THE GEODYNAMIC MEANING OF THE DEEP EARTHQUAKES: FIRST CLUES FOR A GLOBAL PERSPECTIVE FOR FOLD BELTS?

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Abstract: Earthquakes are not uniformly distributed either along mountain belts and arcs or in depth. The zones in which the deeper earthquakes originate are shown, and their regional and global context is examined. The characteristic inhomogeneous pattern is inspected in the Italian region as well on a Mediterranean and global scale. A possible reinterpretation of global tectonics is proposed with non-collisional orogenic processes – involving global expansion, rifting, isostasy, surfaceward flow of deep material, gravitational spreading, and phase changes.

Keywords: deep earthquakes, vertical displacements, orogenic processes, mantle phase changes, expanding Earth

Mediterranean

The Mediterranean is characterised by two well-defined regions of deep earthquakes (Berckhemer and Hsü, 1982; Cadet and Funiciello, 2004; Vannucci et al., 2004; Scalera, 2005a). The hypocenters do not exceed the depth of 200 km beneath the Aegean region, while they reach more than 400 km under the southern Tyrrhenian region (Fig.1b). Minor spots of intermediate-depth earthquakes are present beneath the northern Apennines (Fig.1a; hypocentral depth max 60 km), around the Gibraltar region and under the narrow, near-vertical focal volume (depths 60 - 180 km) in the Vrancea region, Romania. Many little crustal clusters of a narrow vertical pattern of hypocenters have been recently recorded using a very dense seismic network, which are analogous to the larger- scale South Tyrrhenian and Vrancea patterns. Therefore, this is a non-uniform pattern of Mediterranean hypocenters, which should link with an analogous non-uniform state of strain and stress along the Tethyan furrow.

There is a mainstream consensus that the cause of deep seismicity can be ascribed to subduction, albeit some doubt is raised in the case of the Vrancea chimney of hypocenters, which is thought to be the relic of a former wider Wadati-Benioff zone.

Because it is possible to reconstruct the Pangea mosaic (Bullard et al., 1965; Owen, 1983; other references in Scalera and Jacob, 2003) there can be little deformation of plates through geologic time. It is therefore unlikely that the non-uniform pattern of deep hypocenters is generated by the Africa-Eurasia interaction through uniform motion of the two plates. Moreover, in this region a large amount of evidence of extensional processes at odds with the alleged Africa-Europe convergence livens up the discussion (Michard, 2006; among others) or requires new interpretations (Scalera, 2005a; Lavecchia and Scalera, 2006).

These observations of irregular and – in some cases isolated – vertical distribution of hypocentres from local to regional scale in the Mediterranean region are only a particular case of a more general situation.

Global overview of Wadati-Benioff zones

Real Wadati-Benioff zones do not correspond to what is prescribed by plate tectonic theory, and to what we expect to see having in mind the typical two-dimensional plate tectonic diagrams. In these classical vertical sections - perpendicular to the trenches and arcs − well-aligned hypocenters are shown dipping with a slope around 45°.

Abandoning the classical 2-D images, if 3-D plots of the hypocenters of very large areas are drawn, filaments of hypocentres are recognizable (Fig. 2a,b) instead of a regular pattern (data from the catalogue of the relocated events by Engdahl et al., 1998). These filaments are real features of the hypocenters' distribution because their separation can easily reach the order of magnitude of degrees (Fig. 2a, b). The filaments have the tendency to taper to depth, leading to the idea of an origin in a narrow region of disturbance, which becomes progressively larger toward the surface. Instead of suggesting the downgoing slab of subduction, they evoke the image of trees, or smoke coming out of chimneys. If these filaments are taken as basic features to be explained in constructing new scheme for the Wadati-Benioff zones, it would almost be necessary to build a mechanism in which there is no place for a downgoing slab. It seems more credible that an upward migration of matter or energy (wide sense) would be involved in these zones.

More clues of surfaceward matter movements from eruptions and Polar Motion.

