Polynomial and Harmonic Representations of Regional Heat Flow Fields in the South American Continent.

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Summary

The geothermal data base for South America has recently been updated incorporating results of new heat flow measurements in the western (Bolivia and Chile) and eastern (Brazil) parts of the continent. This data base has been found to be useful in investigating regional trends of heat flow in the central parts of South America, even though the geographic distribution is highly non-uniform over large areas in the southern and northeastern parts. As a first step, polynomial methods were employed in generating maps of regional heat flow. The technique adopted is based on a general purpose least squares solution to determine the coefficients of a sixth order polynomial in latitude and longitude that provide best fit to the observational data set. The results obtained indicate low to normal values of regional heat flow (in the range of 40 to 70 mW/m^2) in the Brazilian platform and in the central Andes and higher than normal values (> 70 mW/m^2) in the Patagonian platform and in the southern Andes. The regional trends also reveal isolated pockets of higher than normal heat flow in some parts on the eastern continental margin. However, problems arising from low data density allow only limited insights into the nature of heat flow variations along and across the Andean region. Thus trends associated with changing tectonic patterns and subduction related magmatism cannot easily be identified in polynomial representations of the regional heat flow field. Comparison with manually contoured maps reveal that usefulness of polynomial and harmonic representations of regional thermal fields can be improved by incorporating empirical estimators of heat flow for peripheral areas, especially in cases where data quality is highly variable.

Introduction

Basic geothermal data is currently available for several hundred localities in South America, but there has been only a few attempts to evaluate the significance of such observations on a continental scale. Lack of understanding of regional geothermal fields has been an obstacle not only in understanding the nature of large scale tectonic processes but also in the development of geothermal resources (Barberi et al, 1987). In the first set of heat flow maps of the South American continent, by Hamza and Munoz (1996), manual and automatic contour maps of the observed heat flow values were presented. However, few efforts have so far been carried out to provide functional representations of regional heat flow fields. In this context, the present work is an attempt to present polynomial representation of heat flow in the South American continent, based on recent compilations of geothermal data.

Characteristics of the Data Base and Regional Distribution

Hamza and Munoz (1996) reported a data base consisting of heat flow values for 655 localities in South America. Since then additional heat flow measurements has been carried out in the Central Andean subduction zone in Bolivia and Chile (Springer and Foerster, 1998) and in the coastal region of southeastern Brazil (Hamza, 1997; Branco da Silva and Hamza, 1999). These new data sets provide valuable information on the nature of geothermal regime in selected localities and has lead to some improvement in the overall data density, which now stands at about 40 per million square kilometers. A summary of the mean heat flow values of the main geological structures is presented in Table 1.

The quality of the available data set is variable as different methods have been used for determining heat flow, depending on the nature and availability of primary geothermal data. Hamza and Munoz (1996) adopted a priority scheme, based on qualitative considerations of the relative advantages and disadvantages of the various methods, in the preparation of their heat flow maps. However, setting any specific rule concerning the reliability of the final calculated heat flow values is a difficult task, as the measurement techniques and data acquisition procedures have changed significantly over the years.

The non-uniform distribution of heat flow data in relation to the large scale-geological structures is another obstacle in understanding regional variations in the geothermal regime of South American continent and its relation to tectonics. The available data set allow estimation of representative values of heat flow for 39 out of 52 regional structures. The geographic distribution is relatively better for structures belonging to the Brazilian Platform and the Andean Region and modest to poor elsewhere. Heat flow is found to be variable in the Cordilleran region, with the eastern and southern parts having relatively high values compared to the western and northern parts. The general trend of increasing heat flow from the western coastal regions towards inland is found to be interrupted by a north-south trending low heat flow belt in the Pre-Cordilleran basins. In the eastern part of the continent heat flow is low to normal (<75 mW/m^2) in most parts of the Brazilian Platform. But relatively high values have been encountered in the Mesozoic rift basins (Potiguar, Recôncavo and Taubaté) situated within this platform area. There are some indications that heat flow relatively high in the western parts of the Patagonian Platform relative to its eastern parts.

