

SOUTH AMERICAN PACIFIC MARGIN AS KEY TARGET FOR GEOSCIENCES AND GENERAL CULTURE

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Abstract: Analysis of a relocated hypocentres database and of a global volcanic eruptions catalogue has made clear that the South American Pacific margin is a site of peculiar phenomena and related geophysical events.

The already known maximum rate of deep earthquakes, the expected mean recurrence time of extreme magnitude earthquakes of a few tens of years, and the closeness of the region to the Nazca triple point – i.e. the region with the maximum rate of sea floor expansion – mean that the Andean margin deserves priority in preparing stable geophysical instrument arrays in anticipation of the next great earthquake, with the aim of increasing our understanding of the real nature of earthquakes, of the real geodynamics of active margins, and of global geodynamics and tectonics.

Keywords: *South American Pacific margin, great earthquakes, eruptions rate, active margin interpretation, global geodynamics*

A number of clues coming from historical and recent data converge toward the necessity of a reinterpreting both so-called subduction zones and the associated orogenic arcs (Scalera, 2007a & 2007b).

An unavoidable indication of prevailing surfaceward movements of mantle materials comes from analysis of polar motion in the case of the great Sumatran ‘subduction’ earthquake (Scalera, 2005b, 2006c & 2007b). A similar indication came from the correlation between eruption and great earthquakes recognizable along the Andes region (Figure 1). Although observational data from a long supplemental period of time is needed, a common cause of both earthquakes and eruptions can be envisaged in episodic mantle material movements.

The 3-D plots of the hypocentral locations of a number of Wadati-Benioff zones reveal that planar or spoon-like distribution of intermediate and deep hypocenters is not a normal characteristic pattern (e.g. Figure 3). The hypocentres spatially distribute on groups of elongated clusters or filaments that taper downward. ‘Single filaments’ can also be recognized beneath the Messina Strait – Southern Tyrrhenian Sea – and the Vrancea region. No subduction process can produce such a pattern, which can be more easily ascribed to an upward transport of matter and energy *sensu lato* (Scalera, 2005b).

As a consequence of the preceding clues, a Wadati-Benioff zone reinterpretation and an orogenic model that could be in harmony with an upward transport of mass have been searched for. The high-velocity anomalies revealed by means of seismic tomography – regional and global – under the trench-arc zones (Van der Voo et al., 1999; Fukao et al., 2001; Piromallo and Morelli, 2003; Spakman and Wortel, 2004; Cimini and Marchetti, 2006; among others) can be reinterpreted as isostatically uplifted columns of denser mantle material that intrude between two decoupling plates (Scalera, 2005, 2006b, 2006c & 2007a). The uplifting columns experience episodic phase changes toward a less closely-packed crystal structure leading to intermediate and deep earthquakes. The concomitant cause of earthquakes can be envisaged as rising water stored in the mantle (Lawrence and Wysession, 2006), which can produce deep instability phenomena. The cause of the outpouring of materials involved in orogenesis should be searched for in the increasing volume of the isostatically upwelling material and the cooperating buoyancy at the downward displaced Clapeyron phase boundary (Figs. 4 and 5). The trenches and the backarc higher heat flow can be explained without additional assumptions as a direct consequence of the tensional stress state and of the surfaceward transport of the isotherms associated with the columns of uplifting mantle material. While contrasting phenomena are present in the old framework, it is noteworthy that the new interpretation involves a simple and natural cooperation of deep natural phenomena able to explain the surface characteristics of the trench-arc-backarc zones.