A preliminary analysis of seismic (data USGS, 2006) and eruption data on the arcs of Indonesia and western South America (dataSmithsonian Institution, 2006) has shown that a correlation between extreme magnitude earthquakes exists for the Cordilleran region (Fig. 3). Seismic and volcanic phenomena seem to be related in a cause-effect chain, and some eruptions precede the great seismic event. This correlation – and the lack of similar demonstrable correlation on Indonesian arcs – has some links with a general view of the global geodynamic processes (Scalera, 2006) in an asymmetrically expanding Earth framework (see several papers on Earth expansion and alternative views in: Scalera and Jacob, 2003; Lavecchia and Scalera, 2006) and suggests a primary vertical movement of matter, which can be envisaged more effectively in the zone of maximum rate of expansion in the Nazca region (Scalera, 2002 & 2006).

An analogous good correlation cannot be recognizable in the data of the global Smithsonian catalogue of volcanic eruption for the Indonesian zone and in particular for the great Sumatran earthquake of December 2004.

This presence (in the Nazca region) and lacking (far from Nazca region) of the eruptions-earthquakes correlation could be put in relation to a global tectonic and geodynamic view of an asymmetrically expanding Earth (Scalera 2006).

An additional important clue that surfaceward movements are the primary ones in the Wadati-Benioff zone has come from the analysis of the coseismic Polar Motion (PM) anomalies (see discussion in Scalera, 2005b). About 3.0 marcsec (≈10.0 cm) of polhody displacement – in a direction exactly opposite to the epicentre azimuth - can be only explained if an abrupt rising of mantle material has occurred along 1,200 km of the Sunda arc. Plate tectonics and its adopted subhorizontal elastic rebound focal mechanism was unable to explain both qualitatively and quantitatively – a lower order of magnitude was foreseen – the onset of the observed Polar Motion anomaly. Only vertical and largely non-elastic processes can account for the observed phenomena (Scalera, 2005b).

Therefore both the PM-great earthquakes and eruptions-earthquakes correlations provide precise clues that in the natural world surfaceward movements are predominant. The causes of these deep movements and their bearing to the surface uplifted and folded regions of the Earth are considered in the following pages.

A new model of fold belt evolution

As a consequence of the above considerations, and keeping in mind the presence of water in the mantle at considerable depth, a heuristic model of evolution of an idealised fold belt is proposed, which does not resort to subduction (Fig. 4). It also explains the occurrence of seismically activated zones of hypocenters in the form of filaments, by irregular and episodic activation of mass and energy transmigration in a laterally non-homogeneous mantle in terms of thermal distribution, stress, strain, and composition. The model - with modifications for different local situations - could apply to the evolution of the Italian fold belt.

