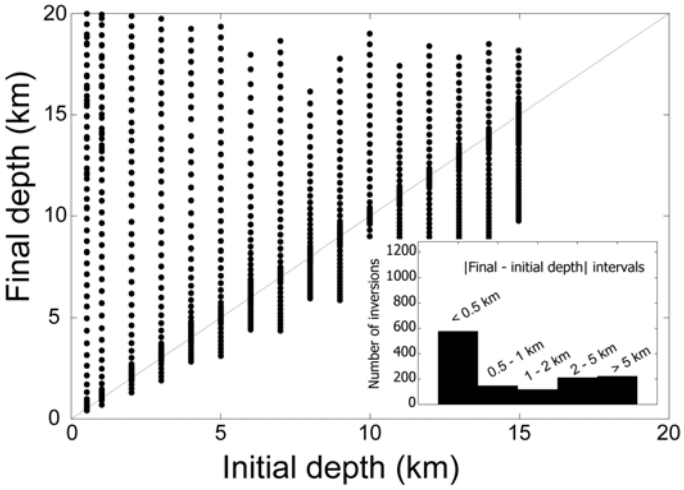

Figure 1: Comparison between inversions with a priori depth standard deviation of 0.1 km in the one source configuration with 3 km – altitude synthetic clean data (regular grid). Distribution of different absolute (final – initial) depth intervals is shown in the bottom right panel.

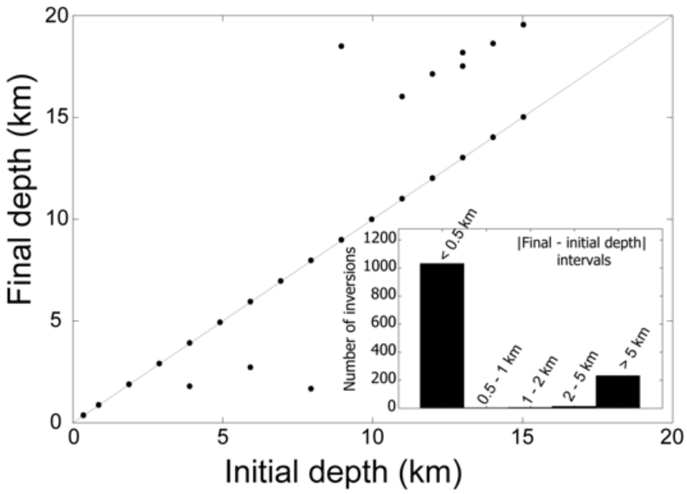

Figure 2: same as Fig. 1 with a priori depth standard deviation of 10 km.

Tests were also performed to study the effect of small or large standard deviations on the other parameters (latitude, longitude, but also magnetization directions and intensities). Although the depth appears to be the most critical parameter, similar conclusions are drawn. The final values are close to the initial ones most of the time. Reasonable *a priori* parameters are necessary. Finally, *a priori* data standard deviations must be proportional to the measurement noise.

3.2. Real case

Magnetic measurements over the Champtoceaux complex are 3 km upward continued. Magnetic anomalies as large as 40 nT are linked to superficial serpentinized rock layers (Fig. 3).

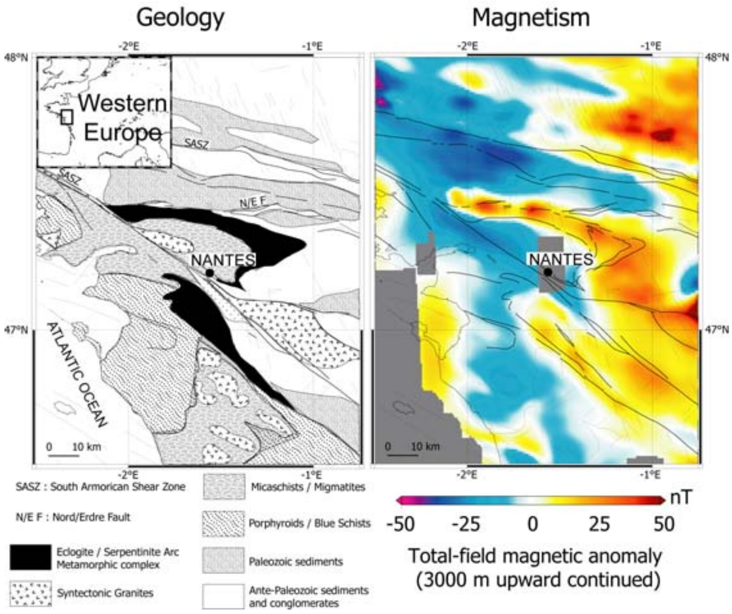

Figure 3: geological (left) and magnetic (right) maps of southeast Armorican massif. Geological map is simplified from [10]. The Champtoceaux belt is the black formation North of Nantes. Magnetic map corresponds with the upward continuation of magnetic measurements acquired at 120 m [5].

Magnetic anomalies are modeled using three uniformly magnetized bodies. Using spheres, prisms or cylinders lead to RMS residuals between observed and predicted lithospheric fields equal to 18, 17 and 16% of the RMS measurements, respectively.

Using reasonable *a priori* parameters given by forward modeling estimations, inversion of measurements improves the fit to 95%. Magnetizations and depths of the three sources vary from 4 to 8 A/m and 3.4 to 6.5 km, from the western to the eastern part of the complex, respectively. These results agree with previous studies [6-9]. Another interesting result comes from the computed magnetization directions, which indicate that the major part of the magnetization may be induced.