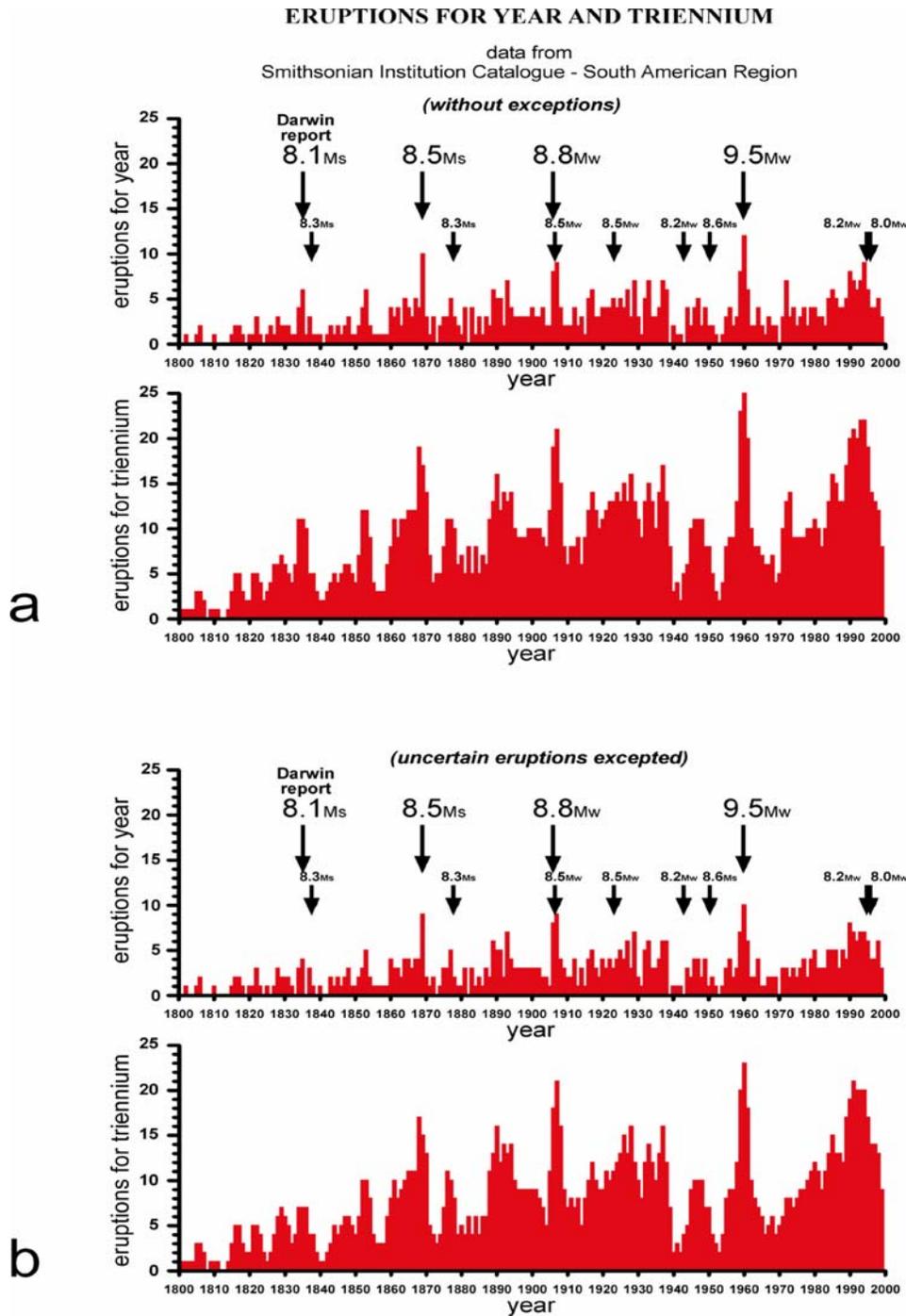


Figure 1 – The data from 1800 to 1999 of the Smithsonian Institution catalogue of eruptions for the South American Region have been used to plot the annual and triennial number of eruptions along the time axis. In a) all the non-discredited data have been used. In b) the uncertain eruptions have been omitted. The cusps of eruptions coinciding with the occurrence of great magnitude earthquakes are clear in both cases. In the time zone where the catalogue is incomplete – the beginning of the 19th century – only the peak of eruption associated with the Conception event of 1835 becomes indiscernible in b). The low rate of eruptions around 1940 could be due to incomplete observations caused by the 2nd World War, but the occurrence of similar low rate periods around 1953 and 1968 is unexplained. Long periods of higher volcanic activity – e.g. 1920-1938, 1980-2000 – are also present. At the moment no explanation of these fluctuations exists nor is it possible to envisage links with the occurrence of very deep and strong seismic events like the 1994 Bolivia one (M=8.2; depth=641 km, data USGS).

The same correlation of great seismic events and increased rate of eruptions cannot be recognized in other Wadati-Benioff zones. The author's conviction is that the enhanced correlation in South America could be the consequence of an asymmetrical expansion of the planet (Scalera and Jacob, 2003). More frequent and stronger or extreme phenomena are expected around the Nazca region, which is the site of the maximum rate of expansion.