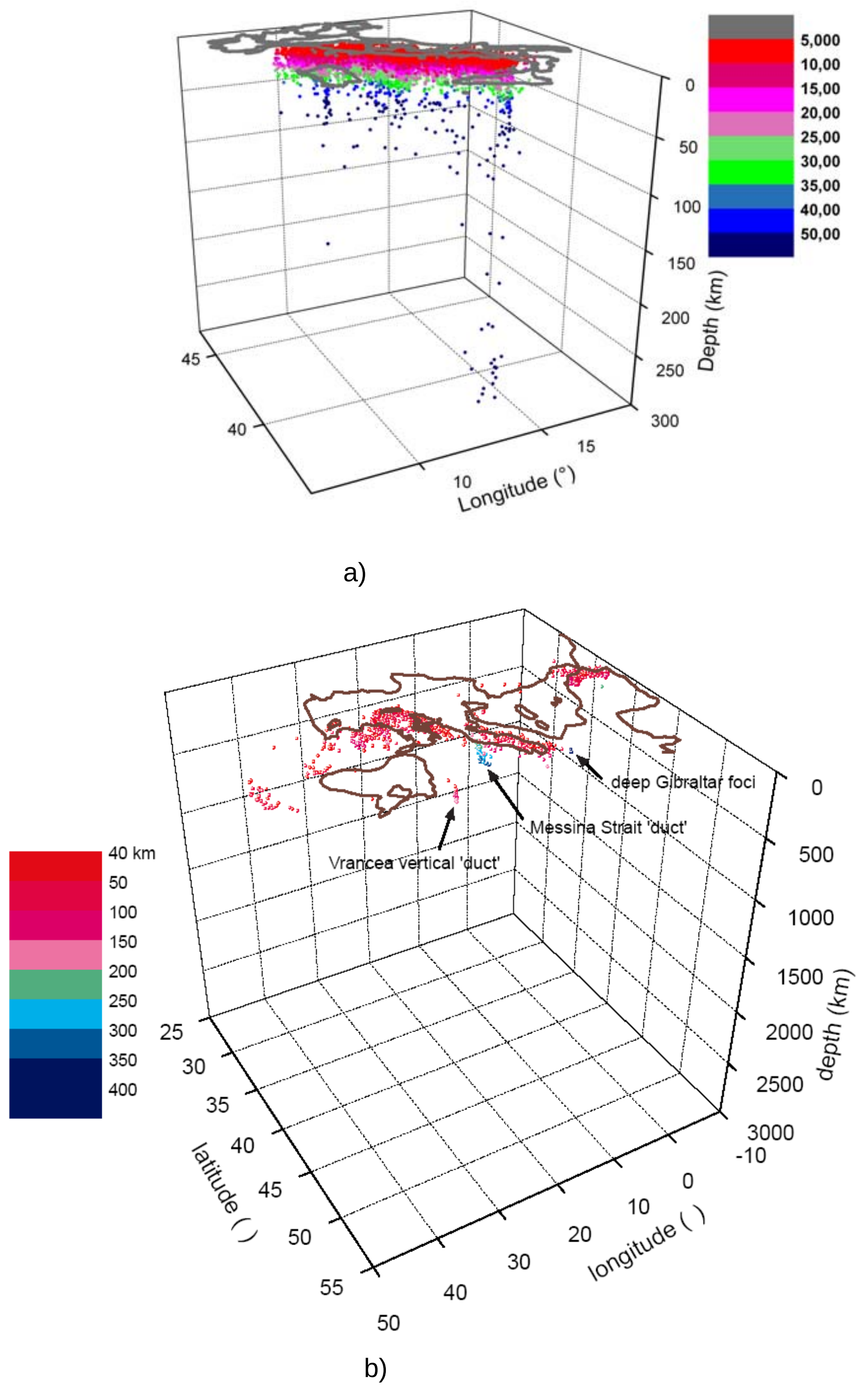

Fig. 1 – Non-uniform distribution of Italian and Mediterranean seismicity.

In a) the hypocenters show zones of higher density at a depth of 50 km below the North Apennines (Garfagnana), Central Apennines (Umbria), Southern Apennines (Irpinia).

In b) the deep earthquake zone under the Messina Strait reaches the depth of 500 km, starting as a near vertical column up to 200 km depth and then tapering along a lower slope. A similar but shorter near-vertical clustering of hypocenters is recognizable in Romania, Vrancea region, depth up to 180 km. This 'single-filament' typical pattern is similar to many other 'multi-filamentous' structures that are observable in most Wadati-Benioff zones around the world.

Italian data from the Italian Seismicity Catalogue (Castello et al., 2006); Mediterranean data from Engdahl et al., 1998; Gibraltar zone data from USGS web extraction facilities (USGS, 2006).

