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On the interpretation of large-scale seismic tomography images in the Aegean sea area

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Abstract
A review of the interpretations given to large-scale seismic tomography anomalies in the Aegean area indicates a strong contradiction between these interpretations and the «traditional» ones based on seismic and tectonic data: 1) the tomographic lithospheric slab penetrates down to at least 400 km which doubles the maximum depth of the Benioff zone seismicity; 2) the resulting minimum time estimates for the subduction process duration at least doubles the seismotectonically calculated maximum time of 13 Ma for the subduction initiation. An alternative interpretation is proposed: the tomography detects not only the South Aegean active Benioff zone but also large remnants of lithospheric material subducted in two phases beneath the Aegean during the Miocene. Given that the geometric features of the paleosubductions are compatible with the features of the tomographic anomalies, it is suggested that the latter represent cool, non-assimilated lithospheric remnants. Then, no contradiction any longer exists and both seismotectonic and tomographic data are well explained.

Key words *Aegean area – seismic tomography – lithospheric slab penetration – paleosubduction*

1. Introduction

The Hellenic arc and trench system and its adjacent regions, like the Aegean sea, the Greek mainland and the western part of Asia Minor (all together hereafter called «the Aegean sea area»), constitute a seismically very active and tectonically highly complicated area. During the last thirty years several geodynamic models have been proposed for the interpretation of its seismic, tectonic and geophysical features.

Seismic tomography images are one of the tools used not only to determine the present large-scale crust-upper mantle structure of the Aegean area, but also to learn more about its geodynamic evolution during the Cenozoic. However, seismic tomography interpretations, presented over the last ten years, contradict «traditional» geodynamic and tectonic models, thus producing important, crucial consequences for the reconstruction of the Tertiary geodynamics of the Aegean area.

The purpose of this paper is to discuss seismic tomography images, presented by other authors, in the light of an alternative interpretation compatible with the «traditional» subductology of the Aegean area. A short preliminary version of the alternative interpretation was presented by Papadopoulos (1993).

2. Geodynamic models of the Aegean area

Two different types of geodynamic models have been proposed for the Aegean area:

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1) plate tectonic models, and 2) models of thermodiapirism. However, models of the second type did not resist in time as they were supported by only very few authors (*e.g.* Schuiling, 1972; Makris 1976, 1978). Therefore, plate tectonic models prevail in the literature on the Aegean geodynamics (*e.g.* Papazachos and Comninakis, 1969, 1971; McKenzie, 1970, 1972, 1978; Papazachos and Papadopoulos, 1977; Le Pichon and Angelier, 1979; Mercier, 1981; Papadopoulos *et al.*, 1986).

According to plate tectonic models, the Genozoic geodynamic evolution of the Aegean area is characterized by more than one phase of lithospheric subduction. Seismological data have shown that the Wadati-Benioff zone is currently active in the South Aegean dipping from SSW to NNE at an angle of about 35° (see for review and references in Båth, 1983). Earthquake focal depths more than about 200 km have not been determined, which signifies the maximum depth of the descending slab. Then, its maximum length is estimated as equal to about 300 km. Different authors have assumed different subduction rates leading to estimates varying from 5 Ma to 13 Ma for the active subduction initiation. Magmatic, metallogenic, tectonic, metamorphic, sedimentary and geophysical evidence has been used to reconstruct Tertiary paleosubduction zones in the Aegean area (*e.g.* Boccaletti *et al.*, 1974; Papazachos and Papadopoulos, 1977; Jacobshagen *et al.*, 1978; Papadopoulos and Andrinopoulos, 1984). Depending on the evidence used and the interpretations chosen by different authors, one or more distinct paleosubduction zones have been recognized.

A quantitative approach to the geometry and kinematics of Miocene paleosubduction zones was attempted by Papadopoulos (1989). From a long collection of radiometric data he determined the space-time distribution of the Aegean Cenozoic volcanism. As for the latter about 25 Ma three volcanic phases were defined: Early Miocene (23-14 Ma) in the Central-North Aegean, Late Miocene (14-7 Ma) in the South-Central Aegean, Plio-Quaternary (4 Ma-present) in the South Aegean island arc. He also used the diagram of Ninkovitch and Hays (1972) for K_2O/SiO_2 volcanic content against seismic isodepth curves for Indo-Pacific Benioff zones to test depths of the active South Aegean subduction zone from volcanic petrochemistry. An excellent agreement was

Table I. Geometric and kinematic parameters of the subduction zones detected to be present in the Aegean area in the last 25 Ma (summarized from Papadopoulos, 1989). Key: d = dip; a = direction; m = length of the magmatically active part of the slab; t_m = time of the volcanism initiation; r = mean subduction rate; l = total length of the descending slab; t_0 = time of subduction initiation; t_t = time of subduction termination (not applicable to the active zone); p = position of the subduction zone.