The data set also reveal some variability in heat flow between structures falling into the same general group. For example in the Cordilleran Region the heat flow varies from values as low as 25 mW/m^2 in the coastal zones, to over 100 mW/m^2 in the Altiplano structure. Within the relatively stable Brazilian Platform heat flow is low (less than 40 mW/m^2) in Cratonic regions, but higher values of over 100 mW/m^2 has also been encountered in some isolated localities, in Precambrian fold belts in the northeast. The variability is however much less within individual structures. Regions with heat flow in the range 45 to 75 mW/m^2 include the Proterozoic fold belts of the Brazilian Platform, most of the intracratonic basins in the Brazilian Platform and eastern parts of the Patagonian Platform. The overall picture thus seems to be closely related to the tectonic setting of the continent.

Contour Maps of Observational Data

The available data base was used in generating automatic contour maps based on different grid construction and interpolation schemes (Jones et al, 1986). A variety of contouring schemes were tested using commercially available software packages that allow such methods as linear, nearest neighbor, kernel smoothing, weighted fill and kriging for data interpolation. In the present case, where data density is low and its distribution non-uniform, efforts were concentrated on testing contour maps produced by weighted fill and kriging.

An example of the contour map in which kriging is employed as the interpolation method is presented in **figure–1**. The dominant features in this map are the low heat flow zones in northern Peru and central Chile and the high heat flow zones in the southern Andes and in the Altiplano. The map also reveal the presence of areas with higher than normal heat flow in the south-central and northeastern parts of Brazil. Most of the Brazilian platform, comprising cratonic areas and Precambrian fold belts, have low to normal heat flow. Thus, in spite of problems associated with quality and non-uniform distribution the contour map of the observed heat flow values can be considered as providing an approximate picture of the regional heat flow pattern in the South American continent. The limitations imposed by the available data set are obvious and the extent to which such features represent true variations in the regional geothermal field depend on how representative the data are of the deep thermal regime. This problem is intimately related to the specific nature of data set and further advances can be achieved only with improvements in both the quality and quantity of the data base available.

Polynomial Representation of Regional Heat Flow Field

Polynomial (or trend surface) analysis is usually recommended for examining regional heat flow patterns of areas, generally not exceeding the size of continents (Cermak, 1983). In this method the spatial distribution of heat flow is represented by a polynorm, of selected order of expansion, the coefficients of which are determined using a system of equations, corresponding to the number of measured values. This in turn allow calculation of the trends of surface heat flow depending on the order of expansion of the polynomial (Haenel, 1971; Vassour and Nouri, 1980). In the present case, the computer implementation of the trend surface analysis by least squares method was achieved using a modified version of the algorithm by Malin et al (1982). The choice of optimal degree of the polynomial representation is based on the procedure suggested by Zeng (1989). Examination of the magnitude and distribution of residual anomalies indicate that sixth order representation is a reasonable choice, that is also compatible with the quality of the basic data. Trend surface maps were generated subsequently using commercially available software packages such as GMT (Wessel and Smith, 1992) and SURFER (Golden Software Inc., 1994).

As an example of the results obtained we present in **figure–2** the sixth order representation of the heat flow pattern based on 695 data. As expected, the polynomial representation has filtered out short wavelength anomalies. Large variations in data density has also lead to elimination of some of the structurally important features discernible in the contour map of observational data (Figure 1). Increasing the order of the polynomial for the recognition of such features is possible only with considerable improvements in the existing data base. The most conspicuous feature in the polynomial representation is the presence of a belt of low heat flow extending from the western border of the content in Peru to the mouth of Amazon river in the east. It is noteworthy that this belt cut across not only the geologically recent cordilleran region in the west but also the older cratonic areas in the east. The width of the belt, in its eastern parts, follows roughly the geometry of the east-west sequence of sedimentary depressions in the Amazon region. Heat flow data from the adjacent cratonic areas of Guyana and Guaporé are necessary to rule out the possibility that it is an artifact of trend surface analysis in regions of poor data density.

