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Evidence for lithospheric delamination and buoyancy-driven deformations in the central Apennines

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Abstract - Seismic data from Central Italy are combined to image the crust and upper mantle and to understand the complex lithospheric deformations observed in the Apennines. The well developed low velocity zone in the uppermost mantle between the crust and the underlying continental lithosphere supports the lithospheric delamination beneath the peninsula and provides a new background for the genesis and age of recent magmatism. The modeling of mantle flow and tectonic stress in the imaged lithosphere shows that buoyancy solely can explain the enigmatic juxtaposed crustal contraction and extension and the unusual intermediate-depth seismicity distribution.

The coexistence of two end-member deformation mechanisms (contraction and extension) has been recognized in different geodynamic frameworks worldwide, but well exposed at the surface and active nowadays only in the Italian Peninsula. