Downloaded 02/07/24 to 143.107.252.247. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/page/policies/terms
DOI:10.1190/sbgf2007-064

Geoelectrical investigation to select an area to install a sanitary landfill over the Guarani aquifer

José Domingos Faraco Gallas, INSTITUTO DE GEOCIÊNCIAS DA USP, Brazil
Fabio Taioli, INSTITUTO DE GEOCIÊNCIAS DA USP, Brazil
Flávio Luiz Vieira, INSTITUTO DE GEOCIÊNCIAS DA USP, Brazil

Copyright 2007, SBGf - Sociedade Brasileira de Geofísica.

This paper was prepared for presentation at the 10th International Congress of the Brazilian Geophysical Society, held in Rio de Janeiro, Brazil, November 19–22, 2007.

Contents of this paper were reviewed by the Technical Committee of the 10th International Congress of the Brazilian Geophysical Society and do not necessarily represent any position of the SBGf, its officers or members. Electronic reproduction, or storage of any part of this paper for commercial purposes without the written consent of the Brazilian Geophysical Society is prohibited.

Abstract

Located mainly in Brazil, the Guarani Aquifer covers around 1.2 million square kilometers (463,323 square miles) and is characterized by sandstones (named, in Brazil, the Pirambóia and Botucatu Sandstones) covered by lava flows of the Serra Geral Formation of the Paraná Basin. It is considered one of the most important fresh water supplies in the world. The municipality of Timburi is located in the São Paulo State, Brazil, on the border of the basin where there are outcrops of basaltic rocks of the Serra Geral Formation and of the Botucatu Sandstone. The municipality has a population of about 3000 inhabitants and plans to become an important tourist attraction mainly due to its beautiful landscapes and the occurrence of several freshwater springs. One of the problems to be faced is that the domestic waste is taken to a landfill located over the Botucatu Sandstone, in the recharge zone of the aquifer. A geophysical survey was carried out to select an area over basaltic rocks for the installation of a new sanitary landfill. Several vertical electrical soundings were carried out to measure the thickness of the basaltic rock and the weathered basalt soil, which is relatively impermeable and considered an appropriate material for the foundation of the landfill. Profiles of resistivity imaging were carried out to verify the presence of vertical fractures in the basaltic rocks which could provide a hydraulic connection, allowing the percolation of the leachate in the event of leakage in the landfill. In addition, self potential measurements were taken to evaluate the groundwater flow direction. The results facilitated the rejection of areas with thin basalt and weathering thickness and areas where the basaltic rock contained vertical fractures and enabled the selection of an appropriate area to install a new sanitary landfill.

Introduction

Geophysical studies, particularly using electrical resistivity methods, have been increasingly applied to hydrogeological and environmental studies. Timburi is a municipality located in the southern region of São Paulo state, Brazil, and the domestic solid waste is disposed in a landfill in Botucatu Sandstone. This sandstone is characterized by its high porosity and permeability and is the main formation of the Guarani Aquifer. The landfill does not have any foundation treatment and the leachate generated by the waste infiltrates directly into the aquifer. The authorities of the county, following concerns from the scientific community, decided to move the landfill to an appropriate area. They selected an area located on the Serra Geral Formation (weathering soil from basaltic rocks) that, due to its low permeability would make a suitable choice for installation of a sanitary landfill. A geophysical investigation utilizing Vertical Electrical Soundings (VES) to define the thickness of the weathered soil, electrical profiling to analyze potential fracture zones with the potential to provide hydraulic connection between the landfill and the aquifer and, following, a self potential (SP) survey to analyze the groundwater flow direction was designed to confirm the site suitability.

Regional geology

The Paraná Sedimentary Basin is located in the South American Platform and is the location of the largest volcanic manifestation on earth. Its fractures and extension faults allowed the ascension of an enormous quantity of basaltic lava. The extent of the volcanism can be evaluated from the dimensions of the dykes, which can reach extents of more than 100 km and few hundreds meters of thickness (Almeida 1976). Fragmentation of the crust is closely related to the Gondwana partition. The Botucatu Sandstone (Triassic - Jurassic) was formed in a desert environment. It extends to a large portion of the southern region of Brazil, Argentina, Uruguay and Paraguay and is the main formation of the Guarani Aquifer, which has an area of 1.2 million km The aquifer thickness can reach 800 meters with an average thickness of 250 m and effective porosity of 15%. The estimated permanent water reserve is about 45,000 km. In most of the basin the Serra Geral Formation caps the Botucatu Formation, but the Botucatu Formation crops out in the marginal border of the basin. Timburi municipality is located in the Paraná Basin and in the region there are outcrops of both sandstone (Botucatu Formation) and basaltic rocks (Serra Geral Formation).

Methodology

An area was selected on the weathered basalt soil as being appropriate to receive the sanitary landfill. The area was investigated by geophysical survey techniques in order to determine the thickness of the weathered soil, the basalt thickness and eventually the presence of discontinuities with the potential to connect the sandstone to the landfill. Six Vertical Electrical Soundings (VES) were carried out using the Schlumberger array with current electrodes distances (AB) varying up to 400 m to determine the thickness of the different strata. They were

Downloaded 02/07/24 to 143.107.252.247. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/page/policies/terms
DOI:10.1190/sbgf2007-064

located at points where it was possible to carry out profiling and provide information to orientate the parameters for electrical resistivity imaging.

Electrical resistivity imaging was carried out using the dipole-dipole array, dipoles AB=MN=20m and five levels of investigation (n1= 20m; n2= 30m; n3= 40; n4= 50m e n5= 50m, respectively (Hallof 1957)). The dipole-dipole array was chosen in order to detect resistivity anomalies associated with faults or fractures in the basaltic strata. Three profiles (A, B and C) were carried out and the distance between the profiles were 30 m between A and B and 40 m between B and C. The length of the profiles was 380 m covering a total area of 26,600 m. A self potential (SP) survey was also carried out on the same profiles to detect the water flow direction. The same geophysical survey procedure was adopted for the second area.

Data processing and discussion

The vertical electrical soundings (VES) were interpreted based on pre-established geoelectrical models, consistent with the available geological data. The models were processed using public domain software that adjusts the initial model through mathematical iteration. The interpreter must be able to make modifications during the processing to impose limits and conditions that ensure compatibility with geological understanding. Figure 1 present a typical field bi-log VES curve (apparent resistivity versus distance), adjusted curve and interpretation of the resistivities and thickness of the different geoelectrical strata. The VESs results defined a soil thickness between 48 and 68 m, considered to be perfectly adequate to protect the Guarani aquifer.

Resistivity profiling (or imaging) measurements are normally presented as interpolated pseudo-sections (Hallof 1957). These pseudo-sections show the apparent resistivity distribution in the ground. The contour forms depend not only on the distribution of the resistivities measured but also the geometry of the adopted electrode array. Even very simple anomalous bodies (e.g. rectangular) may present completely different pseudo-sections, depending on the electrode array. Accordingly, it is necessary to apply inversion techniques in order to obtain a more precise (and geologically consistent) resistivity image. The resultant modelled sections are more representative of the ground resistivity distribution and consequently easier to correlate with the geological characteristics.

The modelled sections are the result of an automatic process of bi-dimensional (2D) inversion. The field data were processed using the RES2DINV (ABEM 1998) and Surfer 8 (Golden Softwares). The RES2DINV is inversion software that can be applied for electrical resistivity and induced polarization surveys. The results were exported in the format XYZ file to Surfer 8 that performed the data interpolation. RES2DINV uses a technique developed by deGroot-Hedlin & Constable (1990) and Loke & Barker (1996a, 1996b), which is based on the smoothness-constrained method being both fast and efficient in inverting resistivity data. Theoretically it produces a 2D subsurface model without the normal distortions caused by the geometry of the electrodes array.

Figure 2 presents one of the apparent resistivity pseudo-sections and the respective modelled section. Both show the resistivity contrast very clearly. The low resistivity (yellow and red) has a horizontal behaviour and is related to the soil and weathered rock. The stratum represented by green-blue colours, with higher resistivity, corresponds with the sound basalt. The vertical-sub-vertical zone with lower resistivity (marked with a bar in the figure) is clear evidence of a fractured zone. This association is normally expected since the fracture zones are more susceptible to the water percolation and consequent weathering of the minerals, which makes this zones richer in ions that favour electrical conduction and result in zones of lower resistivity (Gallas, 2000, Gallas 2003). Further sections of the same area present very similar results and are not presented here.

