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Geologic interpretation of the aeromagnetic survey in the Agourai area (Central Morocco)

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The aim of this work is to interpret the geologic structures of the Agourai area (Paleozoic and Mesozoic structures) from processed magnetic maps. The detected magnetic anomalies from different standard methods used in aeromagnetism (Residual map, RTP map, horizontal gradient map) were compared to geologic structures and permit enhancing the mapping quality of some areas, and thus defining many geologic features. Existing geologic maps and geologic field studies allow interpreting some detected anomalies. It was thus possible to define the limits between the Paleozoic basement and the Mesozoic cover, to determine magnetic anomalies according to NE–SW trends compatible with the regional geologic structures and finally to detect a NE to SW-oriented fault system in the Mesozoic cover of the Agourai Plateau. Despite the reliability of this approach, some folded basaltic sills occurring in this region were not well detected, probably because of their reduced thickness.

Key words: mapping, aeromagnetic data, field data, geological structures, Central Morocco

Introduction

Aeromagnetic data have been used for a long time in the mining areas to detect magnetic anomalies that may correspond to metal concentrations. They are now widely used for onshore geologic reconnaissance, especially in areas with extensive soil or thick vegetation cover. It allows highlighting different petrographic types at map scale (Gleizes 1992; Bouchez 1997). However, the

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interpretation of magnetic anomalies in terms of geologic features requires great care (Henkel 1991; Clark 1997; Naba 2007; Naba et al. 2004; Randrianasolo 2009); it is not always a straightforward matter to assign magnetic signatures to rocks. Aeromagnetic surveys are widely used throughout the world in regional geologic studies (Galdeano 1980; Blakely 1995; Grauch et al. 2001; Aspler et al. 2003; Naba et al. 2004; Randrianasolo 2009; Groune et al. 2009; Aryamanesh 2009). However in Morocco, aeromagnetic surveys have only concerned regions with mining potential (Hercynian Central Massif, Anti Atlas, Tazekka Massif, Akil et al. 2008; El Gout et al. 2010; Bouya et al. 2012; Amar et al. 2012). Our present work is a contribution toward the use of aeromagnetic data for mapping the northeastern part of the Central Moroccan Massif and the sub-tabular plateau of Agourai (Figs 1, 2 and 3). The detected "magnetic facies" and different identified linear anomalies are compared to field and geologic map data.

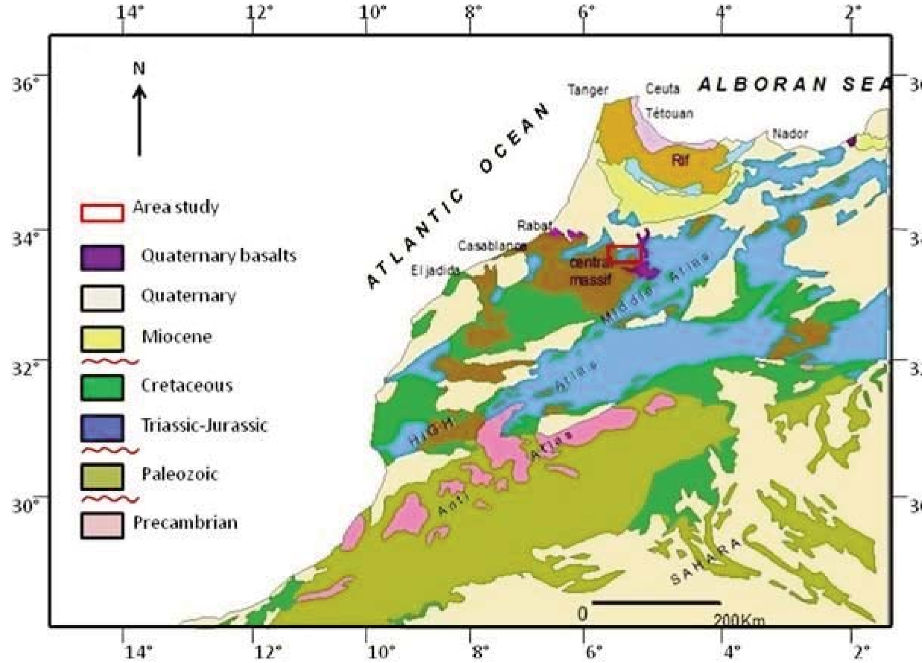


Fig. 1
Geological map of Northern Morocco and location of area study (from Geological map of Morocco 1/1.000.000)

Fig. 2 → upper
Geological map of Central Moroccan Massif and location of Agourai area (adapted from Bouabdelli, 1989). 1. post Paleozoic; 2. Permian; 3. Namuro Wesphalian; 4. Lower Namurian; 5. Visean; 6. Devono-Dinantian; 7. Silurian; 8. Late-Variscan granites; 9. Pre-Silurian

