Ingeniería
Revista Semestral de la Universidad de Costa Rica

Vol. 16 (1) Ene/Jul 2006

CONTENIDO

1856 - 2006

EDITORIAL DE LA UNIVERSIDAD DE COSTA RICA

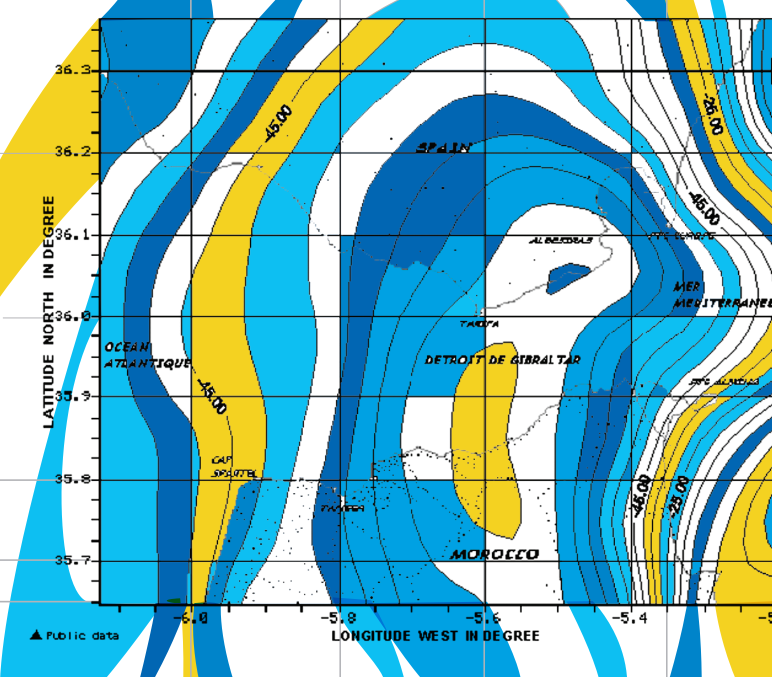
REVISTA INGENIERÍA Volumen 16 Enero / Julio 2006 Número (1)

http://www.revistaingenieria.inii.ucr.ac.cr
www.ucr.ac.cr
ISSN 1409-2441

Ingeniería

Revista de la Universidad de Costa Rica

ENERO/JULIO 2006 - VOLUMEN 16 - Número (1)



Ingeniería 16 (1): 53-60, ISSN: 1409-2441; 2006. San José, Costa Rica

GRAVITY SIGNATURES OF THE GIBRALTAR STRAIT ZONE

Saad Bakkali
Mahacine Amrani

Abstract

Aerial and terrestrial gravimetric surveys were carried out in the Gibraltar Strait Zone both in the northern and the southern sides between Spain and Morocco. From the observed and measured data of gravity a Bouguer gravity anomalies map was prepared. The present study aims to display gravity signatures of the Strait of Gibraltar using numerical filtering methods like horizontal gradient and second vertical derivative. This study makes the possible to map the gravimetric singularities of the strait zone. The vertical contacts and the density variation in the basement are put in evidence.

Key words: Morocco, gravity, Gibraltar, gradient, Fourier

Resumen

Los datos gravimétricos aéreos y terrestres fueron realizados en la zona del Estrecho de Gibraltar en los lados norteños y meridionales entre España y Marruecos. De los datos observados y medidos fue elaborado el mapa de las anomalías de Bouguer. El estudio presenta el mapeo de las singularidades gravimétricas del Estrecho de Gibraltar usando métodos de filtración númericos como gradiente horizontal y derivado en segundo vertical. Se pone en evidencia los contactos verticales y las variaciones laterales de la densidad.