The area investigated supported a reasonable thickness of soil (soil and weathered rock) and rock above the sandstone. The maximum thickness encountered was 68 m and the minimum 48 m, both interpreted by the vertical electrical soundings. Potentially, soil compaction and the adoption of other simple engineering procedures could ensure the suitability of the area for the installation of a sanitary landfill. However, the geophysical survey detected a discontinuity crossing the area, this has been interpreted as a fracture in the basaltic rock, which reaches the sandstone.

This feature could lead to the eventual migration of the leachate produced by the waste, resulting in contamination of the Guarani Aquifer. The SP data were interpolated (Figure 3) and results indicate that the groundwater flow is towards the fracture. Based on these data the area was considered inappropriate and discarded.

Another area was selected by the municipality (based on geological mapping) and the same methodology was adopted. Since the area had the same dimensions as the first, the same amount of VES and resistivity profiling were carried out, as well as the SP survey.

The vertical electrical soundings indicate that the contact between the basalt and the sandstone lies at depths varying from 18 to 27 m (Figure 4). This thickness, despite being less than the first area, might be considered appropriate due to high percentage of clay (with hydraulic conductivity of about 10^{-5} cm/s) in the weathered basalt soil.

Figure 5 shows the central resistivity profile, which is representative of the results in the area. The results indicate good horizontal continuity of the strata and the absence of fractures, and the SP map shows no anomalous flow. The blue line in the modelled section indicates, approximately, the contact between the basaltic rock and the sandstone.

Conclusions

The proposed installation of a sanitary landfill in a region close to the border of the Paraná Basin, where outcrop rocks of the Botucatu Formation (main constituent of the Guarani Aquifer) necessitates careful planning and implementation in order to avoid the contamination of such an important groundwater reservoir. Despite the covering of basaltic rocks, the common presence of vertical/sub-vertical system of fractures, which may create preferential flow paths for contamination by leachate generated by the waste required investigation.

This study illustrated the methodology used for selection and testing of two areas. The first area presented thick rock and soil cover (48 to 68 m), which is appropriate for the installation of the landfill. However, the presence of fractures in the basalt meant the area was discarded due to the potential for aquifer contamination resulting from the migration of leachate down to the sandstone via fracture flow-paths. The second area presented a thinner cover (18 to 27 m) but is still suitable, due to its clayey composition. Furthermore, the absence of fractures indicated that area would be more appropriate for the locating of the sanitary landfill.

Acknowledgements: This work was supported by Pró-Reitoria de Cultura e Extensão of the Universidade de São Paulo. The Centro de Pesquisas de Águas Subterrâneas – CEPAS of the Universidade de São Paulo contributed with the infrastructure for the field survey.

References

Abem Instruments, 1998, Geoelectrical Imaging 2D & 3D – RES2DINV, ver. 3.3 for Windows 3.1, 95 and NT. Rapid 2D Resistivity & IP inversion using the least-squares method. By M. H. Loke. ABEM Instruments, P. O. Box 20086, S-161 02 Bromma, Sweden.

Almeida, F.F.M.; Hasui, Y.; Neves, B.B.B., 1976, The upper precambrian of South America. São Paulo, *Instituto de Geociência*s, Universidade de São Paulo, São Paulo. Bulletim 7, 45-80.

deGroot-Hedlin, C. & Constable, S., 1990, Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysic*s, **55** (12), 1613-1624.

Gallas, **J. D. F.,** 2000, *Main geoelectrical methods and their applications in mineral prospecting, hydrogeology, engineering geology and environmental geolog*y. DSc Thesis. Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Rio Claro, 174p. (in portuguese).

Gallas, J. D. F., 2003, Groundwater prospecting using indirect methods. *Revista do Instituto Geológic*o, **2**4, 43-51. (in portuguese).

Hallof, P. G., 1957, On the interpretation of resistivity and induced polarization measurements: Cambridge, MIT, Ph. D. thesis.

Loke, M. H. & Barker, **R. D.,** 1995, Least-squares deconvolution of apparent resistivity pseudosections. G*eophysic*s, **60** (6), 1682-1690.