4. APPLICATION TO SATELLITE DATA

The case for satellite magnetic measurements is very similar to the one we described above. The main difference comes from the much higher altitude of the measurements. Sources parameters are modified accordingly, in terms of depth and lateral distance.

In the following, we first show the usefulness of multiple altitude coverages, by applying our method on

Mars Global Surveyor magnetic measurements. Then we estimate what is the minimum lateral distance between adjacent sources that it is possible to detect using the Swarm satellite measurements.

4.1. The martian "experience"

Mars Global Surveyor probe (launch: 1996) has provided with martian magnetic measurements during different phases. During the AeroBraking (AB) and Science Phase Orbit (SPO) phase, sparse measurements were acquired as low as 100 km in altitude, along elliptical orbits. Since 1999, the Mapping Orbit (MO) phase is characterized by a circular orbit, near an altitude of 400 km. These two distinct phases can be used together, although acquired at different epochs: the magnetic field on Mars is of lithospheric origin [11], and there is no secular variation correction to make.
We studied several strong magnetic anomalies over the ancient Terra Sirenum region (-35°N, 200°E) [12]. One AB anomaly has a 1500 nT peak in the radial component at 100 km altitude. Both the forward and inverse models of the single altitude dataset do not explain the signal observed at higher altitude. Similarly, forward or inverse models based on the MO anomaly do not explain the AB one. But the situation is greatly improved when using both AB and MO dataset in a joint inversion process. This gives the best fit to the AB and MO signals. This demonstrates the usefulness of measurements by two satellites at different altitudes. Final source magnetization is about 50 A/m for a 55-km depth. Having two distinct altitude coverage of the same magnetic anomalies allows the magnetic crust and the associated magnetization processes to be better understood.

4.2. Tests with synthetic Swarm data

Swarm-A and -B satellites will measure the terrestrial magnetic field at an altitude of 450 km, whereas the Swarm-C satellite will simultaneously measure it at 530 km. In order to estimate how these dual altitude coverage will help in differentiating adjacent lithospheric magnetized sources, several tests were performed. Two synthetic datasets at 450 and 530 km were created. Fig. 4 shows two N-S profiles centered on the synthetic anomaly corresponding to the two satellite altitudes. These profiles underlines how two close magnetic sources may create only one visible magnetic anomaly. A 1 nT gaussian noise was added. This value is chosen to be the *a priori* standard deviation associated with input data for the inversion. The three components of the magnetic field anomaly are considered.

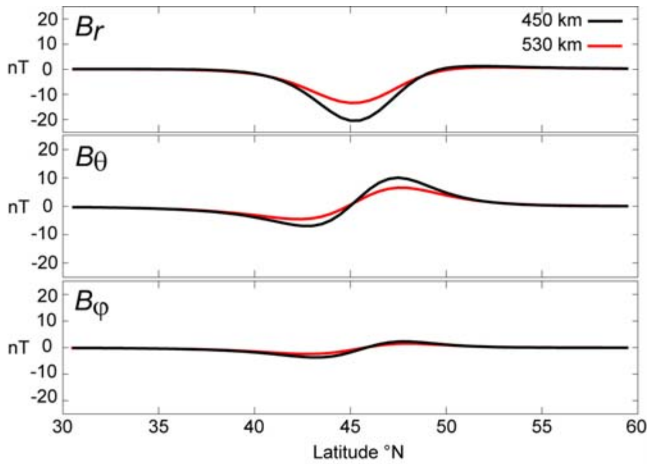

Figure 4: synthetic 3-components magnetic field anomaly profiles generated by two magnetized sources located in 45 and 46.5°N (space interval ~ 170 km). B_r, B_θ and B_φ components are represented from top to bottom, respectively. The black line corresponds at the altitude of Swarm-A or -B satellite, whereas the red one is for the Swarm-C altitude.

In the following, latitudinal distance between magnetic sources (40-km deep) is set to 2.7° or 1.5°. (Tab. 1). In the first case, the inversion of the Swarm-A (or -B) dataset alone allows the two sources to be distinguished (error ~ 15%), whereas it is not possible using the Swarm-C subset alone (error ~ 100%). In this case, the two final dipoles are at the same location with different depths. The final space interval is better (error ~ 7%) than the one using only Swarm-A (or -B) subset.
In the second case, only the combined inversion of the two datasets is able to distinguish the sources (error ~ 20% vs. 93% if using the low-altitude dataset). The final parameters are close to their initial values. This result emphasizes the usefulness of the Swarm constellation.

Table 1: Final latitudinal differences vs. initial ones wwwhen using either Swarm-A (or -B), Swarm-C or the two subsets together. Two initial cases are considered: 2.7°(300 km) and 1.5° (170 km).

		$\Delta\lambda_i$	2.7°	1.5°
Swarm-inverted dataset	A (or B)	$\Delta\lambda_f$	2.3°	0.1°
	C		0.0°	0.1°
	A (or B) + C		2.5°	1.8°

5. CONCLUSIONS AND OPENED QUESTIONS

These preliminary results show that our method can be used to derive magnetization parameters of lithospheric sources using aeromagnetic and satellite magnetic surveys. Realistic *a priori* parameter values and standard deviations have to be carefully chosen for the inversion.

The Swarm satellites will be separated by 80 km in altitude. This difference will allow magnetic sources as close as 170 km to be differentiated. In this preliminary study, we did not consider the lateral distance between Swarm-A and Swarm-B, but this will very likely increase the accuracy of the method.

These results confirm the need for this new Swarm mission, and more generally emphasize the needs for low altitude magnetic surveys, especially on Mars, to characterize the deep-seated magnetic sources embedded in the lithosphere.

6. REFERENCES

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