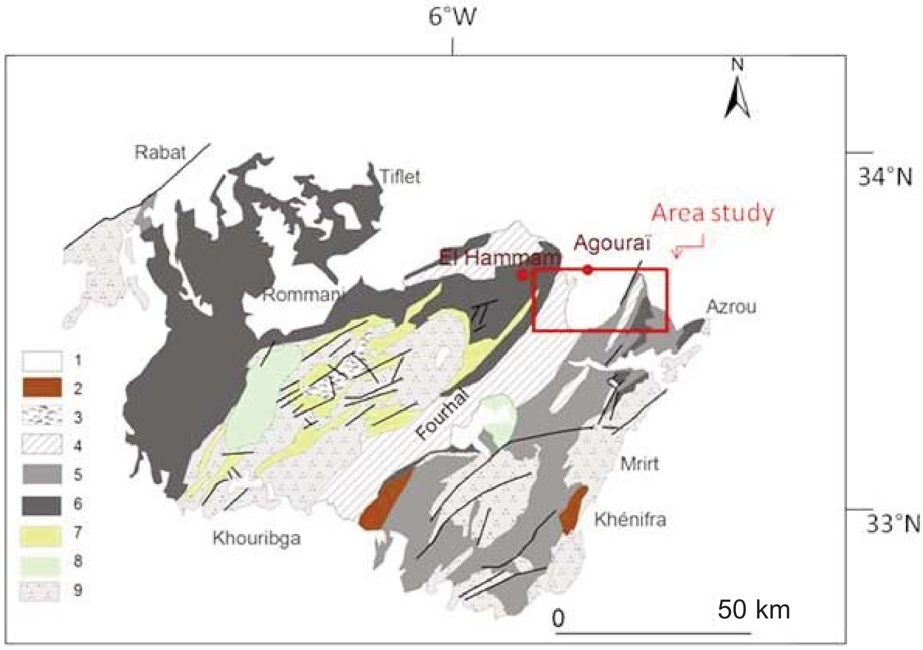


Fig. 2

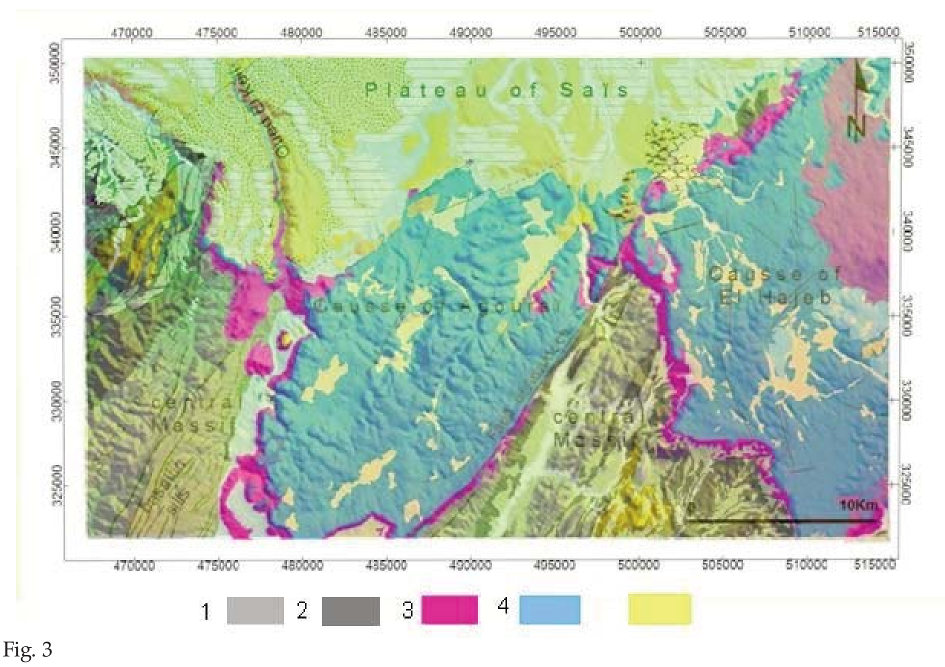


Fig. 3
Geological map of area study superimposed on the Digital Elevation Model 1, 2. Paleozoic, 3. Triassic, 4. Jurassic, 5. Tertiary