Palabras clave: Marruecos, gravedad, Gibraltar, gradiente, Fourier

Received: September 28 th, 2005 • **Accepted:** January 20 th, 2006

1. INTRODUCTION

The Strait of Gibraltar is the strait which separates the Atlantic Ocean from the Mediterranean Sea. On the northern side is Spain and Gibraltar, on the southern side Morocco. Its boundaries were known to antiquity as the Pillars of Hercules. The Strait of Gibraltar has a very strategic location. Ships that travel from the Atlantic to the Mediterranean and vice versa, pass through this strait. Also, very many people who travel from Europe to Africa and vice versa, travel through this strait. The depth is about 300 m, and it is about 13 km wide at its narrowest point. For a number of years the Spanish and Moroccan governments have been jointly investigating the feasibility of a tunnel underneath the strait, similar to the Channel tunnel between England and France. Also, a group of American and British engineers have studied the feasibility of building a bridge to span the straits. Such a bridge would be of a suspension-truss combination design and would dwarf any existing bridge over 0,914 km height and 15 km length.

For all these strategic considerations, it appeared necessary to us to study the gravity signatures of the Gibraltar Strait Zone and to expose the first singularities.

2. OVERVIEW OF THE LOCAL GEOLOGY

The geology of the Mediterranean is quite complex, involving multiple periods of drying and re-flooding from the Atlantic Ocean. Sediment samples from the bottom of the Mediterranean

Figure 1. Gibraltar Strait between Spain and Morocco (Smitha, 2006)

Sea that include evaporite minerals, soils, and fossil plants show that about 7,2 million years ago, in the late Miocene period, the Strait of Gibraltar was blocked and the Mediterranean Sea evaporated into a deep basin with a bottom over two miles below the world ocean level.

The Strait of Gibraltar is a recent morphological feature that cuts across the structures of the Gibraltar arc, whose similarity on both shorelines has recently been established. The differential movements between Iberia and Africa since the Jurassic probably did not occur at the present location of the Gibraltar strait, but such evidence should be looked for farther north or south (Biju-Duval & Montadert, 1977). Likewise, communication between the Mediterranean and the Atlantic in the Messinian could have existed only farther north (Guadalquivir) or south (external Rif). See Figure 2.

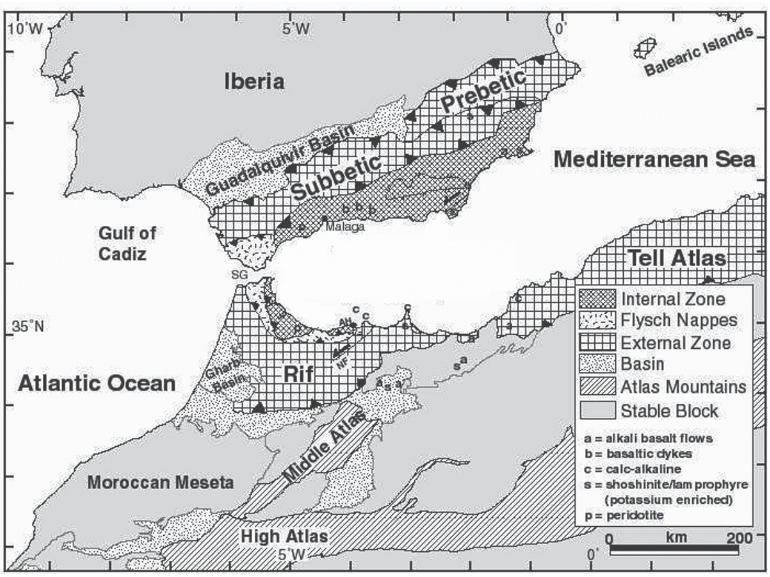


Figure 2. Principal geological features of the Gibraltar Strait Zone (Serrano et al., 2003)

3. GRAVITY DATA

The gravitation is the force of attraction which a body exerts on another. When it is exerted by the Earth, this force is called “gravity”. According to Newton's law of gravitation, the force of attraction increases when the mass increases. It also increases when one approaches the centre of mass. If a geological body is denser than another, its mass per unit of volume will be larger and the gravitational attraction which will be exerted on him will be stronger. Measurements of gravity do not provide much direct geological information, put aside the representation of the flattened spheroid shape of the Earth, unless corrections are not applied to them to compensate for the effects of the form of the Earth and its relief.