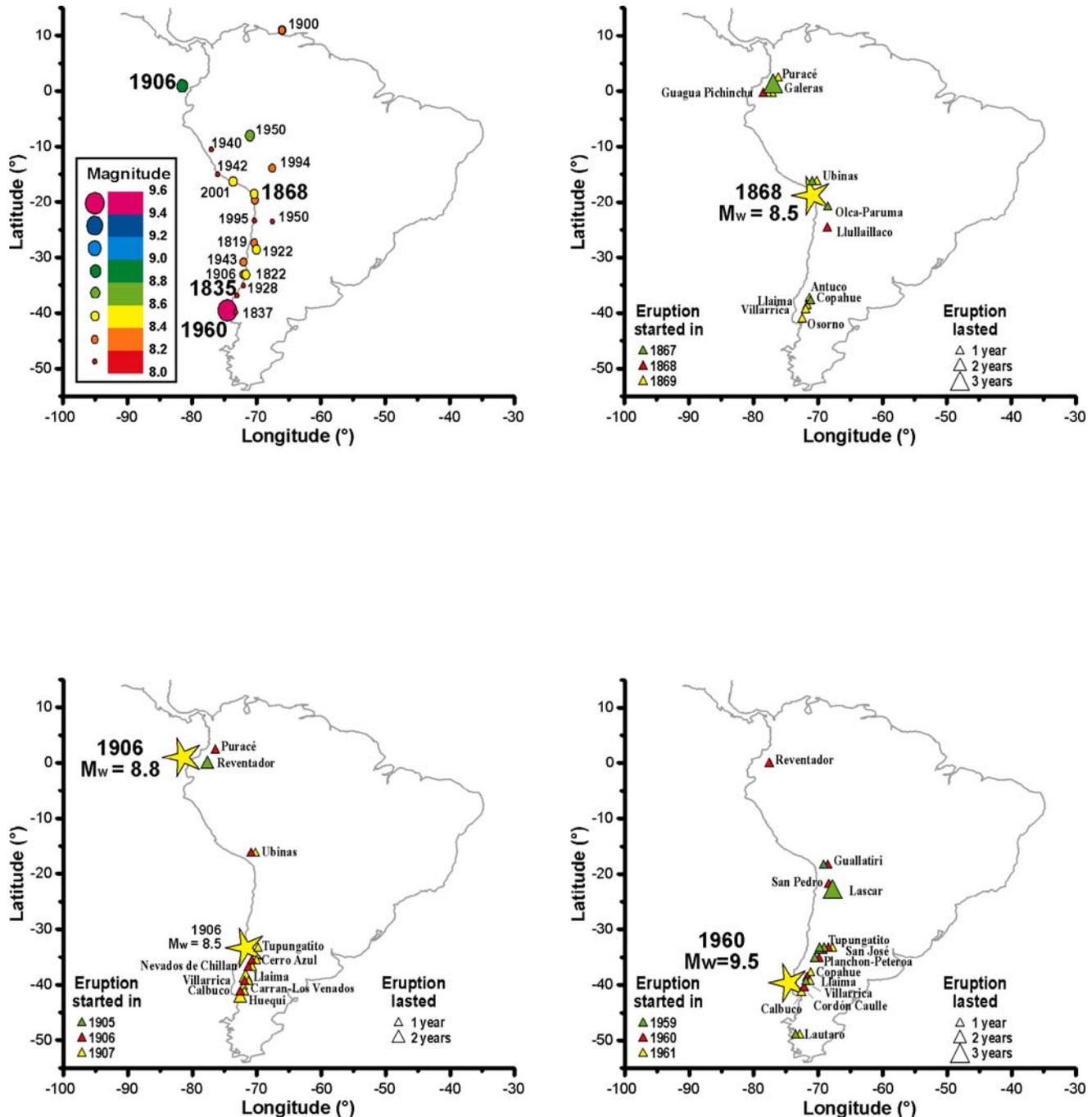


Figure 2 – a) Main earthquakes along the South American Pacific margin ($M \geq 8.0$). b) The epicentre of the 1868 earthquake and the volcanoes that erupted in the triennium 1867-1869. c) The epicentres of the two great earthquakes of 1906 and the eruptions that occurred in the triennium 1905-1907. d) The eruptions of the triennium 1959-1961, and the epicentre of the great Chilean earthquake of 1960.

In addition, a unified view can be attained of marine orogenesis – namely the mid-oceanic ridges – and the continental one. Indeed, the extension of mid-oceanic ridges into dryland fold belts (California, Tonga-Kermadec-New Zealand) has been considered contradictory to plate tectonics because of the different state of stress (distensive versus compressive) between them. In this framework a tentative suggestion is proposed here that the difference between the mid-oceanic ridges (marine orogen) and the continental fold belts is probably maintained by the different rate of rifting; the mid-oceanic ridges having a higher rifting rate which does not allow the growing volume to reach and overcome the sea level altitude. The mid-oceanic ridges can be seen as an oceanic version of the continental fold belts; in the oceanic ridges the folds and overthrusts are unlikely to occur due to the higher rate of rifting.