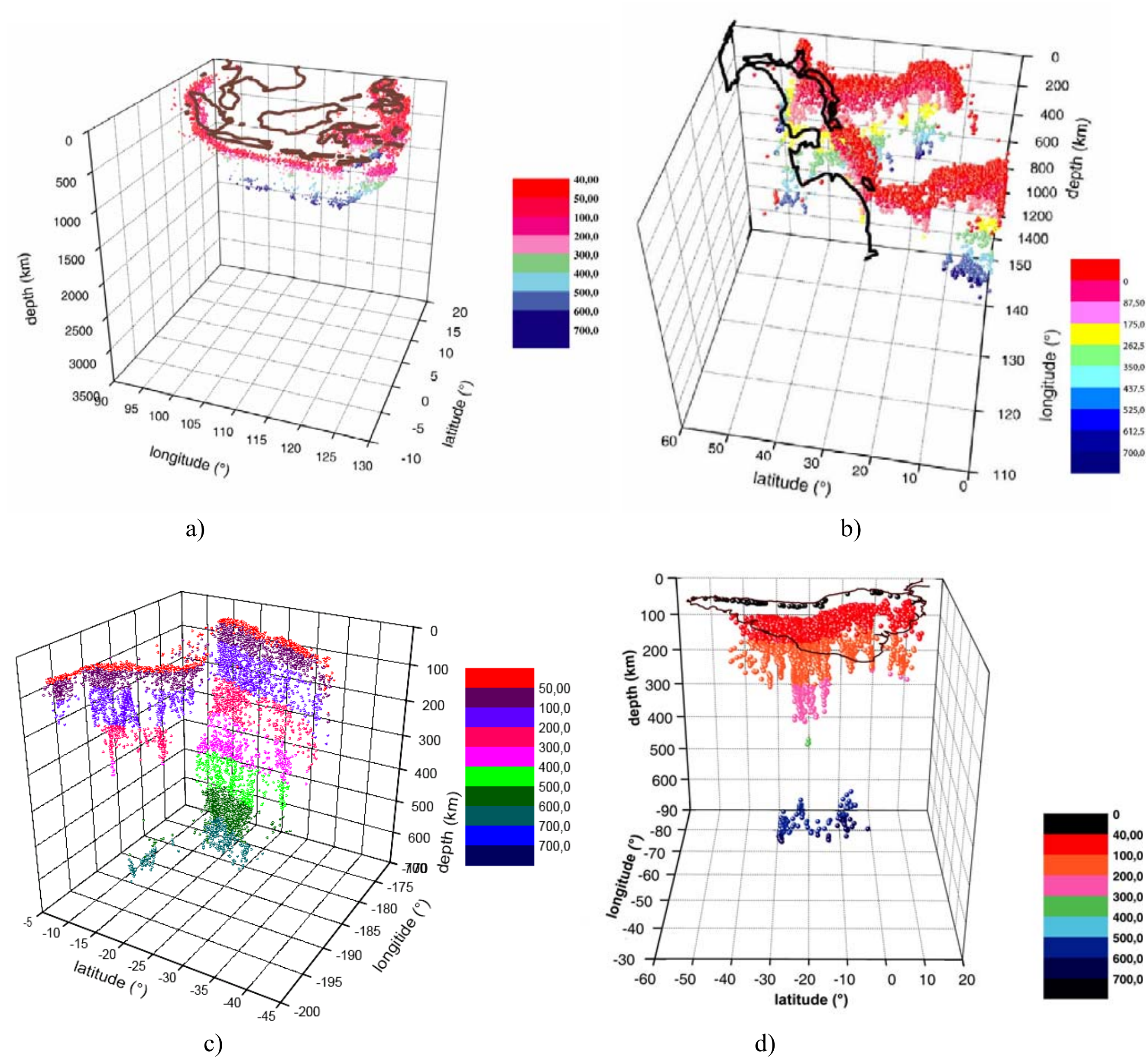

Fig. 2 - Most of the classical iconography of the 'subduction zone' is taken from vertical sections perpendicular to the circum-Pacific arcs. The reality is somewhat different. Plotting the entire Wadati-Benioff zones in 3D, using a larger scale, a filamentous structure of the subduction zones is highlighted.

In a) the Sunda arc (from Sumatra to Andaman islands) shows hypocenters not deeper than 250-300 km. The deepest seismicity is present under Java up to New Guinea, with focal sources down to 700 km. Here the hypocenters have the tendency to group in large columnar zones of which the islands are like architectural capitals.

In b) the filamentous pattern of the East Asian Wadati-Benioff zones (from 60°N to equator) is plotted.

In c) the pattern of deep hypocentres of the Salomon-Fiji-Tonga-Kermadek is plotted, making evident its irregular structure.

In d) the South American Wadati-Benioff zone has been entirely plotted. The brown circles represent the seventy-two volcanoes along the Andes Cordillera, which has been active in historical time (data from Smithsonian Institution, 2006). The volcanic provinces are grossly divided in relation to the seismofocal zone features. Some North-South gaps in the deep hypocentral pattern (depth >500 km) correspond to gaps and lower density of the volcanoes' distribution, adding further elements to the possibly stronger-than-supposed link between seismic and volcanic phenomena.

'Subduction' is an improbable process as a cause of this kind of uneven pattern. (All data from the 'Centennial Catalogue' by Engdahl et al., 1998.)