As the diameter of the Earth is of approximately 20 km shorter from one pole to another than in the equatorial plan, the force of gravity increases when one approaches the poles. Moreover, the rotation of the Earth makes so that the measured value of gravity is slightly lower at the equator than with the poles. In order to isolate the effects ascribable to side variations of density inside the Earth, it is necessary to remove the sum of the gravitational effects ascribable to the latitude.

4. BOUGUER GRAVITY ANOMALY

The studied zone is limited between longitudes West 5, 3 ° to 6, 2 °, and latitudes North 35, 7° to 36, 3°. The gravity data used were obtained from the “Bureau Géodésique International” showed in Figure 3, and were supplemented by aerial gravity data.

All measurements were brought back to the level of reference of the International Network of gravimetric standardization (International Association of Geodesy [I.A.G], 1971). The theoretical values of gravity were calculated using the gravimetric formula of the geodetic system of reference (I.A.G, 1971). The Bouguer anomaly was calculated by employing a vertical gradient of the gravity of 0,3086 mGal/m (Swick, 1942) and a density of 2, 67 kg/m^3 for crustal lithologies. A milligal is a convenient unit for describing variations in gravity over the surface of the Earth. 1 milligal (or mGal) = 0,00001 m/s^2, which can be compared to the total gravity on the Earth’s surface of approximately 9,8 m/s^2. Thus,

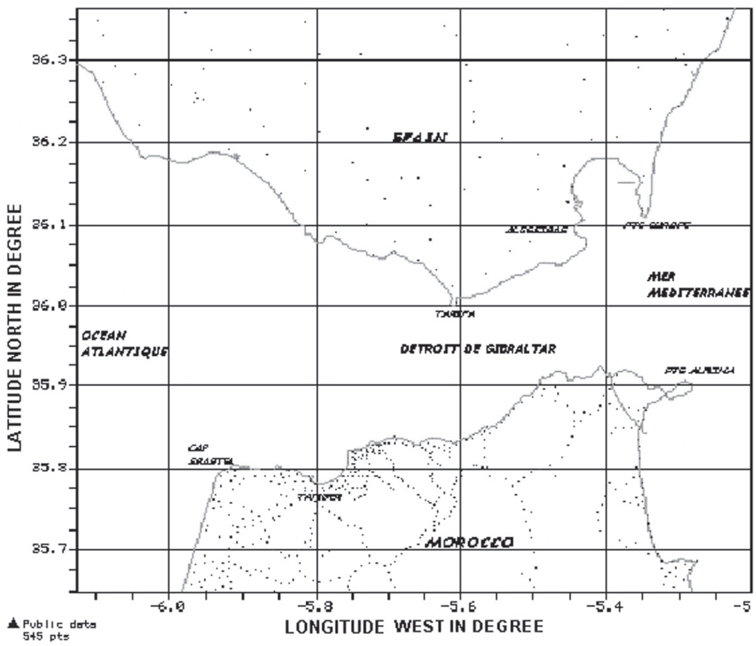


Figure 3. Data gravity reference map (Bureau Géodésique International B.G.I, 2005)

a milligal is about 1 millionth of the standard acceleration on the Earth's surface (Naudy et al., 1965).

If ϑ represents the geographical latitude of the station in degrees of a point given to the surface of the Earth, the theoretical value of gravity g_T in this point is provided by the following international gravimetric formula:

$$g_T = 978031{,}85(1+0{,}005278895\ \sin^2(\vartheta) + 0{,}000023462\ \sin^4(2\ \vartheta)\ \text{mGal}) \quad (1)$$

Bouguer (Δg_B) anomalies for each station were calculated using the following expression:

$$\Delta g_B = g_{obs} + (0.386 - 2\pi G\rho)\ H - g_T \quad (2)$$

where g_{obs} is the observed gravity, H is the orthometric altitude in meters, ρ is the average density of the crust (2,67 $kg \cdot m^{-3}$) and G the universal gravitational constant whose value is $6{,}673 \cdot 10^{-11}$ $N.m^3.kg^{-2}$. We applied this method to the gravimetric map of the area of the Strait of Gibraltar including Southern and Northern sides respectively of Spain and Morocco. This map, showed in Figure 4, was generated using about 540 stations of reference which made it possible to calculate a regular grid with a step of 450 m and also with about 1 mGal of precision. The Bouguer anomaly reflects the lateral variations of the density of the rocks.