Data and methods

Data acquisition, processing procedures, and digital data from the survey are described and available from the Ministry of Energy and Mines in Rabat, Morocco. Aeromagnetic data used in this work were acquired in a campaign of airborne geophysics in the Central Moroccan Massif during April – June, 2000. The acquisition was performed using a Eurocopter AS35OB3 equipped with a video recording system (PAL camera). These surveys were flown along NW–SE traverse lines spaced 500 m apart and 60 m above ground, with NE–SW tie lines spaced 5 km apart. The magnetometer used was a Scintrex type cesium or Geometrics, brought to a nominal altitude of 30 m and with a sensitivity of 0.01 nT. The magnetic data were recorded in flight with a sampling interval of 0.1 seconds. The values of the residual magnetic field thus obtained were interpolated to a square grid, the length of each side of which was 125 m. Thus, the aeromagnetic data used in this work were provided in the form of fixed maps of the residual magnetic field containing contours and lines of flight. The processing of these data consisted in digitizing intersection points between flight lines and isovalue curves. A total of 9950 points were digitized and later processing was carried out with the Oasis Montaj program. This work covered an area of about 944 km^2. The processed total-field magnetic data were gridded using a minimum curvature routine (Webring 1981) with a grid spacing of 125 meters, approximately one-fourth of the line spacing of the survey. Once the database is loaded into ArcGIS it is then exported into the Oasis Montaj program. The maps presented in this work correspond to the residual magnetic field, which allows applying different filters in order to detect the magnetic signatures and their possible geologic significance.

Geologic setting

The study area corresponds to the northeastern part of the Central Moroccan Massif, which is the continuation of the NE to SW-trending Fourhal-Telt Carboniferous Basin (Figs 2 and 3). The stratigraphic series correspond to alternating clay and sandstone beds attributed to the Visean–Namurian. In the Agourai area these series are folded, with a NE–SW trend similar to that of the rest of the Central Moroccan Meseta (Figs 2 and 3). The Paleozoic basement is overlain by weakly deformed Triassic–Liassic units consisting of red clay with intercalated basalt flows and Lower Jurassic (Liassic) dolomitic limestone (Fig. 4). The Paleozoic series are made up of sandstone and pelite arranged as turbidite sequences. They are cut by N30–40-striking basaltic dikes and sills of variable thickness, folded along with the sediments (El Ouardi et al. 2008). The turbidites of Late Visean–Namurian age are folded and display cleavage according to the major NW to SE-oriented shortening, characteristic of the Variscides of Central Morocco (Bouabdelli 1989; Hoepffner 1994; Tahiri 1994; Ben Abbou 2001). The folds correspond to upright anticlines and synclines in turbidites and appear as

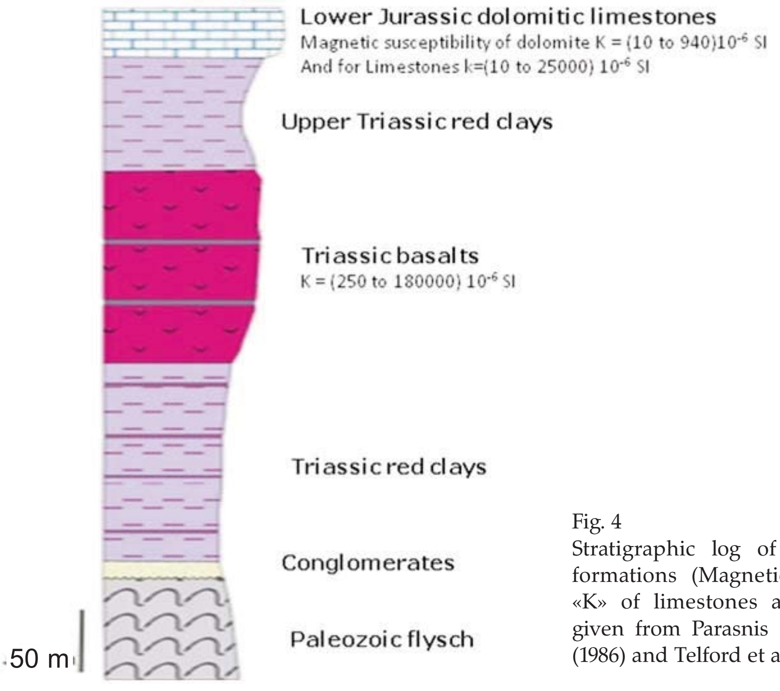


Fig. 4
Stratigraphic log of main studied formations (Magnetic susceptibility «K» of limestones and basalts are given from Parasnis (1997), Sharma (1986) and Telford et al. (1990)

neatly-arranged and uniformly thick, shortened layers showing several slip traces of layer upon layer. They correspond to flexural slip folds with subhorizontal axes (N35–40, 05–20°SW and NE). The main cleavage (N30–40, 80°NW) is axial planar and seems to be more pervasive in this area than in other localities of Central Morocco. The Carboniferous rocks are intruded by a NE to SW-trending dikes 15–20 m thick (Fig. 3). Some intrusive basaltic bodies (sills) lie parallel to layered beds of sandstone and pelite of the country rocks and induced small aureoles of metamorphism. These magmatic dikes and sills were previously studied by different authors (Cheilletz and Zimmerman 1982; Kharbouch 1994; Ntarmouchant 2003; Driouch et al. 2010). According to their petrographic and chemical composition, they were attributed to calc-alkaline magmatism and were interpreted as the result of an hypothetical continental subduction zone occurring in this region during Carboniferous (Ben Abbou 1990; Ntarmouchant 2003; Driouch et al. 2010).