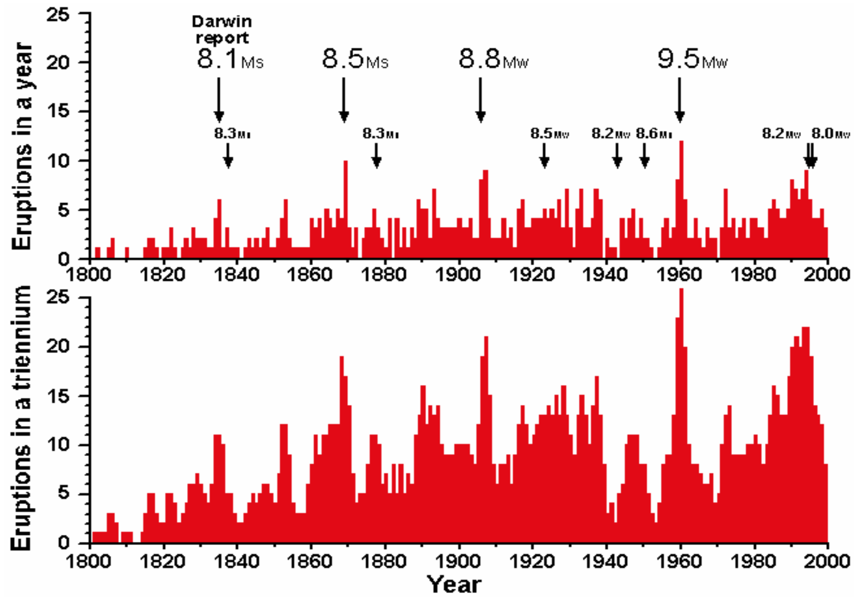

Fig. 3 - The data of the global Smithsonian catalogue of volcanic eruption for the South American Andean volcanoes which have erupted from 1800 to 1999 (Smithsonian Institution, 2006). The number of volcanic eruptions in a year and the number of volcanic eruptions in a triennium are plotted. The earthquake data are from Engdahl et al. (1998; the Centennial Catalogue) and from USGS (2006). Although observations and reports of occurred eruptions could increase in the event of major earthquakes (increased compulsion to search for correlation between seismology and volcanology on these occasions), the peaks in the number of eruptions seem neat and well evident with respect to the normal background noise when some M>8.4 earthquakes occur. Especially neat is the cluster of eruptions which matches the great Chilean earthquake of 1960 (M=9.5, the greatest magnitude ever recorded). An analogous good correlation cannot be recognized in the data of the global Smithsonian catalogue of volcanic eruptions for the Indonesian zone and in particular for the great Sumatran earthquake of December 2004. This presence (in the Nazca region) or the lack (far from Nazca region) of an eruptions-earthquakes correlation could be related to a global tectonic and geodynamic view of an asymmetrically expanding Earth (Scalera, 2006).

An undisturbed layer is the starting situation. Tension is assumed to act and a stretching of the lithosphere is envisaged to gradually develop. A surface furrow appears. The trough increases its depth (no more than a tenth of kilometres of depth can be attained on the Earth's surface. See e.g. Hilgenberg, 1974, for an explanation of the oceanic trenches), the crust grows thin, and induces a similar symmetrical geometrical change at the lithosphere and upper mantle bottoms, with development of an uplift of the layer interfaces (Fig. 4). Isostasy makes the inverted troughs at the mantle interfaces and their evolution more pronounced than the superficial ones. The furrow of the stretched crust is eventually filled with water, providing a sedimentary basin (Fig. 4).

In a situation of horizontal tension and no phase change of the upward moving materials, it would be impossible to uplift the topographic surface. But if the tensional state and the upward movement are associated with a phase change (Green and Ringwood, 1970; Ringwood, 1991), then the resulting increase in volume can lead to updoming of the topography, starting a process that could evolve into a fold belt. It is possible to speak of phase changes driven by isostatic deep uplift (Fig.4).

This additional uplift of materials driven by phase changes (with increasing volume along all the isostatically rising column) could cause seismicity (shallow, intermediate and deep) with a pattern of hypocentres distributed along Wadati-Benioff zones. Moreover, this uplift will cause the warping of crustal layers, exposure of the top of the doming zone to the action of gravitational spreading and erosion, all phenomena well documented on fold belts.

A possible asymmetrical spreading of the excess material – caused by the heterogeneous condition around the initial furrow – could drive the gravitational nappes to overthrust the sediments of the pre-existing trough, forcing them on a burial path that simulates the subduction process, but without reaching depths greater than 50-70 km. In Fig. 4 this asymmetrical spreading is represented, but bilateral spreading is also allowed.