4.1 Field procedures

Gravity is an excellent parameter and marker for distinguishing between different types and degree of alteration of rocks. Gravity surveys have long been successfully used by geophysicists and engineering geologists and the procedures are well established. The study area was selected for its representativity.

High values of Bouguer gravity anomaly were encountered due to the presence of near-vertical faulting between areas of contrasting resistivity, and fault zones which may contain more or less highly contrasting density materials. The lateral inhomogeneities of the ground can be

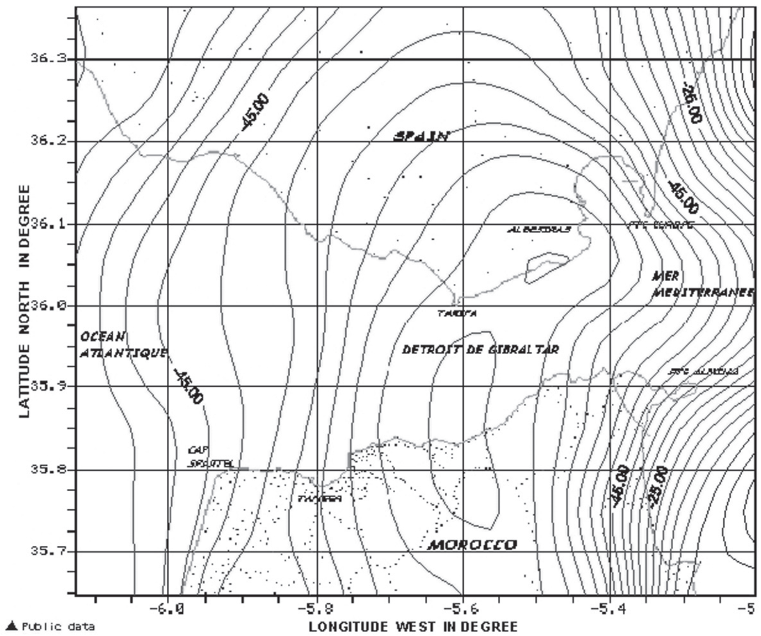


Figure 4. Bouguer anomalies map of the Gibraltar Strait Zone (interval contour 5 mGal) (The authors)

investigated by means of the gravity obtained from the survey. As the surface extension of the layers is displayed we may infer the presence or absence of any disturbances as well as any facies variations.

Gravity measurements are obtained from the harmonic potential V which fulfils Laplace's equation DV=0 in the surrounding space external to the body. The potential gradient falls off as $1/r^2$ (Blakely, 1995). As a first approximation, the scalar potential in the neighborhood of the perturbations and within the sources complies with the equation $\Delta V = -4\pi r^2 \rho\, \delta(r)$ whe $\delta(r)$ is the Dirac delta, ρ is the contrasting density in the anomalous region of the study area. The Bouguer gravity anomaly map which one obtains from such a survey is actually a map of discrete potentials on the free surface, and any major singularity in the Bouguer gravity anomaly due to the presence of a perturbation will be due to the crossing from a "normal" into a "perturbed" area or vice versa. In other words, the Bouguer gravity anomaly map may be considered a map of scalar potential differences assumed to be harmonic everywhere except over the perturbed areas which correspond to high contrasting density areas.

Interpretation of the Bouguer gravity anomaly is the process of extracting information on the position and composition of a target mineral body in the ground. The amplitude of an anomaly may be assumed to be proportional to the volume of a target body and to the contrasting density with the mother lode.

The horizontal and the vertical derivatives of the Bouguer gravity anomaly map produced by a potential source form a Hilbert transform pair and define an analytic signal (Nabighian, 1972). The analytical processing method also called the total gradient method is used for defining the edges of density anomalies in terms of spatial derivatives in orthogonal directions.