Parameter	Subduction zone		
	Active	Late Miocene	Early Miocene
d	38°	32°	21°
a	N26°E	N45°E	N78°E
m(km)	80	230	350
t_m(Ma)	4	14	23
r(cm/yr)	2.1	3.2	3.9
l(km)	290	490	730
t_0(Ma)	14	22	33
t_t(Ma)	–	7	14
p	South Aegean	South-Central Aegean	Central-North Aegean

found for depths determined independently from seismic and volcanic data. Then, Papadopoulos (1989) extended this test to the Late and Early Miocene volcanism of the Aegean and defined geometric and kinematic features of two corresponding paleosubduction zones. The results of this analysis are summarized in table I. The importance of these results for an alternative geodynamic interpretation of the Aegean seismic tomography images will be discussed later.

3. Seismic tomography and slab penetration in the Aegean area

The depth of penetration of the subducting lithosphere in the Aegean area, as deduced from seismic tomography images, has been debated since the late '70s. Agarwal *et al.* (1976) used teleseismic *P*-wave residuals, observed in local stations, and confirmed the existence of a high velocity slab beneath the Aegean. Their data, however, do not allow a conclusion on the depth of slab penetration. On the contrary, Gregersen (1977) calculated a subduction depth of about 150-200 km from a study of residuals using local earthquakes and observations in Europe and Greenland. Hovland and Husebye (1981) used *P*-delays of events from outside Mediterranean and Middle East regions and imaged a high velocity anomaly beneath the Central Aegean down to about 550 km. They attributed this anomaly rather to changes in the depth of a «400 km» phase change.

In a number of papers published by Spakman and his collaborators (Spakman, 1986, 1988; Spakman and Nolet, 1988; Spakman *et al.*, 1988; Spakman, 1990) a detailed investigation of the *P*-wave velocity heterogeneity of the upper mantle beneath Europe and Mediterranean was attempted. Over half a million delay times selected from the ISC bulletin tapes were used. About 77% of the data were recorded in European and Mediterranean stations and originated from earthquakes in the Mediterranean realm and Central Europe. As far as the Aegean area is concerned, tomographic images were produced with an accuracy up to a 50-130 km spatial error. A zone of positive heterogeneity, in the sense of percentages of the ambient Jeffreys-Bullen mantle *P*-wave seismic velocity, was imaged and on this basis they suggested that a lithospheric slab penetrates down to at least 600 km. After this they 1) concluded that much more oceanic subduction has taken place beneath the Aegean than was previously estimated from seismicity patterns, and 2) schematically derived minimum time estimates for the duration of the Hellenic subduction process that range from 26 to 40 Ma.

In a more recent study by Spakman *et al.* (1993), the Earth's volume under study encompassed the mantle to a depth of 1400 km and the number of ISC data for inversion increased by a factor of four including data from teleseismic events. Moreover, they did not use the Jeffreys-Bullen model as a reference model, but an improved radially symmetric velocity model which is appropriate for the European-Mediterranean mantle. In this case, the interpretation of large-scale positive anomalies indicated a slab anomaly mapped down to depths of at least 670 km, possibly down to 800-900 km. They suggested that if the Aegean subduction relates to the destruction of one oceanic basin (the Eastern Mediterranean part of the Tethys ocean) then the duration of subduction may possibly be extended to even larger than 40 Ma.

Greater depths of the subducting lithosphere than those inferred from the Benioff zone seismicity were also indicated by the large-scale *P*-velocity structures found in the Aegean sea area by Granet and Trampert (1989). Ligdas and Main (1991) used a data set of well-controlled local and teleseismic ray paths (Ligdas, 1990; Ligdas *et al.*, 1990) to put some bounds to the depth of penetration of the slab in the Aegean. They concluded that the peak amplitude of the tomographic image of a lithospheric slab is found from the inversion of travel-time data to be at depths at or below 400 km. However, no constraints of the maximum depth of penetration could be established with the data set used by them. Finally, they shared the idea that subduction in the Aegean sea may have started much earlier than the present-day back-arc extension.