On the other hand, the polynomial representation reveals clearly the presence of regions of high heat flow along cordilleras in the southern parts (including the western margin of the Patagonian Platform) and areas comprising Venezuelan Andes in the northern parts of the continent. Lack of suitable heat flow data has not allowed identification of major geothermal areas in Colombia and Ecuador. The map also reveal the presence of relatively high heat flow areas along the eastern border of Brazil. Low to normal values of heat flow are indicated for most of the Brazilian platform that include São Fransisco craton and areas of Proterozoic fold belts.

Discussion and Conclusions

The results obtained in the present work has allowed additional insights into the thermal regimes of tectonic processes affecting the western segment of the South American continent. For example, the elongated east-west trending belts of low heat flow in northern Peru (between latitudes 5 and 15^{o}S) occurs in a region where active volcanism is absent and where, according to several studies (e.g., Cahill and Isacks, 1992), a flattening of the Wadati-Benioff zone is observed. Van den Beukel and Wortel (1987, 1988) presented results of thermo-mechanical models indicating that heat flow may remain at values below 40 mW/m^2 for distances of up to several hundred kilometers from the trench line, as a result of sub-horizontal subduction. It is thus possible that low heat flow values in the cordilleran regions in Perú is a consequence of underthrusting of cold oceanic crust eastward of the trench line in western South America. However, the eastward extent of the low heat flow belt is quite large, having dimensions of several thousand kilometers. It would mean that low angle subduction started almost at the same time as the opening of the Atlantic. Suitable thermo-mechanical model studies are necessary to examine the efficiency of low angle subduction process in generating such elongated belts of low heat flow.

In contrast, zones of high angle subduction in southern Peru and Chile, as well as that in southern Patagonian Cordillera are characterized by high heat flow. Thus, the trend surface maps of the present work seem to suggest that the thermal regimes of wide tectonically active plateaus associated with high-angle subduction zones are distinctly different from those of the narrow non-volcanic cordilleras overlying the low-angle subduction zones. Supporting evidences can be found in the recent results of geoelctromagnetic soundings and seismic tomographic studies. For example, two-dimensional imaging of shear wave velocities by Zhang and Tanimoto (1991) as well as its extension to three dimensions by Anderson et al. (1992) indicate high-velocity structures beneath the central part of western South America, that can be interpreted as indicative of a relatively cold environment at the lower crustal and upper mantle depths in these regions. Studies of anelastic attenuation by Sacks and Okada (1974), Chinn et al (1980) and Whitman et al. (1992) also reveal a pattern that is compatible with the heat flow variations depicted in the maps of the present work. Thus, high heat flow areas such as the Altiplano and Puna blocks are characterized by high values of (anelastic) attenuation while relatively low values of attenuation are observed in areas of low heat flow. Results of geoelectromagnetic soundings in the high heat flow areas of central Andes by Muñoz et al. (1992) and Schwarz et al. (1994) indicate the presence of extremely high values of electrical conductance. Though the nature of source material giving rise to such electrical conductance anomalies is not known in detail, the possibility that it is related to the presence of partially molten rocks cannot be ruled out.

In conclusion, the trend surface maps of heat flow presented here may be considered as providing an overall view of large-scale heat flow variations within the South American continent. The maps have allowed identification of several new features in the regional geothermal regime and, with further improvements in the data base, can serve as a convenient starting point in the analysis of local anomalies.

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References

Anderson, D. L., Tanimoto, T. and Zhang, Y. S., 1992, Plate tectonics and hot spots: the third dimension. *Science* **256**, 1645-1651.