5. PROCESS

We have applied to the data operators in the spectral domain. Second vertical derivative and horizontal gradient are applied to the Bouguer gravity anomaly data. GeoGrid (Cooper, 2000, 2002) software was used for calculations. Indeed, the only knowledge of Bouguer gravity anomaly does not make it possible to delimit contours in a precise way. The interest of the spectral transformations appears thus fundamental in order to circumscribe the various gravity signatures of the studied zone. *f,g,h* are the expressions of the data, the transformed data and a filter respectively. F, G and H are their respective spectral expressions. In the space domain we have the following expression: $g = f * h$ where $*$ is the convolution symbol. FFT is the Fast Fourier Transform. The process is described as follows taking into consideration that the phenomena of aliasing and Gibbs being in addition are perfectly circumscribed by the symmetrization of the data in the space domain (regular grid) (Bakkali, 2005) :

$$\underset{\text{(space domain)}}{\text{data } f} \xrightarrow[\text{FFT}]{} \underset{\text{(spectral domain)}}{G(u,v) = F(u,v)xH(u,v)} \xrightarrow[\text{Inverse FFT}]{} \underset{\text{(space domain)}}{\text{transformed data } g} \quad (3)$$

6. GRAVITY SIGNATURES

6.1 Second vertical derivative:

A second vertical derivative Bouguer gravity anomaly map, showed in Figure 5, is calculated by the application of a spectral domain or space domain filter to the grid file. This results in an anomaly enhancement related to the "curvature" of the input data gravity. The second vertical derivative operator has the effect of sharpening anomalies (Bakkali, 2006a). The second vertical derivative operator in the spectral domain is:

$$\left(\pi^2 \left(u^2+v^2\right)\right) \quad (4)$$

where u and v are the orthogonal wave-numbers present in the map. When a second-derivative procedure is used, some additional improvement

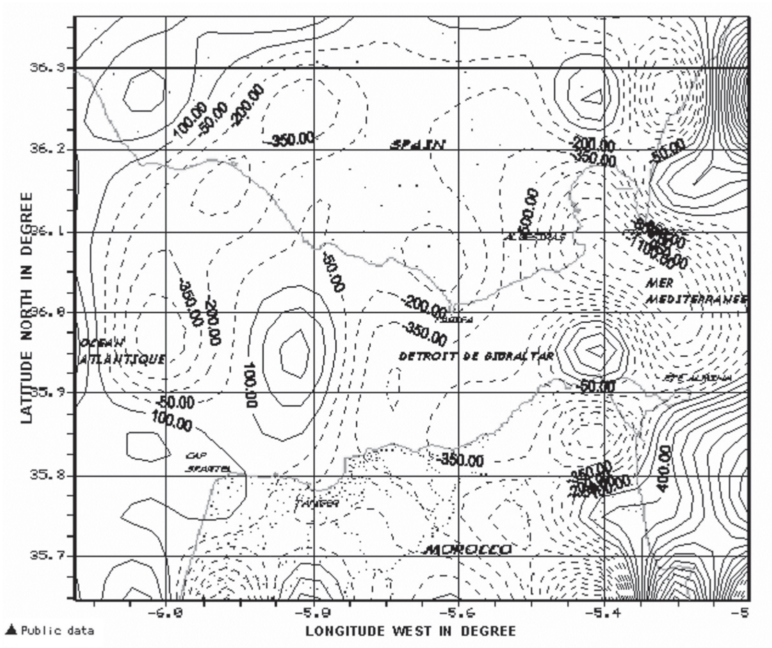


Figure 5. Second vertical derivative map of Bouguer anomalies of the Gibraltar Strait Zone (interval contour 150 mGal·km^{-2}, dash contours correspond to negative second vertical derivative signal)

(The authors)