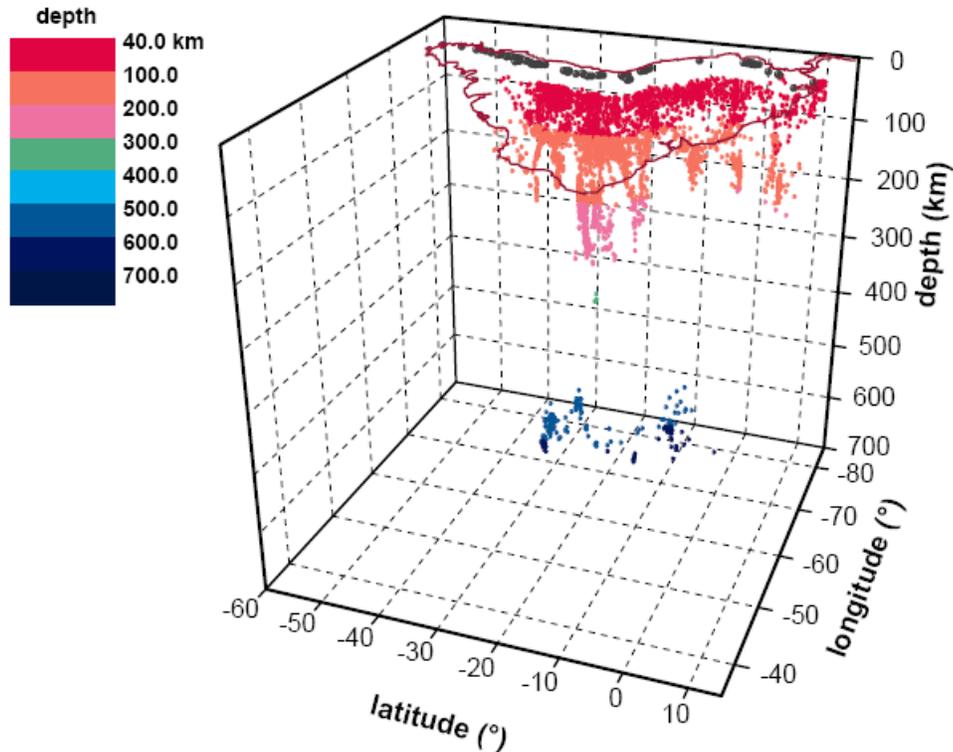


Figure 3 – A 3-D plot of the entire Wadati-Benioff zone beneath the South American Pacific margin. Planar distributions of hypocentres cannot be recognized. Clusters of hypocentres tapering downward are the typical patterns. The earthquake data (depth ≥ 40 km) came from the Catalogue of the Relocated Hypocentres by Engdahl et al. (1998). The black circles on the surface represent the 72 volcanoes that have erupted in historical times (data from Smithsonian Institution Catalogue). It is possible to discern a correspondence between zones without intermediate-depth hypocentres ($100 \text{ km} \leq \text{depth} \leq 300 \text{ km}$) and surface zones without active volcanoes. This fact reveals another case of a stronger than expected link between volcanism and seismicity already highlighted in other tectonic situations (Scalera, 1997).

This model can be considered the first causal explanation – linked to deep mineralogical phases, isostasy and expanding Earth – of at least part of an already existing more general class of orogenic non-collisional models (Ollier and Pain, 2000; Ollier, 2003) that derive their evidence above all from surface geology and morphology. Older conceptions appeal to diapirical rises (Van Bemmelen, 1966 & 1978; Carey, 1976 & 1986) or to uplift of buoyant asthenolithes (Krebs, 1975), but are at odds with the recent seismic tomographic images. The first idea on whether the mantle-phase transformation - whether progrades or retrogrades - in the formation of depressions or uplands was formulated by Subbotin (1970).

The proposed new interpretation is able to explain the observed non-uniformity in time of the growth of the fold belts. Periods of enhanced growth are linked with deep mineralogical phase which – rising isostatically from depth and having reached and overcome the appropriate lesser depth, pressure, temperature, and/or coming into the presence of suitable fluid catalyser – can gradually transform to lighter phases. The widespread phenomenon of uplifted terraces (Darwin, 1840 & 1897; Doglioni et al., 1994; Moretti and Guerra, 1997; Cucci, 2004; Galli and Bosi, 2004; Cucci and Tertulliani, 2006; among others) can be related to non-uniform development of deep phase changes.

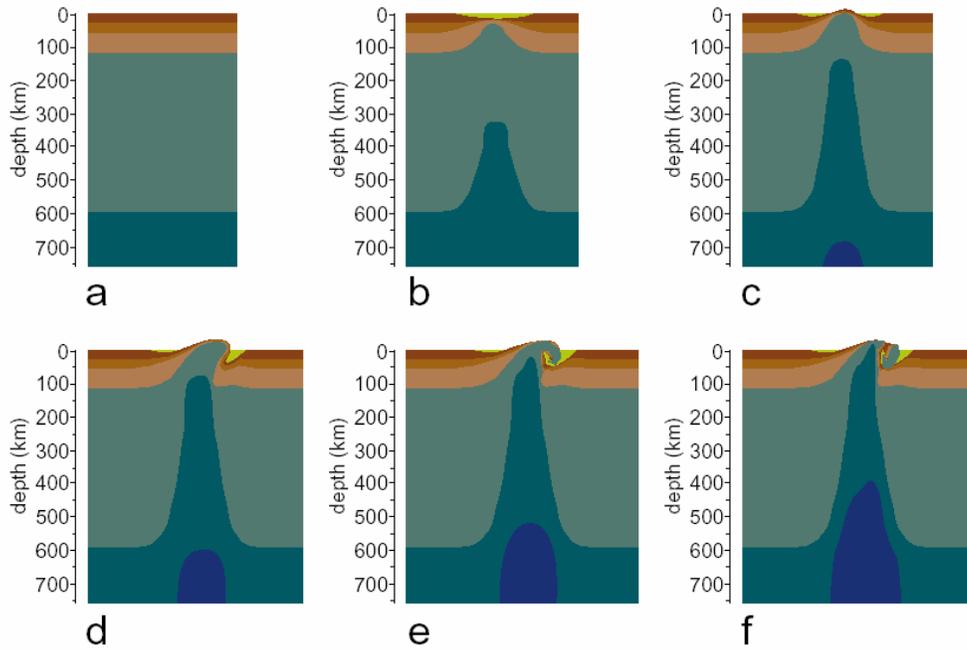


Figure 4 – The proposed new model of mountain building. Starting from left, a tensional situation produces a stretching of crust, lithosphere and mantle. Due to the necessity of isostatic compensation (no more than about ten kilometres of depth can be attained on the Earth's surface. See e.g. Hilgenberg, 1974) the greater effect of the stretching appears as a strong uplift of the lithospheric and mantle strata. On this uplifting column an excess of room becomes necessary because the mantle material must undergo phase changes toward more unpacked crystal structures (Green and Ringwood, 1970; Ringwood, 1991). This surplus of increasing volume of the decompressed material is sufficient not only to fill the space between the vertically split lithosphere and mantle, but can also produce updoming of the crust, and subsequent relatively quick (centimetres per year) uplift. A facilitating effect in driving the uplift is the downward displacement of the phase transition zones due to the effect of the Clapeyron curve slope (see Figure 5). Then the created true orogen can undergo erosion, summital collapse and gravitational spreading, with final denudation of metamorphosed crustal material previously buried by gravity nappes, together with several kinds of mantle facies. Different rates of rifting – and evolution of the rate through geological time – can lead to different kinds of continental orogens and to mid-oceanic ridges.

