GEOTEMPERATURES, RHEOLOGICAL ZONATION AND SEISMICITY OF THE CONTINENTAL CRUST OF WESTERN SOUTH AMERICA

MUÑOZ, M., Sc. Coll., Departamento de Geofisica, CRICYT, Mendoza, Argentina

Summary

The relevant thermophysical parameters and models of gravity structure are used to determine the rheological stratification of the crust in several areas along the Andes region. Brittle and ductile behaviours are studied in the frame of the Anderson-Sibson faulting theory and Dorn's formulation of non-linear rheology. The seismogenic thickness **Z(Q)** thus obtained for different areas is compared with the maximum observed seismogenic depth **Z(S)** in the same areas. It is shown that geotemperature generally imposes a cut-off to the generation of earthquakes. This reflects the property of crustal materials to flow under stresses when some characteristic thermal conditions are attained. In the cases examined here, the stress field is mainly induced because of the interaction between the Nazca and the South American plates. A visco-elastic to viscous zonation characterizes these plates which are thought to represent the upper parts of convection cells in the tectonosphere.

Introduction

Surface heat flow in the Andes region is very variable spanning the whole range of values observed in continental areas, i.e. from about 10 to 180 mW/m2 (Hamza and Muñoz 1996; Springer and Förster 1998). A variable thermal structure and the associated rheological zonation with different depths of the brittle-ductile transition have been seen to conform significant constraints on the distribution of seismicity (e.g., Magnitskiy 1967; Sibson 1982; Ito 1990; Kononov *et al.* 1993; Muñoz 1994; Magistrale and Zhou 1996).

Knowledge of the thermal and gravity fields of the earth, and of parameters derived from seismological studies and creep experiments, allows the construction of rheological profiles of the lithosphere. The approach followed here is the comparison between a linear frictional fracture criterion describing a brittle regime (Anderson-Sibson's formulation) and a nonlinear flow stress (Dorn's equation) corresponding to a ductile rheology (e.g., Ranalli 1991). Creep experiments provide a set of parameters for lithospheric rocks in the ductile domain (e.g., Carter and Tsenn 1987) from which temperatures for the transition from brittle behaviour in different lithologic media can be estimated. These estimates have been proven to be in agreement with temperatures determined for the rheological transition in different tectonic regions where thermal and seismological observations are available. In some cases this transition is observed at temperatures of about 250 - 400 °C (e.g., Williams 1996) but generally in the crust, 450 $\pm$ 100 °C isotherms separate the brittle from the ductile regime (e.g., Ito 1990; Lewis *et al.* 1992; Muñoz 1994). In the upper mantle the critical isotherm for the rheological transition is usually in the temperature range 600 $\pm$ 50 °C (e.g., Keith 1993; Anderson 1995).

In the Andes, the distribution of seismic activity in the continental crust and uppermost mantle has been seen to be strongly related to the thermal structure. In this contribution some previous results (Muñoz 1995) are revisited and new observations and inferences are presented and discussed.

Thermal Structure

Geotherms in this work are generally computed in zones far from the oceanic trench (200-300 km) where the thermal structure of the continental crust and uppermost mantle and the distribution of seismic activity in these layers are not significantly related to processes occurring in connection with the Wadati-Benioff zone (e.g., Szádeczky-Kardoss 1977; Honda and Uyeda 1983; Cahill and Isacks 1992). In the volcanic arc and geothermal areas, very high values of heat flow can be due to isolated magmatic bodies where the circulation of fluids adds a strong convecting component to the observed heat flow (Muñoz and Hamza 1993; Springer 1999). This effect has to be considered for calculating thermal models, and independent methods should be used to impose a limit to these high values.