In the Agourai Plateau, considered as a continuation of the Middle Atlasic sub-tabular formations, the Mesozoic series are limited only to the Upper Triassic–Lower Jurassic stages, corresponding to red silty clay intercalated by basalt, and overlain by dolomitic limestone forming the youngest Mesozoic strata. These formations are weakly deformed and show many gentle folds occurring in Jurassic limestone, with a dip of about 20–40° in some localities, especially near major faults. Many fractures also affect Liassic limestone (Fig. 3); they are mainly oriented NE–SW, defining many panels in the Agourai Plateau and sometimes delimiting very narrow, distensive structures corresponding to half-grabens, with tilted blocks recording continental Mio-Plio-Quaternary sedimentation.

Magnetic data processing

Aeromagnetic measurements were used to obtain the residual magnetic anomaly map of the Agourai Plateau and the surrounding northeastern part of the Central Massif (Fig. 5). We used different standard methods (filters) known in aeromagnetism. A reduction-to-pole (RTP) transformation is applied to aeromagnetic data to minimize polarity effects (Blakely 1995) (Fig. 6) and to eliminate distortions caused by the tilt of the Earth's magnetic field vector. The RTP map allows finding different anomalies that correspond to major geologic structures (Naba 2007; Saheel et al. 2011). The horizontal-gradient method (Fig. 7) (Blakely 1995; Grauch et al. 2006) is based on a principle from gravity methods according to which steep gradients occur over near vertical contacts between units with differing physical properties (Grauch et al. 2001).

The obtained processed maps from the Agourai area show different zones of strong and low anomalies trending NE–SW, corresponding to the Paleozoic basement and Mesozoic cover. Thus, the strong anomalies underline the contact