Further phenomena that can be linked to an ascending flow are the observed greater iron content in lavas characterized by higher temperature. This can be caused by the surfaceward transport of the isotherms associated with a deeper provenance of the mantle material – from zones richer in this metal. Some other geochemical properties of the HIMU and EM-1 mantle source incorporated in orogens can be explained by erosion of old continental crust instead of recycling of ancient crust and deep-sea sediments (Gasparini et al., 2000; Hanan, 2000), in an interpretation of the Mediterranean as a continuously nascent ocean (Scalera, 2005b). In this slowly expanding Mediterranean the emplacement of basalts has always occurred in proximity to continental lithosphere. Obduction of ophiolites is a further process that can find a simple explanation in this framework.

Because of the unique occurrence of a correlation between great earthquakes and increased eruption rates, South America should be considered a high priority target of investigation. This continent is special because the occurrence of the maximum rate of strong deep earthquakes (depth ≥ 300 km; Frohlich, 2006). The author of this paper considers that this special status of the Nazca-South American region may be a consequence of an asymmetrical global expansion of the planet (Scalera 2002, 2003 & 2006a), with the maximum expansion rate at the Nazca triple point region. Obviously these researches are still in development and we need a greater amount of data and a longer period of good observations before we can provide firmer answers to all the problems. But the scientific community should be ready to take advantage of the opportunities offered by this special continent.

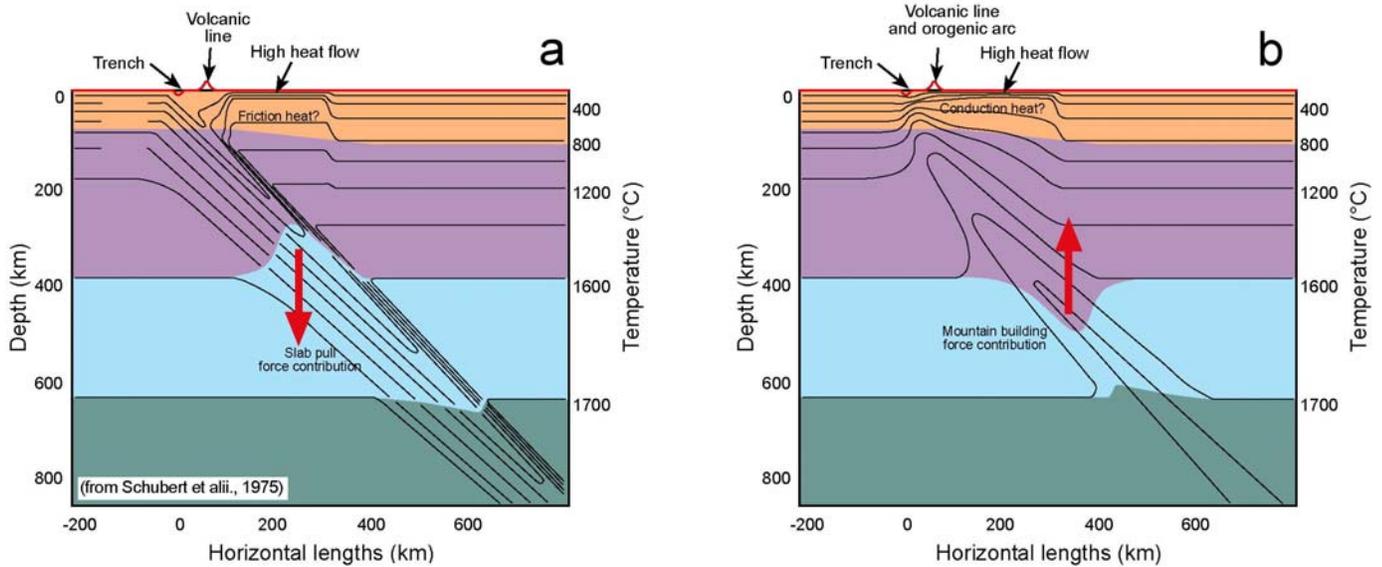


Figure 5 – Two rival models of the active margins. In a) the subduction model is represented with an effect of the downward adiabatic transport of isotherms. Because at lower temperature the phase transformation occurs at greater depth, a protuberance of denser material over the 410 km discontinuity contributes to the so-called ‘slab pull’ force. In b) the positive anomalies in seismic velocity underneath the trench-arc zones – revealed by tomographic methods – are interpreted as intrusions of material being isostatically transported surfaceward. In this case the isotherms are transported toward the surface so influencing locally the depth to which the phase transition at 400 km occurs. The effect in b) is opposite to the effect in a) and a protuberance of lower density material is created in the denser transition zone. The buoyancy of this protuberance cooperates, together with the excess of volume involved in phase transitions toward less-packed lattice, to the outpouring of material on the surface, namely to the orogenesis.