Loke, M. H. & Barker, **R. D.,** 1996a, Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophysical Prospectin*g, **4**4, 131-152 .

Loke, M. H. & Barker, **R. D.,** 1996b, Practical techniques for 3D resistivity surveys and data inversion. *Geophysical Prospectin*g, **4**4, 499-523.

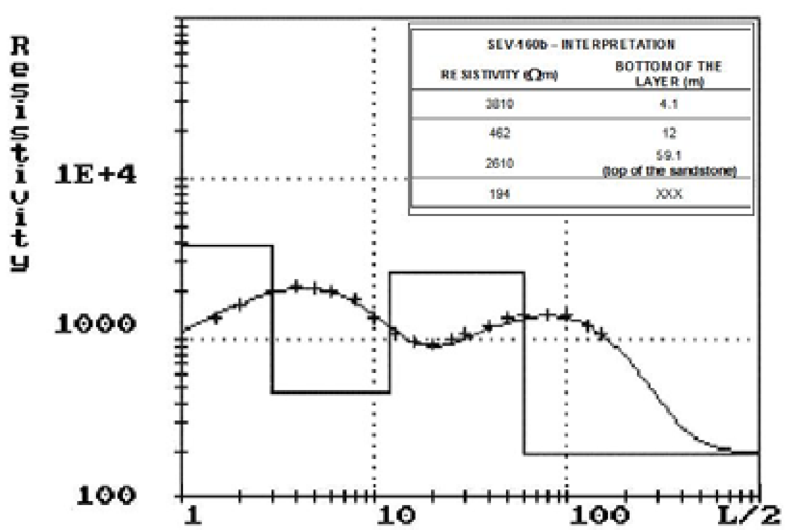

Figure 1. Typical VES result of the first area showing the contact between the basalt and the sandstone at 68 m of dept**h.**

Downloaded 02/07/24 to 143.107.252.247. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/page/policies/terms
DOI:10.1190/sbgf2007-064

Downloaded 02/07/24 to 143.107.252.247. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/page/policies/terms
DOI:10.1190/sbgf2007-064