A large number of geotherms were computed following the procedure described by Chapman and Furlong (1992). Temperatures at the crust-mantle boundary (CMB) are shown in Table 1. L, N, A and J represent different cordilleran areas in Peru where gravity and seismicity data are available also. The description (L - Lima, N - Nazca, A - Arequipa, J - Juanjui) follows from Fukao *et al.* (1989). AP corresponds to areas of the Altiplano where high heat flow has been observed (see Table 1). In the coast range of Perú it was obtained that temperature of the CMB does not exceed values of about 150-200 °C, increasing eastwards to about 450-830 °C. This depends not only on the characteristic heat flow pattern (Hamza and Muñoz 1996) but also on the crustal thickness and stratification (Fukao *et al.* 1989). In areas of the Altiplano with high heat flow, temperature of the CMB can reach values of about 1000-1100 °C.

Low mean geothermal gradients in the crust (8 - 12 °C/km) are characteristic of large areas in the Peruvian Andes, Norte Chico (Chile), Sierra Pie de Palo and Central Cordillera (Argentina). Mean gradients of intermediate magnitude (12 - 15 °C/km) are characteristic of zones of Venezuela, Colombia, Ecuador, some areas of the Altiplano (Bolivia - Chile), southwestern Peru and central Chile. Excepting hot spring areas and zones very close to active volcanoes, high mean gradients (20 - 30 °C/km) are obtained in the cordilleras of Colombia, in the south volcanic zone and in the Patagonian Cordillera. High gradients are principally due to transient phenomena and not to heat generated by radioactive elements. At the present time no high value of radiogenic heat production has been obtained in granitoids of the Andes region. Erosion seems to be an important factor involved in the removal of crustal radioactive sources (Muñoz, 1991).

Rheological Zonation

A variable thermal structure beneath the Andes is manifested as a complex rheological zonation both in the N-S and E-W directions with different levels of the brittle-ductile transition. **Z(Q)** is calculated for several cases assuming the pore fluid to be hydrostatic and a strain rate of 10**(-15) /s in the ductile region. Creep parameters corresponding to different rocks in a layered tectonosphere are taken from the compilation of Ranalli (1991). The description of a layered crust follows from the regional seismic velocity structure or from density

TABLE 1. Andes Region. Thermo-rheological and seismic parameters. Q: surface heat flow; H: thickness of the crust; TCMB: temperature crust-mantle boundary; TBD: temperature brittle-ductile transition; Z(Q): crustal seismogenic thickness determined in this work; Z(S): maximum depth of observed crustal seismicity.

Area	Q mW/m2	H km	TCMB °C	TBD °C	Z(Q) km	Z(S) km
Colombia-Ecuador						
Central Cordillera	100 - 60	45	1100 - 800	320 - 500	10 - 15 - 20	20 *
Perú						
Zone L	35	50	450	450	50	50
Zone N	40	65	650	530 - 570	45 - 50	60
Zone A	50	64	830	570	35	35 - [60]
Zone J	50	33	480	460	30	33
Bolivia-Chile						
Altiplano	100 - 80	70	1100	440	15 - 10	shallow seismicity
Argentina						
Eastern Cordillera	80 - 60	60 - 50	800 - 700	570 - 520	40 - 30	50 - 30
Sierra Pie de Palo and Central Precordillera	50 - 35	50	650 - 400	330 - 370	20 - 45	25 - 45
Chile						
Norte Chico	35	40	340	300 - 350 ductile range	33 - 42 ductile domain	52 **
Central Valley	85 - 65	30	800 - 700	410	7 - 10 - 15	shallow seismicity
Cajón del Maipo	60	50	730 - 840	470	20 - 25	20 - 25
South Volcanic Zone	100 - 75	35	1100 - 1030	390	7 - 12	not explored
Region of the Lakes-Coastal Range	50	26	490	370	18	shallow seismicity

Notes

1. In the Central Cordillera (Colombia-Ecuador) (see *), seismic activity is observed at deeper depths also (...seismogenesis in the brittle-ductile transition?)