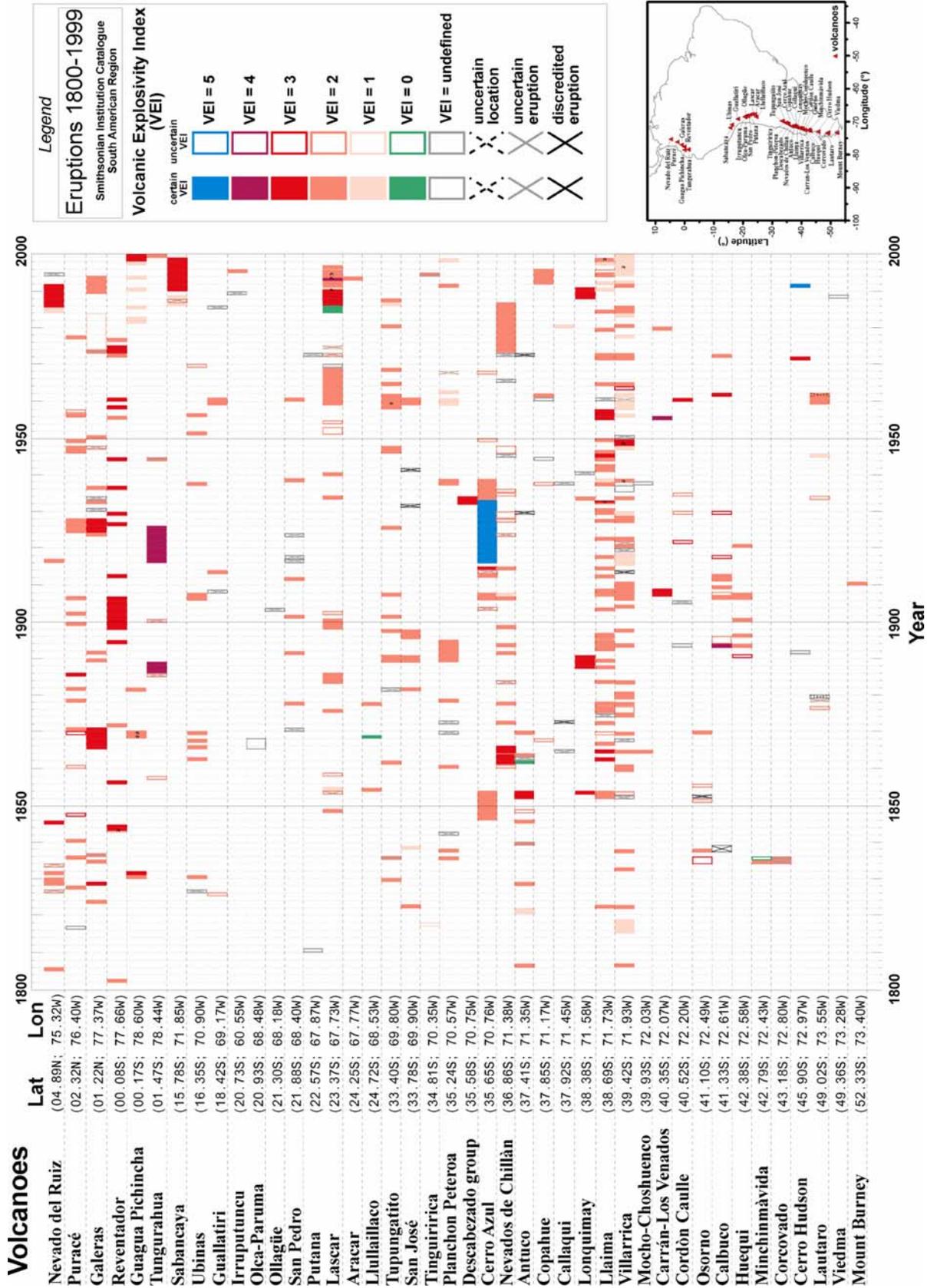
To understand the uniqueness of the region, to obtain geophysical information and perspective, and to increase our knowledge of the real nature of great shallow earthquakes as well as active margins’ real geodynamics, it is strongly recommended to install a permanent OBS and a network of geophysical instruments (Favali and Beranzoli, 2006) along the South American Pacific margin, where extreme magnitude earthquakes and related phenomena are expected to occur (see the recurrence of great seismic events and pulses of eruptions rate in Figure 1). There is a need for continuous observation by satellites for ionospheric anomalies, which are possible precursors of strong earthquakes (Pulinets and Boyarchuk, 2004; Pulinets, 2007; among vast literature), because South America is a highly recommendable region for investigations to evaluate the reliability and limits of this new methodology, which is similarly related to an emission-activity of the Earth. All the acquired benefits would be not only in the fields of geosciences and civil protection, but also in other fields; this eventual endeavour would be of comparable scientific and cultural value with respect to the ‘great physics’ enterprises, but would be achieved at a lower cost.