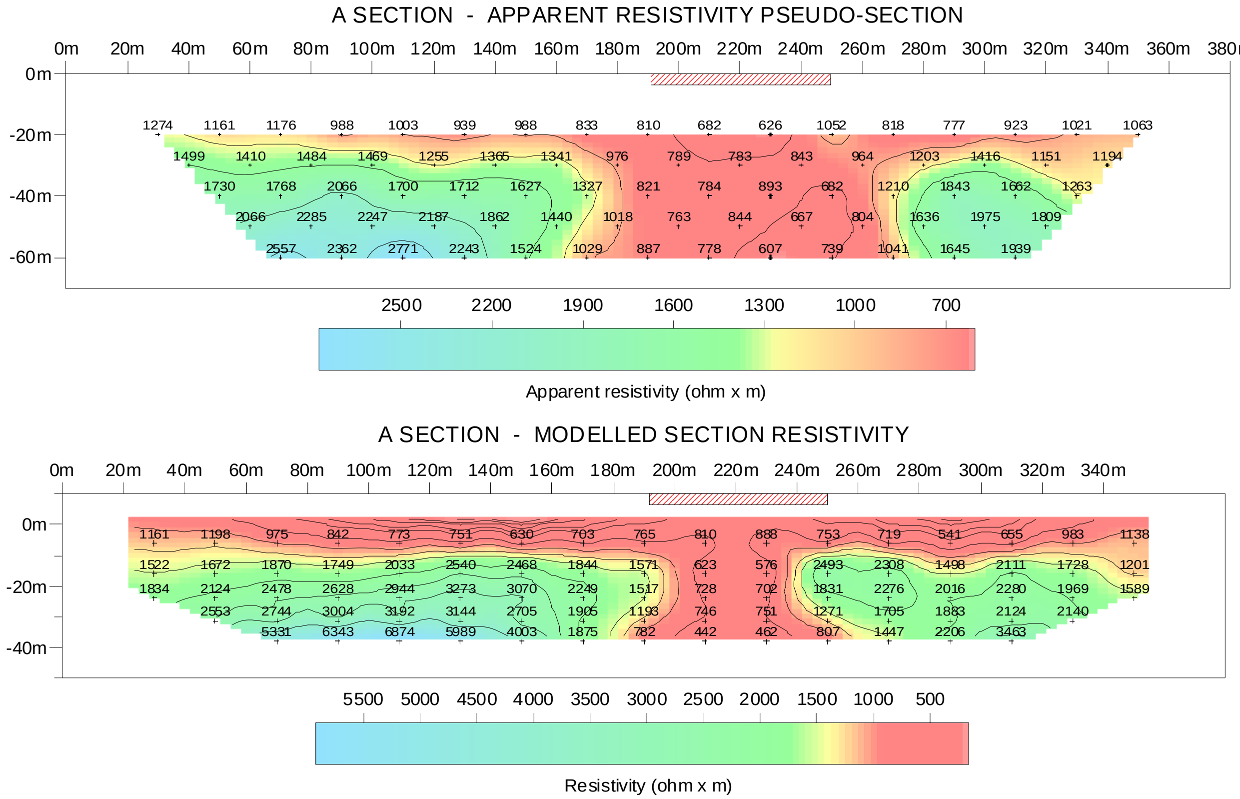

Figure 2 . Apparent resistivity pseudo-section and respective modelled section showing the fracture zone.

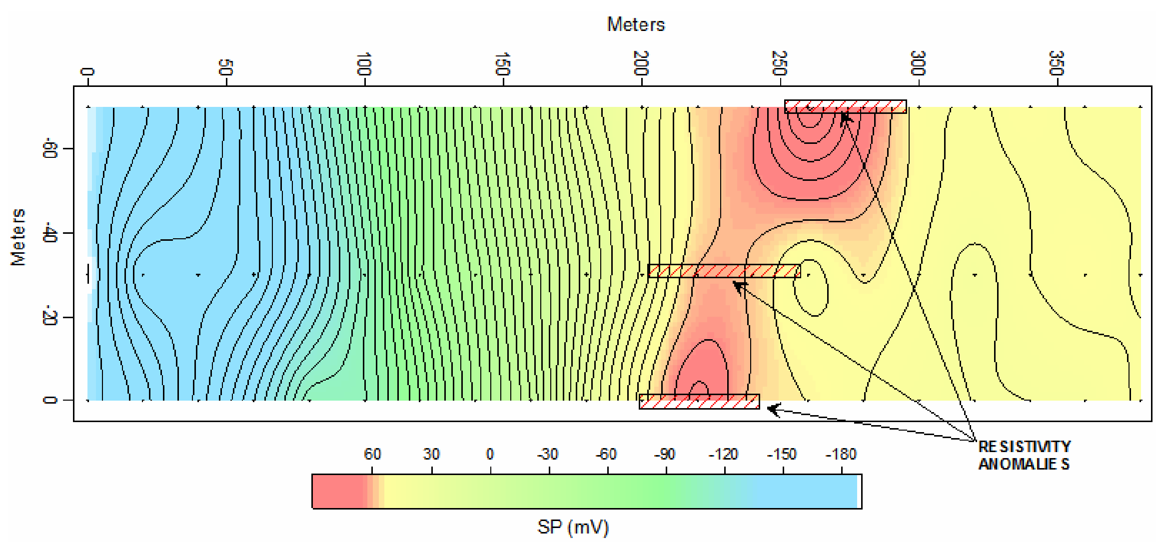

Figure 3. Self potential map pf the first area investigated.