2. In the Norte Chico (Chile), the uppermost mantle is brittle and there is only a short transition to the ductile domain between 33 and 42 km depth. For other models the whole crust and uppermost mantle are brittle. Z(S) is indicating seismic activity in the uppermost mantle (see **)

3. Tectonics and the heat flow pattern of Venezuela are very complex. Heat flow values from about 60 to 80 mW/m2, increasing estwards of the Gulf of Venezuela, could indicate that the thickness of the seismogenic layer decreases from 20 to 10 km. These values accord with observed seismic activity of moderate magnitude associated to the Oca-Ancón fault system.

4. In the Altiplano, these values of Z(Q) correspond to zones of high heat flow. Z(Q) can reach values of about 25 km in zones of the Altiplano where heat flow is not high.

5. Z(Q) was determined using the appropriate thermal and energy activation parameters, and gravity models communicated by several authors in the last two decades. Z(S) is taken mainly from works published during the period 1989-1999. Reasons of space prevent complete references.

distribution in regional gravity structures. Reasons of space prevent the presentation of detailed rheological profiles in this abstract. In Table 1, several parameteres and results are shown and the seismogenic thickness **Z(Q)** for different areas as obtained in the rheological approximation is compared with the maximum observed seismogenic depth **Z(S)**. From these results, it is seen that in some cases -like in large areas of Peru, in the Norte Chico (Chile) and in the Sierra Pie de Palo (Argentina)- the brittle regime dominates almost throughout the crust; in these cases the total strength of the crust is very large and earthquakes of intermediate magnitude can be there generated. In one model for the Norte Chico (Chile), the brittle regime reinitiates in the uppermost mantle after a short transition into the ductile regime; in other model, the complete section down to 75 km -nearly the depth of the Wadati-Benioff zone in the area considered- is brittle. Also, in cordilleran areas of central Chile (e.g., Cajón del Maipo) the total strength of the crust is large. The strength is low in the south volcanic zone, which should mean that no earthquake of significant magnitude can be generated in this area.

Conclusions and Discussion

Low and "normal" heat flow areas where mean geothermal gradients are not large may be subjected to earthquakes of significant magnitude with foci in the middle and lower crust and uppermost mantle. The geotemperature generally imposes a cut-off to the seismic activity. Generally, the cut-off temperatures for crustal seismicity are encompassed by 450 $\pm$ 100 °C. The lowest temperatures in this range usually represent short transitions into the ductile regime in areas of low heat flow (Table 1), Earthquakes of moderate or intermediate magnitude can be generated in mountain areas of Colombia and Ecuador, large cordilleran areas of Perú, surrounding areas of the Altiplano, Norte Chico (Chile), Central Precordillera (Argentina), Cajón del Maipo and central cordilleran zone of Chile. The south volcanic zone is free from this class of earthquakes.

The areas of the Altiplano with high heat flow -like the one lying from about 20 ° to 21 °S- have large crustal temperatures reaching 800 - 1100 °C. There is agreeement with magnetotelluric results showing a high electrical conducting zone from the middle to the lower crust in such areas (Schwalenberg *et al.* 1999). These results contrast with the suggestion of Beck *et al.* (1999) -done on the basis of crustal velocities and Poisson's ratio studies- that there is less than a few percent of melt in the Altiplano crust. The thermal structure of the Altiplano is greatly inhomogeneous, and interpretations based on average crustal seismic parameters should be avoided. A good agreement has also been observed between thermal and rheological studies and magnetotelluric results at latitude 24.5 °S comprising areas from the Eastern Cordillera to the Chaco (Lezaeta *et al.* 2000).