Barberi, F., Cataldi, R. and Merla, A., 1987, Resources and development perspectives of geothermal energy in Central and South America. *Proc. Int. Meeting on Geothermics and Geothermal Energy, Guarujá, São Paulo* (Edited by Hamza, V.M. et al.), Special Issue *Rev. Bras. Geofisica* **5**, 245-265.

Branco da Silva, L. and Hamza, V.M., 1999, Fluxo Geotérmico na parte oeste do estado de Rio de Janeiro, 6th International Congress of the Brazlian Geophysical Society, Rio de Janeiro.

Cahill, T. and Isacks, B. L., 1992, Seismicity and shape of the subducted Nazca plate. *J. Geophys. Res.* **97**, 17503-17529.

Cermak, V., 1983, The construction of heat flow density maps. *Zbl. Geol. Palaont*. Teil I, H1/2, 57-69.

Chinn, D.S., Isacks, B. and Barazangi, M., 1980, High frequency seismic wave propagation in western South America along the contiental margin, in the Nazca plate and across the Altiplano. Geophys. J. Roy. Astron. Soc., 60, 209-244.

Golden Software Inc. (1994) SURFER Version 5.01 - May 10 1994 Surface Mapping System. Golden, Colorado (USA).

Haenel, R., 1971, Heat flow measurements and a First Heat Flow Map of Germany, J. Geophys., 37, 119-134.

Hamza, V.M., 1997, Terrestrial heat flow in the Archean Coastal Complex in the state of São Paulo, Brazil.

Hamza, V.M. and Muñoz, M., 1996, Heat flow map of South America, Geothermics, 25(6), 599-646.

Jones, T. A., Hamilton, D.E. and Johnson, C.R. (1986) Contouring geologic surfaces with the computer. Van Norstrand Reinhold, New York, 270p.

Malin, S.R.C., Barraclough, D.R. and Hodder, B.M., 1982, A compact algorithm for the formation and solution of normal equations, Computers and Geosciences, 8, 355-358.

Muñoz, M., Fournier, F. G., Mamani, M. and Borzotta, E. (1992) A critical review of magnetotelluric studies in diverse tectonic areas in Argentina, Chile and Antarctica. In *Electromagnetic Results in Active Orogenic Zones* (Edited by Adam, A.), *Special Issue Acta Geod. Geoph. Mont. Hung*., Budapest **27**, 65-86.

Muñoz, M. and Hamza, V.M. (1993) Heat flow and temperature gradients in Chile. *Studia Geophys. et Geod*., Prague **37**, 315-348.

Pollack, H. N., Hurter, S. J. and Johnson, J.R. (1993) Heat flow from the Earth's interior: Analysis of the global data set. *Reviews of Geophysics* **31**, 267-280.

Polyak, B. G. and Smirnov, Y. A. (1968) Relatioship between terrestrial heat flow and tectonics of continents. *Geotectonics* (Eng. Transl.) **4**, 205-213.

Sacks, I. S. and Okada, H. (1974) A comparison of the anelasticity structure beneath western South America and Japan. *Phys. Earth Planet. Inter*. **9**, 211-219

Schwarz, G., Chong Diaz, G., Kruger, D., Martinez, E., Massow, W., Rath, V. and Viramonte, J. (1994) Crustal high conductivity zones in the southern central Andes. In *Tectonics of the Central Andes* (Edited by Reutter, K.J., Scheuber, E. and Wigger, P.), Springer, Berlin, 49-67.

Smalley, R. and Isacks, B. L. (1990) Seismotectonics of thin- and thick-skinned deformation in the Andean foreland from local network data: evidence for a seismogenic lower crust. *J. Geophys. Res*. **95**, 12487-12498.

Souza, J.L. (1994) Shear wave velocity beneath eastern parts of Brazil. *Regional Seismological Assembly in South America*, Brasilia, August 22-26, Book of Abstracts, 65p.

Springer, M. and Foerster, [a], 1998, Heat flow density across the Central Andean subduction zone, Tectonophysics, 291, 123-139.