At the boundary between uplifting material and down-pushed crust and lithosphere, phenomena like metamorphism, mixing, migmitization, upward transport of fragments of the buried lithosphere etc. are possible. The appearance on the topographic surface of the 'granite series' (Read, 1957; Pitcher, 1993) and of HT/HP-UHP

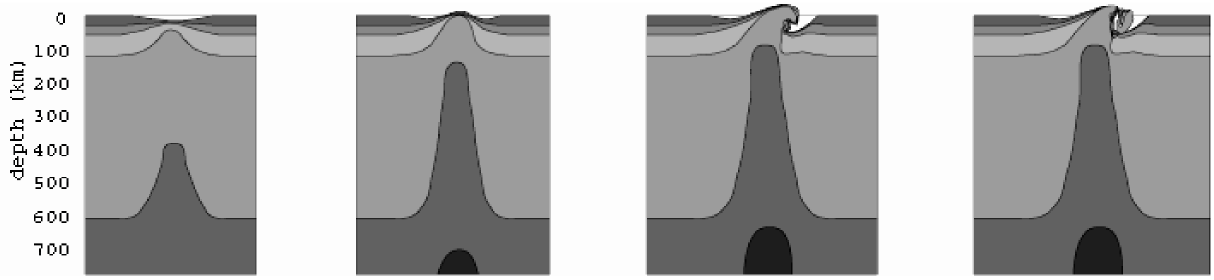

Fig. 4 – The proposed new model of fold belt formation. Starting from the left, a tensional situation produces a stretching of crust, lithosphere and mantle. A surface furrow appears. Due to the necessity of isostatic compensation the greater effect of the stretching appears as a strong uplift of the lithospheric and mantle strata. On this uplifting column an excess of room becomes necessary because the mantle material undergoes phase changes (Green and Ringwood, 1970; Ringwood, 1991). Excess volume of decompressed material is sufficient not only to fill the space between the vertically split lithosphere and mantle, but it can also produce updoming and folding of the crust. The new fold belt 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. The uprising mantle column can act as "elevator" for deep metamorphism facies.

metamorphic facies can be explained by the action of the piston of the phase changes. This action avoids the paradox of the 'two way path' (Ernst, 2005) never resolved by plate tectonics.

The crustal, intermediate and deep (up to 700 km) seismicity of the Earth could be explained - following Ritsema (1970) - by the direct and indirect effects of phase transformations (propagation of strain and of instability conditions). My conclusion is that these phase transformations happen along the isostatic uplift path, and not along a downgoing subduction path. In the upper part of Table 1 the values of the volume variation for a number of typical phase transformations in the mantle are reported (Anderson, 1989). The density of the five more common phases at their typical depth are reported in the lower part of Table 1 (Anderson, 2005), together with the volume variations passing from each mineralogical phase to the next, and the total volume variation – more than 20% – expected for a complete succession of five phase transitions.

If the detachment of plates is very deep – at least the lithosphere thickness – and arguing that γ-spinel (330 km) is involved, the more than 7% increase in volume may be sufficient to build an uplift of more than 20 km in the interior of the Earth. A greater depth of detachment (such as the one envisaged in Fig. 4) can produce internal uplifts of strata of greater values. Obviously the erosion does not allow such order of high uplift on the surface. These values are in agreement with the magnitude order of the uplifts recorded by geologists on real orogens.

The same rate of surface uplift is not to be expected if the rate of rifting of the two plates is different, and probably the difference between mid-oceanic ridges (marine orogen) and continental fold belts is maintained by the different rate of rifting of the two plates involved – mid-oceanic ridges having higher rifting rates which does not allow the growing volume to reach and overcome the sea level altitude. In this interpretation the mid-oceanic ridges are considered the oceanic version of the continental fold belts.

In both cases of this interpretation – low or high rifting rate – the initial phases of the orogenic process provide the forming and the evolution of tectonic structures that resemble the geosyncline tectonic framework (Aubouin, 1965). The rate of rifting determines whether the initial narrow trough – e.g. like the Red Sea trough – evolves into a true ocean divided by a mid-oceanic ridge or becomes filled by sediments and successively undergoes uplift and folding as in the geosyncline scheme.