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REFERENCES

- CAREY, S.W., 1976: The expanding Earth. Elsevier, Amsterdam, 488p.
 CAREY, S.W., 1986: Diapiric Krikogenesis. In: Wezel, F.-C. (ed.): The Origin of Arcs. Book of invited papers presented at the Internat. Conference ‘The origin of arcs’, held at the University of Urbino, Urbino, Italy, September 22-25 1986, Developments in Geotectonics 21, Elsevier, Amsterdam, Netherlands, p. 1-40.
 CIMINI G.B. and MARCHETTI A., 2006: Deep structure of peninsular Italy from seismic tomography and subcrustal seismicity. In: Lavecchia G. & Scalera G. (eds.), 2006: Frontiers in Earth Sciences: New Ideas and Interpretations. *Annals of Geophysics*, Supplement to v. 49, p. 331-345.
 CUCCI, L., 2004: Raised marine terraces in the Northern Calabrian Arc (Southern Italy): a ~ 600 kyr-long geological record of regional uplift. *Annals of Geophysics*, v. 47, p. 1391-1406.
 CUCCI, L. and TERTULLIANI A., 2006: I terrazzi marini nell’area di Capo Vaticano (Arco Calabro): solo un record di sollevamento regionale o anche di deformazione cosismica? *Il Quaternario Italian Journal of Quaternary Sciences*, v. 19, p. 89-101.

TABLE 1



- DARWIN, C., 1840: On the connexion of certain volcanic phenomena in South America; and on the formation of mountains chains and volcanoes, as the effect of the same power by which continents are elevated. Transaction of the Geological Society of London, 2nd ser., pt. 3(5), p. 601-631. (Reprinted in Barrett, P.H. (ed.), "The collected papers of Charles Darwin" [two volumes in one]. The University of Chicago Press, Chicago, 1977, 326p.)
- DARWIN, C., 1897: Geological observations – on the volcanic islands and parts of South America visited during the voyage of H.M.S. 'Beagle'. Third edition. Appleton and Co., New York, 603p.
- DOGLIONI, C., MONGELLI, F. and PIERI, P., 1994: The Puglia uplift (SE Italy): An anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere. *Tectonics*, v. 13, p. 1309-1321.
- ENGDAHL E.R., VAN DER HILST R.D. & BULAND R.P., 1998: Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bull. Seism. Soc. Amer.*, v. 88, p. 722-743.
- FAVALI, P. and L. BERANZOLI, 2006: Seafloor Observatory Science: a review. *Annals of Geophysics*, v. 49 (2/3), p. 515-567.
- FROHLICH, C., 2006: Deep Earthquakes. Cambridge University Press, 588p.
- FUKAO, Y., S. WIDIYANTORO and M. OBAYASHI, 2001: Stagnant slabs in the upper and lower mantle transition region. *Rev. Geophysics*, v. 39, p. 291-323.
- GALLI, P. and BOSI, V. 2004: Catastrophic 1638 earthquakes in Calabria (southern Italy): New insights from paleoseismological investigation. *J. Geophys. Res.*, v. 108 (B1), doi :10.1029/2001JB001713. 1, 1-20.
- GASPERINI, D. Blichert-Toft J., BOSCH D., DEL MORO A., MACERA P., TÉLOUK P. and ALBAREDE, F., 2000: Evidence from Sardinian basalts geochemistry for recycling of plume heads into the Earth's mantle. *Nature*, v. 408, p. 701-704.
- GREEN, D. and RINGWOOD, A. (eds.), 1970: Phase Transformation & the Earth's Interior. Proceedings of the symposium held in Canberra, 6-10 January 1969, by the International Upper Mantle Committee and the Australian Academy of Sciences, North-Holland Publishing Company, Amsterdam, 519p.
- HANAN, B.B., 2000: Mantle recycled in Sardinia. *Nature*, v. 408, p. 657-658.
- KREBS, W. 1975: Formation of southwest Pacific island arc-trench and mountain systems: plate or global vertical tectonics. *Bull. Am. Assoc. Petrol. Geol.*, v. 59, p. 1639-1666.
- LAWRENCE J.F. and M.E. WYSESSION, 2006: Seismic Evidence for Subduction-Transported Water in the Lower Mantle. In: *Earth's Deep Water Cycle*, American Geophysical Union Geophysical Monograph Series 168, p. 251-261.
- MORETTI, A. and GUERRA, I. 1997: Tettonica dal Messiniano ad oggi in Calabria: Implicazioni sulla geodinamica del sistema Tirreno-Arco Calabro. *Boll. Soc. Geol. It.*, v. 116, p. 125-142.
- OLLIER, C.D., 2003: The origin of mountains on an expanding Earth, and other hypotheses. In: Scalera, G. and Jacob, K.-H. (eds.): *Why Expanding Earth? – A book in Honour of Ott Christoph Hilgenberg*. Proceedings of the 3rd Lautenthaler Montanistisches Colloquium, Mining Industry Museum, Lautenthal (Germany) May 26, 2001, INGV, Rome, p. 129-160.
- OLLIER, C. and PAIN, C., 2000: The origin of mountains. Routledge, London and New York, 345 pp.
- PIROMALLO, C. and A. MORELLI (2003): P-wave tomography of the mantle under the Alpine-Mediterranean area. *J. Geophys. Res.*, v. 108 (B2), 2065, doi: 10.1029/2002JB 001757.
- PULINETS, S.A., 2007: Natural radioactivity, earthquakes, and ionosphere. *EOS Transactions AGU*, 88 (20), 217-224.
- PULINETS, S.A. and BOYARCHUK, K.A., 2004: Ionospheric precursors of earthquakes. Springer, New York, 315p.
- RINGWOOD, A.E., 1991: Phase transformations and their bearing on the constitution and dynamics of the mantle. Inaugural Ingerson Lecture delivered on May 12 1988 at the Goldschmidt Conference held in Baltimore. *Geochim. Cosmochim. Acta*, v. 55, p. 2083-2110.
- SCALERA, G., 1997: The relation among seismic activity, volcanic rock emplacement and Bouguer anomalies in Italy. *Natural Hazards*, Kluwer, The Netherlands, v. 15, p. 165-181.
- SCALERA, G., 2002: Possible relations among expanding Earth, TPW and Polar Motion. In: Maslov, L. (ed.): *Proceedings International Symposium on New Concepts in Global Tectonics*, held in May 2002 in La Junta, Colorado, Otero Junior College Press, La Junta, p. 37-50.
- SCALERA, G., 2005b: the geodynamic meaning of the great Sumatran earthquake: inferences from short time windows. *New Concepts in Global Tectonics Newsletter*, No. 35 (June), p. 8-23.
- SCALERA, G., 2005b: A new interpretation of the Mediterranean arcs: Mantle wedge intrusion instead of subduction. *Boll. Soc. Geol. It.*, Volume Speciale n. 5, p. 129-147.
- SCALERA, G., 2006a: TPW and Polar Motion as due to an asymmetrical Earth expansion. *Annals of Geophysics*. In: Lavecchia, G. and G. Scalera (eds.), 2006: *Frontiers in Earth Sciences: New Ideas and Interpretations. Annals of Geophysics*, Supplement to v. 49 (1), p. 483-500.
- SCALERA, G., 2006b: The geodynamic meaning of the Wadati-Benioff earthquakes: From Apennines to a global perspective for mountain-building. In D. Slejko and A. Rebez (eds.): *Extended abstracts book of the 25th GNGTS (National Group for Solid Earth Geophysics) annual Meeting*, held in Rome 28-30 November 2006. p. 8-14.
- SCALERA, G., 2006c: The geodynamic meaning of the deep earthquakes: First clues for a global perspective for fold belts? *New Concepts in Global Tectonics Newsletter*, no. 41 (December), p. 45-54.
- SCALERA, G., 2007a: Terremoti, trasformazioni di fase, catene a pieghe: è possibile una nuova prospettiva globale? (Earthquakes, phase changes, fold belts: it is possible a new global perspective?) (in Italian). *Rendiconti Soc. Geol. It.*, 4, Nuova Serie,