4. Reliability of models

The accuracy and spatial resolution of the several seismic tomographic approaches examined depend on the different data and methods used. The total number of earthquakes, the number of teleseismic events, the epicentral distance range, the size of cells as well as the inversion method applied are the most important factors influencing the resolving power and, therefore, the reliability of the 3D tomographic images. In general, a spatial error ranging between 50 km and 150 km has been achieved in the several tomographic studies discussed. On the other hand, the most powerful result of the «traditional» geodynamic analysis of the Aegean area seems to be the configuration of the South Aegean Wadati-Benioff zone as is based on the earthquake foci determination. The number of the Aegean paleosubduction slabs as well as their geometric and kinematic features strongly depends on the volcanic data used.

However, for the problem discussed in this paper, that is the large-scale geodynamics of the Aegean area, the inaccuracies involved in both the tomographic and tectonic models do not drastically influence our examination and particularly the alternative interpretation presented in section 5.

5. An alternative interpretation – Discussion

Most seismic tomographers of the Aegean area agree on the main consequences of their tomographic images for the subductology of that area:

a) a lithospheric slab penetrating down to at least 400 km is imaged which is at least double the maximum depth of the South Aegean Benioff zone;

b) the above suggestion at least doubles the minimum time estimates for the duration of the subduction zone. According to the group of Spakman (see section 4 for references), this minimum time ranges from 26 to 40 Ma and it is possibly even longer.

Point (b) is a direct consequence of point (a). The basic consideration, therefore, is the tomographically imaged depth of slab penetration. In their interpretation, seismic tomographers apparently considered that the large-scale positive tomographic anomalies of the Aegean upper mantle represent a unique lithospheric slab dipping beneath the Aegean area, and that it is the active one the seismic part of which is configurated by the well-known Benioff zone of the South Aegean. Should this consideration prove correct then the tomographic consequences (a) and (b) appear quite realistic. Such a consideration, however, is not justified by the existing evidence for at least two paleosubduction phases in the Aegean area as the space-time distribution and petrochemistry features of the volcanic activity imply. Even supporters of the «unique Aegean slab» suggestion recognize the important role of volcanism as «... further analysis of the relation between slab geometry as a function of time and volcanic activity will shed light on the peculiar characteristics of Mediterranean volcanism (see a.o. Ninkovitch and Hays, 1972)» (Wortel and Spakman, 1992). As for the Aegean area, a detailed analysis of this type has already been made (Papadopoulos, 1982, 1989) with results summarized in section 2 and table I.

These results imply that a large part of the Aegean upper mantle is presently occupied by remnants of lithospheric material related to Miocene paleosubductions. Their position and main dipping trends coincide with the location and dipping trend of the tomographically mapped positive heterogeneity beneath the Aegean area. In this area, Plomerová *et al.* (1989) observed that clusters of shallow earthquake foci are situated above the places of the deepest sinking of the lithosphere-asthenosphere transition as it derived from the spatial distribution of the average residuals of the teleseismic *P*-arrival times. They suggested a possible relation of the increased shallow seismicity and associated normal faults with remnants of subducted oceanic lithosphere at depths of about 200 km or more.

Seismic tomography certainly detects not only the currently active Aegean lithospheric slab but also the paleolithospheric remnants that are dying-off and have not been assimilated by the asthenospheric material. Within the resolving power and spatial error of 50-150 km, the tomographic positive anomalies of the Aegean area could be easily explained as mainly representing relatively cool paleolithospheric material in the upper mantle. Only the uppermost part of the anomaly could be attributed to the South Aegean Benioff zone. Then, no contradiction arises between «traditional» and tomographic interpretations on the maximum lithospheric slab penetration underneath the Aegean and the time estimates for the duration of the subduction process. This alternative interpretation is compatible with that given by Babuška and Plomerová (1989, 1992) to the positive *P*-residuals observed in Central Europe. In their interpretation the dipping anisotropic structures may represent paleosubductions which retain olivine preferred orientations originating from an ancient lithosphere.

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