Conclusion

The Italian and Mediterranean situation, with small circumscribed regions - Tyrrhenian, Aegean, Vrancea - of deep and intermediate seismicity, can be explained by the presence of a few zones of unstable mantle. This instability may be due to differences in the state of deformation, depressurization, and composition (all linked to each other and to global Earth expansion). The 3-D pattern of intermediate and deep hypocenters – especially the 'filament' beneath the Messina Street (Fig.1b) – is analogous to the filamentous distribution of foci in the Circum-Pacific Wadati-Benioff zones (Fig. 2ab). 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).

The same 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) and from a correlation between eruption and great earthquakes recognizable along the Andes region.

Searching for an orogenic model that could be in harmony with an upward transport of mass, it is possible to envisage the suitable mechanism of fold belts in the framework of an expanding Earth. High velocity anomalies revealed by

TABLE 1

	Phase Transition	Volume variation (cm^3/mol)
	$Mg_2 Si O_4$	
1.	α-olivine → β-spinel	- 3.13
2.	β-spinel → γ-spinel	- 0.89
3.	α-olivine → γ-spinel	- 4.02
4.	β-spinel → oxides	- 4.03
5.	γ-spinel → oxides	- 3.14
6.	γ-spinel → (perovs.+ magnesiowüstite)	- 3.84
7.	(γ-spinel + stishovite) → 2 ilmenite	- 0.79
8.	(β-spinel + stishovite) → 2 ilmenite	- 1.89
	$Mg Si O_3$	
1.	2 piroxene → (β-spinel + stishovite)	- 7.99
2.	2 piroxene → (γ-spinel + stishovite)	- 9.09
3.	piroxene → ilmenite	- 4.94
4.	Ilmenite → perovskite	- 1.91
5.	piroxene → perovskite	- 6.83
6.	piroxene → garnet	- 2.74
	$Si O_3$ (q) → stishovite	- 9.70

	Phase	**and typical depth**	**Density (g/c^3)**	**ΔV/V**	**ΔV/V total**
1.	α-olivine	(85 km)	3.31		
				4.8 %	
2.	β-spinel	(220 km)	3.47		
				2.3%	
3.	γ-spinel	(330 km)	3.55		22 %
				10.4 %	
4.	Ilmenite	(570 km)	3.92		
				4.6 %	
5.	Perovskite	(710 km)	4.10		

means of seismic tomography – regional and global – of Wadati-Benioff 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 interpreted as revealing an uplifted column of denser mantle material, with episodic phase changes linked to intermediate and deep earthquakes. The increasing volume of the isostatically upwelling material is the cause of the outpouring of materials involved in orogenesis (Fig. 4).

The Italian Apennine along-chain geological and stress-strain situation (Valensise and Pantosti, 1992; Lavecchia et al., 2003; Calamita et al., 2004; Cucci, 2004; Scalera, 2005a; Serpelloni et al., 2006; among many others) is consistent with the proposed model. At the moment, this model can be considered the first causal explanation – linked to deep mineralogical phases, isostasy and the 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 –

or hypothesizing an under-crustal or intracrustal creation (by solidus-solidus phase transformation) of granite (Sanchez Cela, 2004). Older conceptions appeal to diapirical rises (Carey, 1976, 1986) or to uplift of asthenoliths (Krebs, 1975), but are at odds with the recent seismic tomographic images.

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 phases which – having reached and overcome the suitable lesser depth, pressure, temperature, and in the presence of a suitable fluid catalyser – can gradually transform to lighter phases. Also the widespread phenomenon of uplifted terraces (Darwin, 1840, 1897; Cucci, 2004; among many others) can also be related to non-uniform development of the deep phase changes.

Although this new framework is still not sufficiently general to cover all the types of mountains (as described in Ollier and Pain, 2000, and Ollier, 2003), the author is confident that future new results and progress – coming from mantle tomography under special types of mountain (e.g. east Australian Range), and from other geological and geophysical fields – will make it possible to also link this kind of uplift of plane or planated surfaces to mineralogical phase changes in the mantle. It will be examined in the future, whether it is possible to link – especially in a biunivocal relation – all the phases of folding, standstill and planation, plateau uplift and dissection (Ollier, 2003), with a succession of increasing volume phase changes in the mantle and with possible non-uniformity in time of the rate of global expansion (see the pulsation in the global map of rate of sea floor expansion in Müller et al., 1997; McElhinny and McFadden, 2000). Admittedly, this is not a simple problem.

Acknowledgements

Cliff Ollier read the manuscript and suggested many improvements and corrections. David Pratt improved English. To them my thanks.

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