Van den Beukel, J. and Wortel, R. (1987) Temperature and shear stresses in the upper part of a subduction zone. *Geophys. Res. Lett*. **14**, 1057-1060.

Van den Beukel, J. and Wortel, R. (1988) Thermo-mechanical modelling of arc-trench regions. *Tectonophysics* **154**, 177-193.

Wessel, P. and Smith, W. H. F. (1992) The GMT-System version 2.1, Technical Reference and Cook-book. School of Ocean and Earth Science and Technology, University of Hawaii, Hawaii (USA).

Vasseur, G. and Nouri, Y., 1980, Trend of heat flow in France: Relation with Deep Structure, Tectonophysics, 65, 209-223.

Whitman, D., Isacks, B. L., Chatelain, J. L., Chiu, J. M. and Perez, A. (1992) Attenuation of high-frequency seismic waves beneath the central Andean plateau. *J. Geophys. Res*. **97**, 19929-19947.

Zeng, H., 1989, Estimation of the degree of polynomial fitted to gravity anomalies and its application, Geophysical Prospecting, 37, 959-973.

Zhang, Y.S. and Tanimoto, T. (1991) Global Love wave phase velocity variation and its significance to plate tectonics. *Phys. Earth and Planet. Inter*. **66**, 160-202.

Table 1. Heat flow values for the main regional structures in South America. 'N' is number of data. "Overall" refers to the entire data set while "Representative" refer to the reduced data set in which values based on geochemical methods have been eliminated.

Structural Unit	Mean Heat Flow (mW/m^2)			
	N_o	Overall	N_R	Representative
Cordilleran Regions	196	103 +/-78	88	59 +/- 32
Precordilleran ranges and basins	100	54 +/- 25	81	44 +/- 11
Cratonic Areas and Fold belts	128	65 +/- 23	69	59 +/-23
Phanerozoic Interior Basins	195	63 +/- 23	171	58 +/- 20
Mesozoic Coastal Basins	22	58 +/- 10	20	59 +/- 10
Post Mesozoic Rift Basins	46	84 +/- 26	39	82 +/- 27
Northern Basins and Depressions	2	106 +/- 24		
Patagonian Platform	6	74 +/- 13	3	76 +/- 21
Total	695	74 +/- 51	471	59 +/- 30

Fig. 1. Automatic contour map of observed heat flow in South America. The contour values are in mW/m^2.

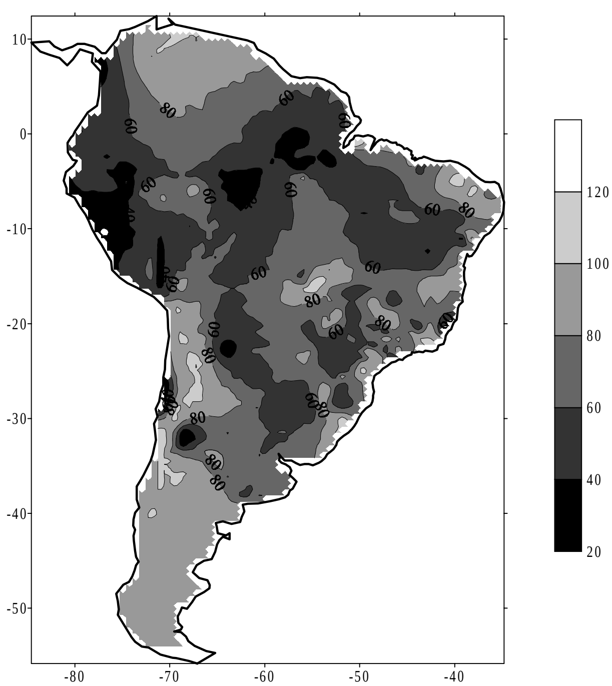

Fig. 2. Degree 6 polynomial representation of heat flow in South America. The contour values are in mW/m^2.