p. 296-299.

- SCALERA, G., 2007b: Geodynamics of Wadati-Benioff zone earthquakes: The 2004 Sumatra earthquake and other great earthquakes. *Geofísica Internacional*, v. 46 (1) (in press)
- SCALERA, G. and JACOB, K.-H. (eds.), 2003: Why Expanding Earth? A book in Honour of Ott Christoph Hilgenberg. Proceedings of the 3rd Lautenthaler Montanistisches Colloquium, Mining Industry Museum, Lautenthal (Germany) May 26, 2001, INGV, Rome, 465p.
- SMITHSONIAN INSTITUTION, 2006: Global Volcanism Program web-site: <http://www.volcano.si.edu>
- SPAKMAN, W. and R. WORTEL, 2004: A tomographic view on Western Mediterranean geodynamics, in "The Transmed Atlas – The Mediterranean Region from Crust to Mantle", edited by CAVAZZA, W., ROURE, F.M., SPAKMAN, W., STAMPFLI, G.M. and ZIEGLER, P.A. (Springer, Berlin), p. 32-52.
- SUBBOTIN, S.I., 1970: Phase transformations within the Earth's mantle as a cause of crustal movement and a source of crustal material. In: Green, D. and A. Ringwood (eds.), 1970: Phase Transformation & the Earth's Interior. Proceedings of the symposium held in Canberra, 6-10 January 1969, by the International Upper Mantle Committee and the Australian Academy of Sciences, North-Holland Publishing Company, Amsterdam, p. 499-502.
- USGS, 2006: Earthquake Hazards Program – Online Earthquakes Global and regional Catalogues Search.
<http://neic.usgs.gov/neis/epic/epic.html>
- VAN BEMMELEN, R.W., 1966: On Mega-Undations: A new model for the Earth's evolution. *Tectonophysics*, v. 3, p. 83-127.
- VAN BEMMELEN, R.W., 1978: The present formulation of the Undation Theory. In: The Frontiers of Human Knowledge. *Acta Universitatis Upsaliensis*, p. 255-274.
- VAN DER VOO R., SPAKMAN W. and BIJWAARD H., 1999: Tethyan subducted slabs under India. *Earth and Planetary Science Letters*, v. 171, p. 7–20.