The coast range of northern Chile is an area of low heat flow that can in part be related to shallow seismicity observed near the coastline and extending inland near the base of the crust (Comte *et al.* 1992). Several seismic occurrences have been associated with the Atacama fault system (Comte *et al.* 1992) but none of them remained in association with it after a relocation carried out subsequently (Comte *et al.* 1994). This last result contrasts with predominantly brittle behaviour of the crust in this area. Moreover, close to the Mejillones peninsula (23 °S) a further decrease of heat flow is observed (Springer and Förster 1998), possibly related to a stiff terrain with high strength. It has been observed that this zone is a limit for rupture propagation of thrust earthquakes occurring both north and southward from it (e.g., Delouis 1997). Very low heat flow singularities could act as barriers for rupture propagation in this and other areas along the coastline.

In the Norte Chico (Chile), an earthquake with Ms = 6.8 occurred in october 1997. The hypocentre at 52 km depth was relocated subsequently at 67 km and the largest aftershock was relocated at 52 km depth (Pardo *et al.* 1999). Most probably, the uppermost continental mantle in this area is yielding under stress accumulation in the Wadati-Benioff zone. Both rheological models for the Norte Chico are in agreement with observations related to these earthquakes (see Table 1 and Muñoz 1994).

The Precordillera of Argentina and the Sierra Pie de Palo at about 31.5 °S have large strength values throughout the crust. This explains the observation of earthquakes of intermediate magnitude (Ms = 6.5 - 7.4) in these areas (e.g., Smalley and Isacks 1990). The highest frequency of earthquakes (Smalley and Isacks 1990) is found near de base of the seismogenic layer (Table 1). This could mean that the tectonic loading of the brittle crust is from plastic flow of underlying mantle, and not from the sides (e.g., Keith 1993). The peculiarity of the central Precordillera of Argentina -low heat flow, seismogenic lower crust- can be related to correspond to its character as an allochtonous terrain derived from Laurentia (Astini *et al.* 1996). Presently, heat flow is anomalously low in a band of the central Appalachians and in Alabama, increasing -yet under the continental mean- in the region of Texas (Blackwell *et al.* 1991). To the north, in New York, low heat flow is associated to low radiogenic heat generation in the basement of Grenville age (Birch *et al.* 1968). In the Precordillera of Argentina, the exposed basement of Grenville age (Astini *et al.* 1996) can then be related to low heat generation in the crust, low heat flow and large thickness of the brittle domain.

In the Central Valley of Chile at 33 ° - 34 °S the middle and the lower crust are ductile, whereas inland the cordilleran area of the Cajón del Maipo exhibits a large strength envelope describing a brittle domain down to 22.5 km depth. In the Central Valley, low Q values of anelastic attenuation (Kausel and Cruzat 1985), low P-wave seismic velocity (Pardo and Fuenzalida 1988) and P-wave time residuals indicating that the whole crust is characterized by low velocities (Herrera and Araya 1988) accord with the present results. In the cordilleran area, crustal earthquakes (Ms = 6.7 - 6.9) have been recorded (Lomnitz 1961) and it is observed that seismic focal depths are mainly confined to the upper 20 - 25 km of the crust (Report, Depto. de Geofísica, Univ. of Chile, period 1906-1988).

In southern areas of Chile, the partition between the brittle and the ductile regimes changes rapidly from the volcanic zone to the coast range. The electrical conductance decreases towards the coast range, and in the upper tectonosphere conducting layers are encountered only beneath the volcanic zone (Muñoz et al. 1990). Radiogenic heat generation decreases strongly from the Miocene granitoids to the Cretaceous, Jurassic and Paleozoic bodies outcropping westward.

References

Anderson, D.L., 1995. Lithosphere, asthenosphere, and perisphere. Rev. Geophys., 33, 125-149.

Astini, R.A., Ramos, V.A., Benedetto, J.L., Vaccari, N.E. and Cañas, F.L., 1996. La Precordillera: un terreno exótico a Gondwana. XIII Congreso Geológico Argentino y III Congreso de Exploración de Hidrocarburos, Argentina, Actas 5, 293-324.