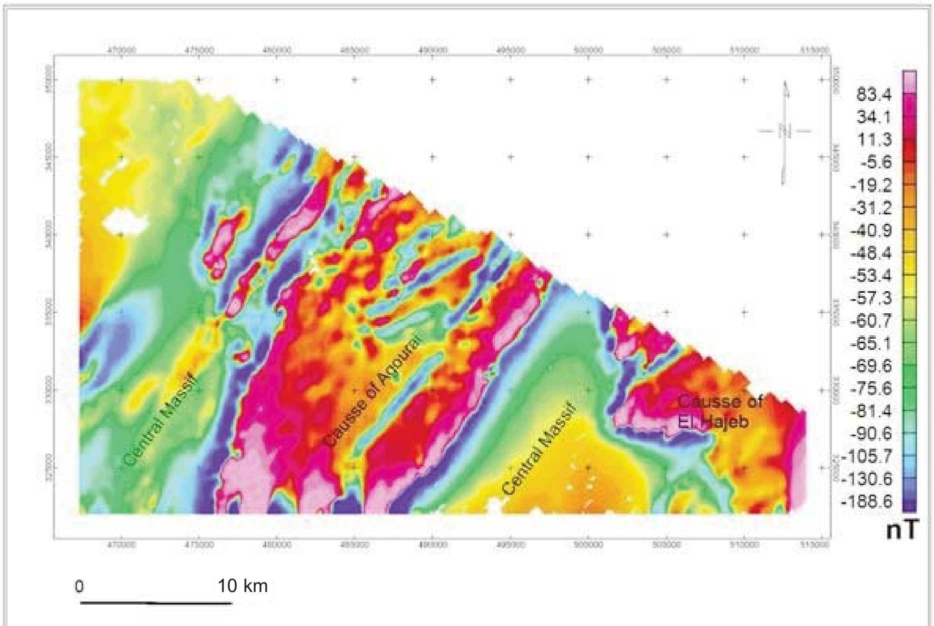


Fig. 5
Residual magnetic map of the Agourai area

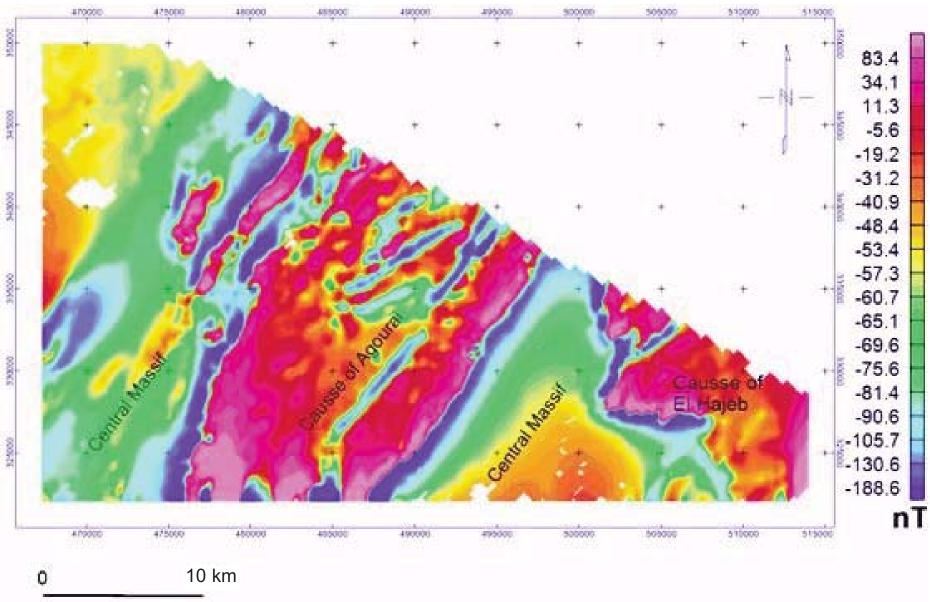


Fig. 6
Reduced-to-pole map (RTP map)

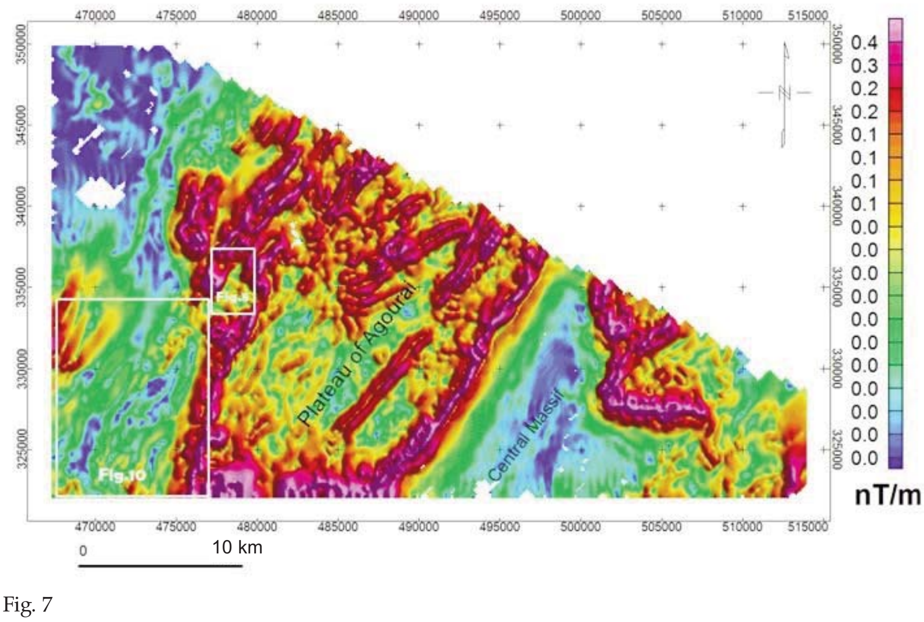


Fig. 7
Horizontal gradient map of the Agourai area. Small and large white rectangles show the locations of Figures 8 and 10, respectively

zone between the Paleozoic basement and the Agourai Plateau. The latter also shows, in the central part, linear anomalies trending NE–SW to ENE–WSW (Figs 5, 6 and 7).

Results

Although recent maps at 1/50,000 and 1/100,000 scale are available (Du Dresney and Suter 1975; El Boursoumi et al. 2002), in many areas their resolution is not enough to define mesoscopic geologic structures occurring in the Agourai region. We will provide some increased detail to the geologic map of Agourai (1/50,000) from three areas. Structures detected from magnetic data processing were controlled by field geology and literature.

Paleozoic basement

Area of Oued el Kell

This area corresponds to a small inlier corresponding to the extreme northeastern termination of the synclinal zone of Fourhal-Telt, characterized by thick series of Carboniferous flysch. It was recently mapped within the framework of the 1/50 000 map of Agourai (El Boursoumi et al. 2002). Unfortunately, the normal fault contact between the Paleozoic basement and the Triassic cover on the northwestern side was not identified but considered as a stratigraphic limit (Fig. 3). Similarly, the magmatic regional sill folded together with hosting sedimentary rocks was not mapped. Therefore the detected lineament trending NE-SW on the processed magnetic map (Fig. 8A), was verified and in fact corresponds to a tectonic contact in the form of an important normal fault, probably contemporaneous to the Triassic rifting in this region (Fig. 8B and D, Fig. 9 (Photos 1, 2, 3). The magnetic signal from profile EF (Fig. 8C) shows some variations, probably caused by this normal fault and the contrast between Paleozoic flysch and Triassic red clay. The folded basaltic sill was not detected through the processed magnetic map, and does not give a strong magnetic anomaly, probably because of it small thickness (15–20 m), but field mapping shows that it is folded together with flysch sediments and determines a kilometric anticline trending NE–SW.