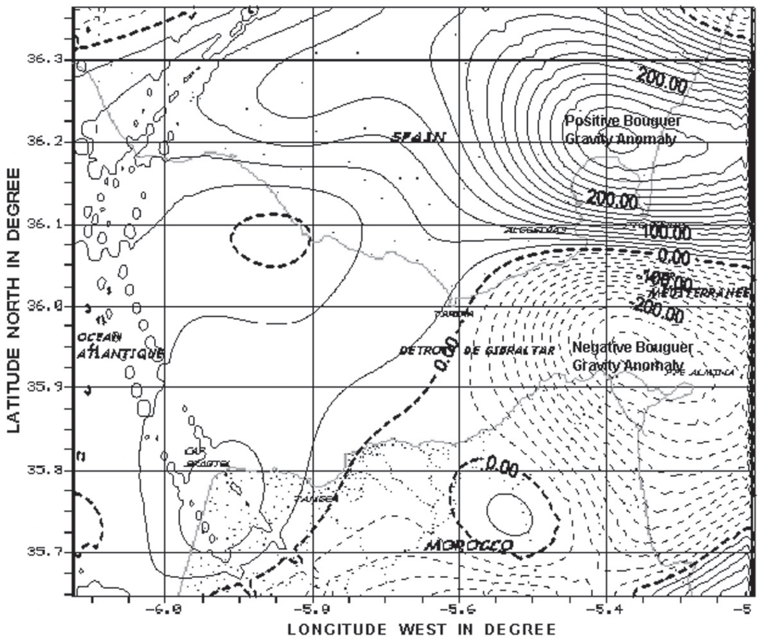


Figure 6. Horizontal gravity gradient map of Bouguer anomalies of the Gibraltar Strait Zone (interval contour 20 mGal·km^{-1}, dash contours correspond to negative horizontal gravity gradient signal)

(The authors)

may be obtained and visualization of the anomalies in depth can be found to be useful. The overall effect is that of scanning the anomalous bodies.

6.2 Horizontal gravity gradient

The magnitude of the horizontal gravity gradient g'(x,y)| is usually estimated by finite difference methods from values measured at gridded points on the Bouguer gravity anomaly map. The magnitude is determined using the following equations:

$$|g'(xy)| = \sqrt{\frac{\partial^2 g(xy)}{\partial x^2} + \frac{\partial^2 g(xy)}{\partial y^2}}$$

$$\text{with } \frac{\partial g(xy)}{\partial x} = \frac{g_i + 1j^{-g} i - 1j}{2\delta x} \text{ and } \frac{\partial g(xy)}{\partial y} = \frac{g_i j + 1^{-g} i\, j - 1}{2\delta y} \qquad (5)$$

where x is the longitudinal coordinate and y the latitude coordinate. g_i,j is the pseudo-gravity defined at grid point (i,j). Grid intervals in the x-direction and y-direction are δx and δy respectively. Maxima gravity gradient occur immediately over steep or vertical boundaries separating rock masses of contrasting densities (Bakkali, 2006b). On the gravity gradient map, lines drawn along ridges formed by enclosed high horizontal gradient magnitudes correspond to these boundaries. If the boundaries dip or if contributions from adjacent sources are significant, the maximum gradient will be shifted a certain distance from the boundaries (Cordell, 1982). The value of the intensity of the horizontal gradient Bouguer anomalies, showed in Figure 6, was calculated starting from a plan obtained by an adjustment by the method of least squares of a grid of five cells out of five cells centered on the point to determine. The filtered data raise the anomalies short wavelength which are the reflection of the existence of density contrasts close the surface.

6.3 Discussion and conclusion

The Bouguer gravity anomaly signatures of the area of study were circumscribed easily. The various gravity signatures show an inherent singularity with the Strait of Gibraltar. Indeed, in spite of the similarities of north and southern sides, the analysis of the map of the second vertical derivative shows that the area is greatly disturbed along longitude West 5, 4º. This effect is the resultant combined effects of topography and the local tectonic undulations. On the horizontal gradient Bouguer gravity anomalous map, the aera is dominated in the same position by an anomalic zone which represents a particular gravity signal of the Gibraltar Strait zone: this result is probably explained by strong gradients which materialize the brutal changes of density in the basement. That could be possibly used to locate the points of inflection of the vertical contacts (Cordell, 1985) between the internal (basalts) and external zones in the Spanish northern side of the Gibraltar Strait zone. The influence of the peridotites present on the southern side has also and probably to be considered.