Beck, S., Swenson, J. and Zandt, G., 1999. The cause of thick, slow crust in the Altiplano, Central Andes; melt or composition? Abstracts Fourth Int. Symp. Andean Geodynamics, 86-89,

Göttingen.
Birch, F., Roy, R.F. and Decker, E.R., 1968. Heat flow and thermal history of New York and New England. In: Zen, E., White, W.S., Hadley, J.B. and Thompson , J.B., Jr., (Eds.) Studies of Appalachian geology: Northern and maritime, Interscience, 437-451, New York.
Blackwell, D.D., Steele, J.L. and Carter, L.S., 1991. Heat-flow patterns of the North American continent; A discussion of the Geothermal Map of North America. In: Slemmons, D.B., Engdahl, E.R., Zoback, M.D. and Blackwell, D.D., (Eds) Neotectonics of North America, Geological Society of America, Decade Map Volume 1, 423-436 Boulder, Colorado.
Cahill, T. and Isacks, B.L., 1992. Seismicity and shape of the subducted Nazca plate. J. Geophys. Res., 97, 17503-17529.
Carter, N.L. and Tsenn, M.C., 1987. Flow properties of continental lithosphere. Tectonophysics, 136, 27-63.
Chapman, D.S. and Furlong, K.P., 1992. Thermal state of the continental lower crust. In: Fountain, D.M., Arculus, R.J. and Kay, R.W., (Eds.) Continental Lower Crust, Dev. Geotecton., 23, Elsevier, 179-199, New York.
Comte, D., Pardo, M., Dorbath, L., Haessler, H., Rivera, L., Cisternas, A. and Ponce, L., 1992. Crustal seismicity and subduction morphology around Antofagasta, Chile: preliminary results from a microearthquake survey. Tectonophysics, 205, 13-22.
Comte, D., Pardo, M., Dorbath, L., Dorbath, C., Haessler, H., Rivera, L., Cisternas, A. and Ponce, L., 1994. Determination of seismogenic interplate contact zone and crustal seismicity around Antofagasta, northern Chile using local data. Geophys. J. Int., 116, 553-561.
Delouis, B., 1997. Lo que nos enseña el terremoto de Antofagasta de 1995. VIII Congreso Geológico Chileno, Actas - vol. III, 1765-1766, Antofagasta.
Fukao, Y., Yamamoto, A. and Kono, M., 1989. Gravity anomaly across the Peruvian Andes. J. Geophys. Res., 94, 3867-3890.
Hamza, V.M. and Muñoz, M., 1996. Heat flow map of South America. Geothermics, 25, 599-646.
Herrera, R.I. and Araya, E., 1988. Determinación de estructura de corteza en el área metropolitana. V Congreso Geológico Chileno, Actas - tomo II, F203-F208.
Honda, S. and Uyeda, S., 1983. Thermal process in subduction zone - A review and preliminary approach on the origin of arc volcanism. In: Shimozuru, D. and Yokoyama, I., (Eds.) Arc Volcanism-Physics and Tectonics, Terra Scientific, 117-140, Tokyo.
Ito, K., 1990. Regional variations of the cutoff depth of seismicity in the crust and their relation to heat flow and large inland-earthquakes. J. Phys. Earth, 38, 223-250.
Kausel, E. and Cruzat, J., 1985. Distribución regional del parámetro de atenuación Q estimado en base a la coda de sismos locales chilenos. Ceresis, Project Sisra, 14, 204-217, Lima.
Keith, M.L., 1993. Geodynamics and mantle flow: an alternative earth model. Earth-Science Rev., 33, 153-337.
Kononov, B.I., Yudakhin, F.N. and Svalova, V.B., (Eds.), 1993. Geotermiya Seysmichnïkh i Aseysmichnïkh Zon. Nauka, 400 pp., Moscow.
Lewis, T.J., Bentkowski, W.H. and Hyndman, R.D., 1992. Crustal temperatures near the Lithoprobe Southern Canadian Cordillera Transect. Can. J. Earth Sci., 29, 1197-1214.