Fig. 9. →
Some geological structures studied in the Agourai area.
Photo 1. Captured image of the Oued El Kell sector (from Google Earth),
Photo 2. NE termination of the Oued El Kell anticline, note the folding of the bsaltic sill,
Photo 3. Normal fault separating Paleozoic basement (grey facies) and Triassic red beds,
Photo 4. Sub-E-W strike-slip fault affecting a basaltic sill, SW of Agourai

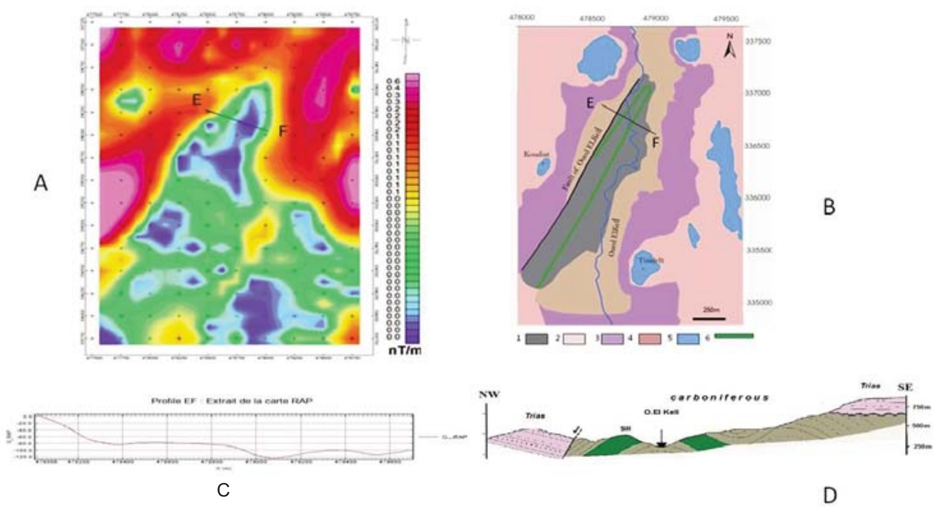
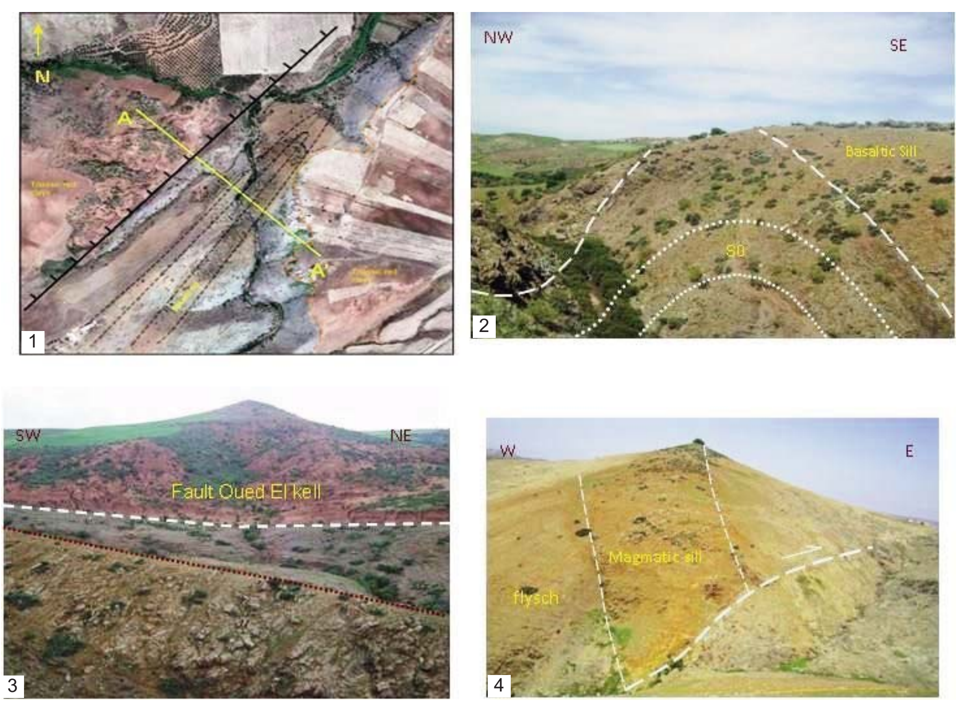


Fig. 8
A. Processed magnetic map of Oued El kell sector (see location figure 7), B. Geological map of the sector (1. Paleozoic, 2. Lower red clays Triassic Formation, 3. Basalts, 4. Upper red clays Triassic Formation, 5. Liassic dolomitic limestones, 6. Carboniferous basaltic sill), C. Magnetic signal from the profile EF, D. Geological section corresponding to the profile EF.