Within sight of these results we propose for the future to consider the study of these strong gradients by multi-scale analysis by wavelets. Indeed, the superposition of the maximas determined on various scales will make it possible to highlight the various contacts present on the horizontal gradient map (Hornby, 1999). The linear contacts generally correspond to faults, whereas the contacts of circular form are the limits of the diapirs or intrusive bodies.

We have described a pilot study to test an analytical one. Standard data processing procedures were found to be consistently useful and the filtered maps may be used as auxiliary tools for decision making under field conditions.

BIBLIOGRAPHICS REFERENCES

Bakkali, S. (2005). *Analysis of phosphate deposit "disturbances" using the horizontal-gradient responses of resistivity data in Oulad Abdoun*. Morocco: Earth.Sci.Res.J.

Bakakli, S. (2006a). *Resistivity survey of phosphate deposits containing hardpan pockets in oulad Abdoun, Morocco, Geofisica Internacional* (pp.73-82). Mexico: Instituto de Geofísica, UNAM.

Bakkali, S. (2006b). *Using a shading method to optimize anomalies in a Moroccan phosphate deposit* (pp.21-32). *Salamanca: Stud.Geol. Salmant*.

Biju-Duval, B & Montadert, L. (1976). *Structural history of the Mediterranean Basin* (pp. 464). Paris: Editions Technip.

Blakely, R. J. (1995). *Potential theory in gravity and magnetic applications* (pp 441). Cambridge:Cambridge University Press.

Bureau Géodésique International (B.G.I.). (2005). Publications du Bureau Géodésique International. Extracted at August 2005 from www.bgi.cnes.fr

Cooper, G. (2000). Gridding gravity data using an equivalent layer. *Computers & Geoscience*, *26*, 227-233.

Cooper, G. (2002). Fixed point inversion of geophysical data. *Computers & Geoscience*, *28*, 799-808.

Cordell, L. & Grauch, V.J.S. (1982). *Reconciliation of the discrete and integral Fourier transforms, Geophysics* (pp. 237-243). Oklahoma: Society of Exploration Geophysicists.

Cordell, L. & Grauch, V.J.S. (1985). *Mapping basement magnetization zones from aeromagnetic data in the San Juan Basin, New Mexico*. *In: W.J. Hinze* (Ed.), of *Regional Gravity and Magnetic Anomaly Maps* (pp. 181-197). Oklahoma: Society of Exploration Geophysicists.

Hornby, P., Boschetti. F. & G. Horowitz. (1999). Analysis of potential field data in the wavelet domain. *Geophysical Journal International*, *137*, 175-196.

International Association of Geodesy (I.A.G.). (1971). Geodetic Reference System 1967. Du Bulletin Géodésique, *3*, 115.

Nabighian, M. N. (1972). The analytic signal of two dimensional bodies with polygonal cross section: its properties and use for automated anomaly interpretation. *Geophysics*, *37* (3), 507-517.

Naudy, H. & Neumann, R. (1965). Sur la définition de l'anomalie de Bouguer et ses conséquences pratiques. *Geophysical Prospecting* ,*13* (1), 1-11.

Serrano, I., Zahon, D., Morales, J. & Torcal, F. (2003). Seismic tomography from local crustal earthquakes beneath eastern Rif Mountains of Morocco. *Tectonophysics*, *367*, 187– 201.

Smitha, F. (2006). Macro History Prehistory of the 21th Century: Special Report. Extracted at April 2006 from www.fsmitha.com/h3/map34sg.html.

Swick, C. H. (1942). Pendulum gravity measurements and isostatics reductions. *U.S Coast and Geodetic Survey*, *232*, 82.

ABOUT THE AUTHORS

Saad Bakkali
Earth Science Department
Faculty of Science & Techniques of Tangier, Morocco
saad.bakkali@menara.ma

Mahacine Amrani
Engineering Process Department
Faculty of Science & Techniques of Tangier, Morocco
amrani.mahacine@menara.ma