Lezaeta, P., Muñoz, M. and Brasse, H., 2000. Magnetotelluric image of the crust and upper mantle beneath the NW Argentinean Andes backarc. (To be published in: Geophys. J. Int.)
Lomnitz, C., 1961. Los terremotos del 4 de septiembre de 1958 en el cajón del Maipo. Anales Fac. Cs. Fís. y Mat., Univ. de Chile, 18, 277-294.
Magistrale, H. and Zhou, H.,1996. Lithologic control of the depth of earthquakes in southern California. Science, 273, 639-642.
Magnitsky, V.A., 1967. The Internal Structure and Physics of the Earth. NASA Tech. Transl., 448 pp., Washington.
Muñoz, M., 1991. Radiogenic heat production and erosion process in central Chile. Intern. Meeting on Terrestrial Heat Flow and the Structure of the Lithosphere, Book of Abstracts, p. 60. , Bechyne Castle.
Muñoz, M., 1994. Reología de la litósfera en Norte Chico y región de los Lagos (Chile). VII Congreso Geológico Chileno, Actas - vol. 1, 674-678, Concepción.
Muñoz, M., 1995. The lithosphere of the Andean region: Thermal structure and rheologic heterogeneity. XXI General Assembly of the International Union of Geodesy and Geophysics, Abstract A445, Boulder (Colorado).
Muñoz, M. and Hamza, V.M., 1993. Heat flow and temperature gradients in Chile. Special Issue Studia Geophys. et Geod., Prague, 37, 315-348.
Muñoz, M., Fournier, H., Mamani, M., Febrer, J., Borzotta, E. and Maidana, A., 1990. A comparative study of results obtained in magnetotelluric deep soundings in Villarrica active volcano zone (south of Chile) with gravity investigations, distribution of earthquakes foci, heat flow empirical relationships, isotopic geochemistry 87Sr/86Sr and SB systematics. Phys. Earth Planet. Inter., 60, 195-211.
Pardo, M. and Fuenzalida, A., 1988. Estructura cortical y subducción en Chile Central. V Congreso Geológico Chileno, Actas - tomo II, F247.
Pardo, M., Comte, D. and Monfret, T., 1999. The Punitaqui earthquake of 14 october 1997 (Ms=6.8): A destructive intraplate event in Central Chile. Abstracts Fourth Int. Symp. Andean Geodynamics, 567-570, Göttingen.
Ranalli, G., 1991. Regional variations in lithosphere rheology from heat flow observations. In: Cermák, V. and Rybach, L. (Eds.) Terrestrial Heat Flow and the Lithosphere Structure, Springer, 1-22, Berlin.
Schwalenberg, K., Lezaeta, P., Soyer, W. and Brasse, H., 1999. Electrical conductivity anomalies around the ANCORP-Profile: An overview of new results. Abstracts Fourth Int. Symp. Andean Geodynamics, 668-672, Göttingen.
Sibson, R.H., 1982. Fault zone models, heat flow, and the depth distribution of earthquakes in the continental crust of the United States. Bull. Seism. Soc. Am., 72, 151-163.
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.
Springer, M., 1999. Interpretation of heat-flow density in the Central Andes. Tectonophysics, 306, 377-395.
Springer, M. and Förster, A., 1998. Heat-flow density across the Central Andean subduction zone. Tectonophysics, 291, 123-139.
Szádeczky-Kardoss, E., 1977. Geothermal energy and plate tectonics. In: Il Fenomeno Geotermico e sue Applicazioni, Accademia Nazionale dei Lincei, 123-139, Roma.
Williams, C.F., 1996. Estimating midcrustal temperatures in regions of active tectonics: Examples from the San Andreas fault system. Fourth International Workshop on Heat Flow and the Structure of the Lithosphere, Abstracts, p. 127, Trest.