Sector of sills and dikes

The SW part of the geologic map of Agourai offers several magmatic bodies corresponding to sills and dykes, trending NE–SW, intersecting a monotonous series of Carboniferous flysch. From this this geologic map it is difficult to understand the geological structures in this sector since the remarkably lacking of dip symbols and there is any structural interpretation giving fold axes or some map markers (Fig. 10 A). In spite of their importance in this region and generally in the entire eastern part of Central Moroccan Massif, this mapping was not carried out as well as it could have been, because of their small thickness of the magmatic structures and perhaps also because of the scale of mapping. In our

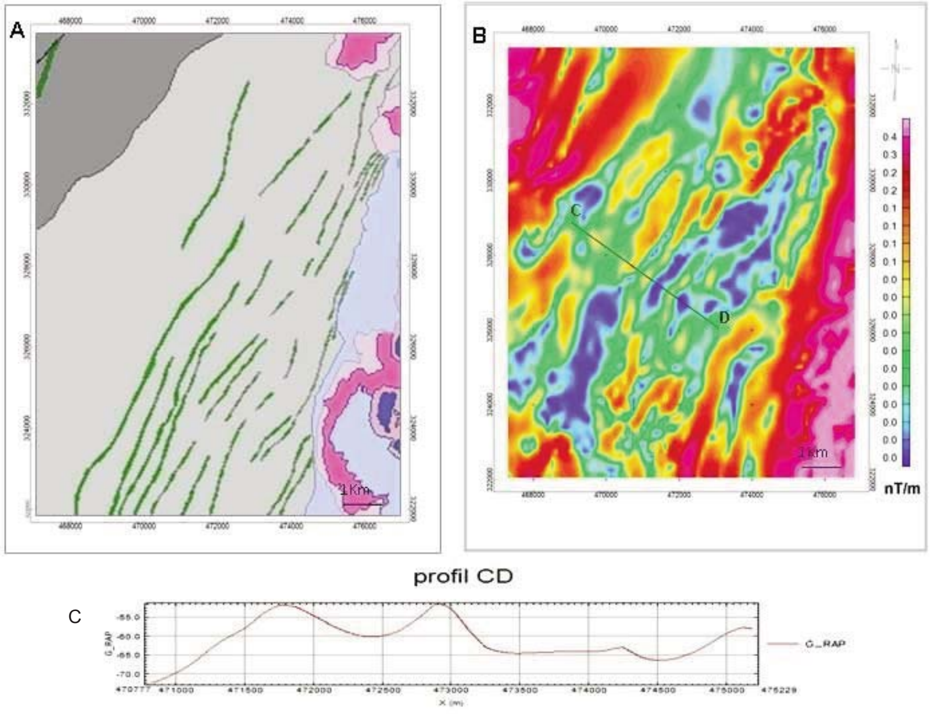


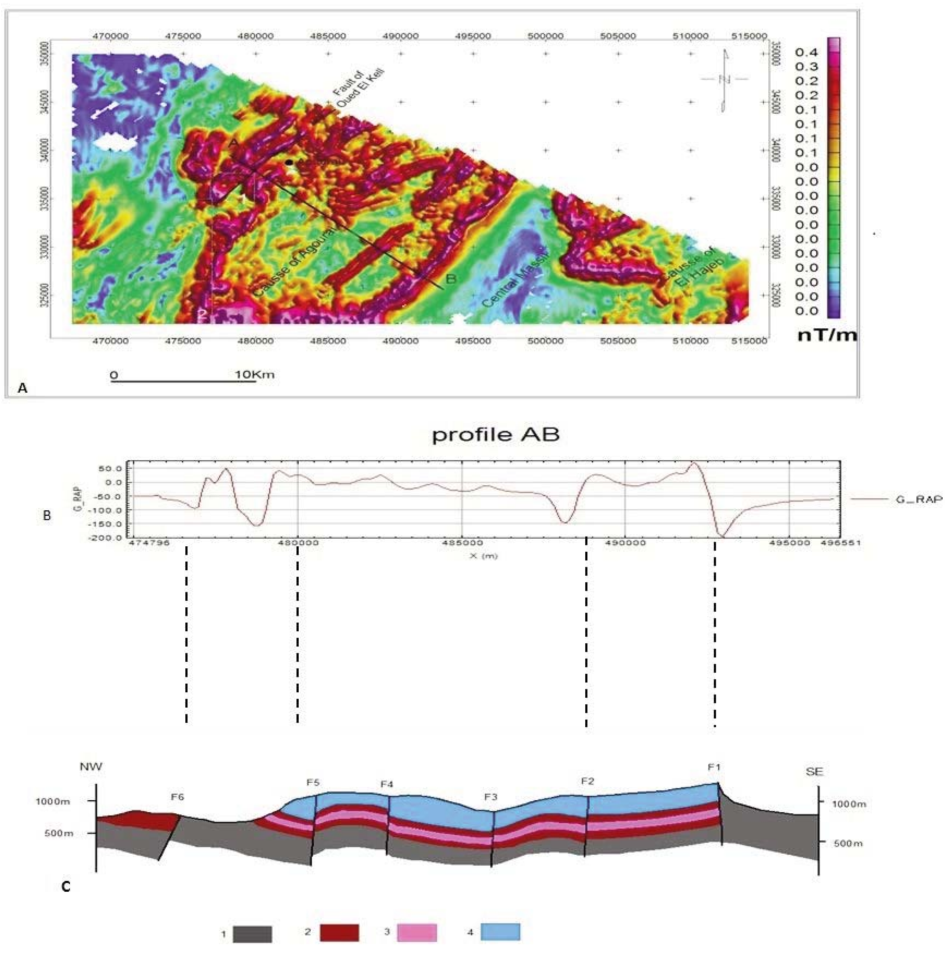
Fig. 10
A. Geological map of the sector of sills and dikes, SW of Agourai (see legend in Figure 3), B. Horizontal gradient magnetic map of the same sector (see location figure 7), C. Magnetic signal from the profile CD