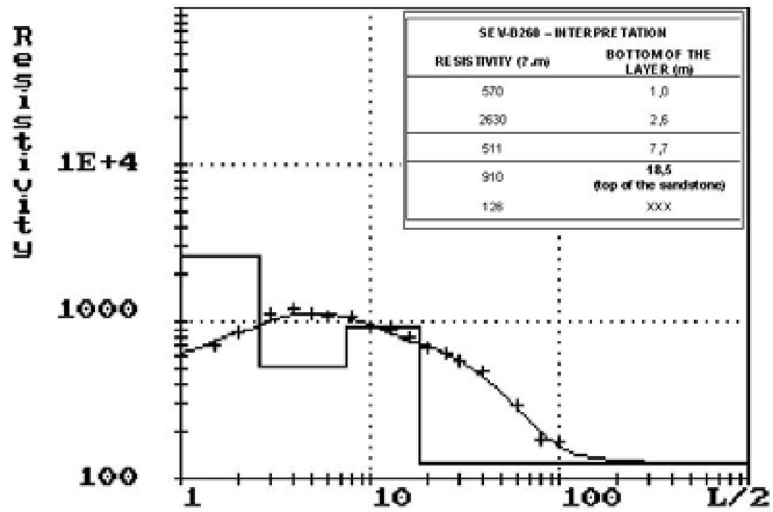

Figure 4. Typical VES result of the second area showing the contact between the basalt and the sandstone at 18.5 m of depth.

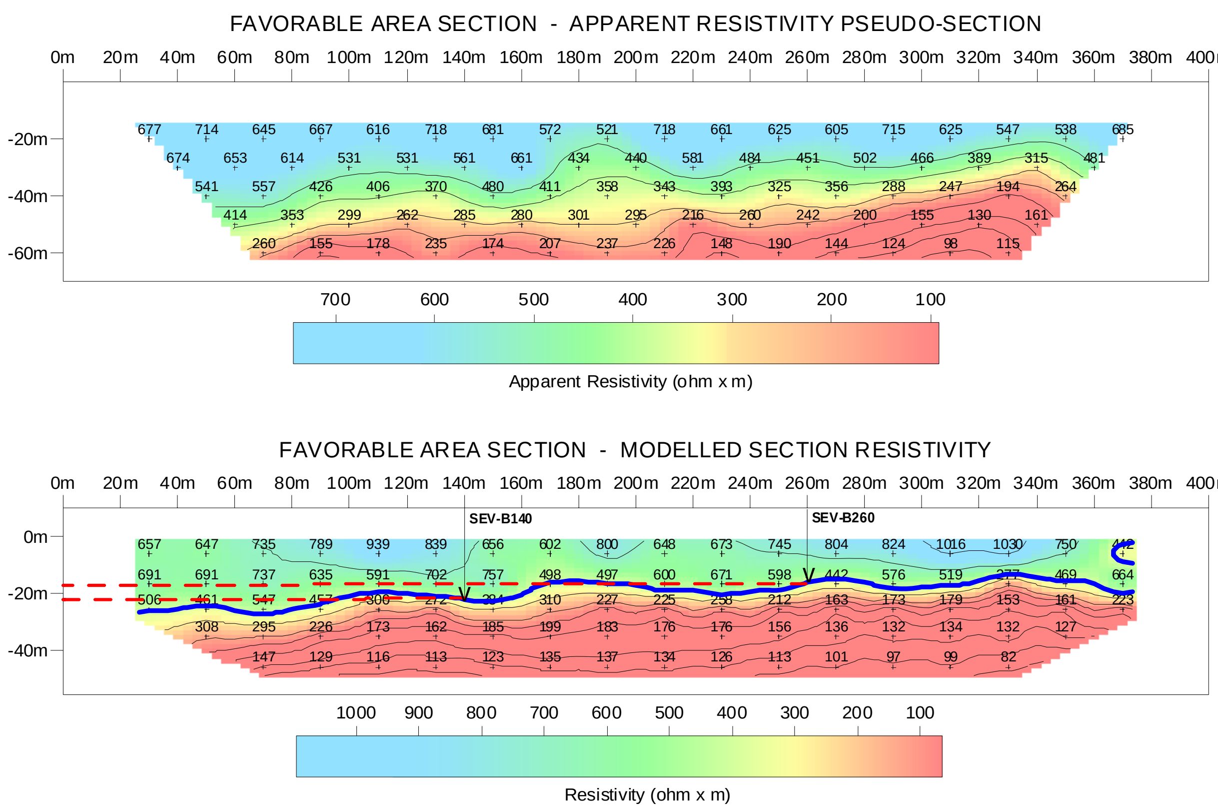

Figure 5. Apparent resistivity pseudo-section and respective modelled section showing the horizontal continuity of the strata.

Downloaded 02/07/24 to 143.107.252.247. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/page/policies/terms
DOI:10.1190/sbgf2007-064