Fig. 11 →
A. Map of horizontal gradient, B. Magnetic signal from the profile AB, C. Geological section through the Agourai plateau. 1. Paleozoic, 2. Triassic red clays, 3. Triassic basalts, 4. Liassic dolomitic limestones, F1 to F6. Main faults affecting the Agourai plateau. Figures show the correlation between linear magnetic anomalies (A), variations of the magnetic signal (B) and the main faults in the region (C)

work, based on processed magnetic data, we note that some magnetic anomalies are repeated and appear to outline features that may correspond to periclinal closures (Fig. 10B). The magnetic signal from profile CD also shows some variations near these magmatic bodies (Fig. 10C). Based on these comments, field work permits us to confirm that some mapped dikes correspond to basaltic and gabbroic sills which are folded together with flysch sediments and are parallel to sedimentary beds (Fig. 9, Photo 4).

Mesozoic cover: Agourai Plateau

The processed magnetic map of the Agourai Plateau shows many linear anomalies trending NE–SW to ENE–WSW (Figs 6 and 7). The comparison of these anomalies to the geologic map of this area allows considering them to be fractures



affecting Jurassic limestone (Fig. 11). Field work permits controlling these predictions and confirming that linear magnetic anomalies correspond more or less to major faults affecting the Agouari Plateau (Fig. 11A and C). This is confirmed by variations of the magnetic signal from profile AB (Fig. 11B). Thus the southeastern border of this plateau shows a linear anomaly trending NE-SW that coincides with the major Adarouch Fault (Fig. 11A and C). The other parallel anomalies detected in the plateau correspond to the main faults affecting Liassic limestone (Fig. 11C).

Discussion and conclusions

It is known that magnetic anomalies can be induced by crystalline rocks or metamorphic basement, or be generated by linear tectonic contacts (Grauch et al. 2006). The processing and the analysis of magnetic data allow detecting various anomalous zones according to different parameters of the main formations. The comparison of processed magnetic maps with geologic ones helped interpret some detected anomalies consistent with geologic structures. Thus the techniques used appear to be appropriate for indirect mapping of some geologic features (formations, folds and faults, dikes and sills). Therefore it was possible to determine (i) the limits between the Paleozoic basement and the Meso-Cenozoic cover, (ii) to define various magnetic anomalies according to NE–SW trends compatible with regional geologic structures (folds and faults) (Simancas et al. 2005) and finally (iii) to detect a NE to SW-oriented fault system in the Mesozoic cover of the Middle Atlas (Agourai Plateau) that appears to be the result of the reactivation of basement faults (Michard 1976; Tahiri 1994; Ben Abbou 2001; Simancas et al. 2005). Thus this strong correlation existing between magnetic anomalies and the regional structures shows that this digital mapping based on an aeromagnetic survey can be used for other regions where access is difficult, in order to apply some corrections to various existing geologic maps. Field data permit locating the detected features corresponding to NE to SW-trending folds characteristic of the Paleozoic basement (Durand-Delga et al. 1960–1962; Faugères 1978; Ait Brahim 1983; Leblanc and Olivier 1984; Hoepffner 1994; Haddaoui 2000; Ben Abbou 2001; Zizi 2002; Moratti et al. 2003; Moratti and Chalouan 2007; Sani et al. 2007; Habibou et al. 2012; Ouarhache et al. 2012) and verifying the existence of the NE–SW fault system, corresponding essentially to normal faults, inherited from the Late Variscan. It should be pointed out that even with this strong correlation of processed magnetic maps with field geology, it was not possible to detect some of the folded basaltic sills occurring in this region, probably because of their small thickness and the spacing of flight lines (500 m). It will be very interesting to use other scales, with 250 or 100 m spaced lines in order to detect smaller geologic features.

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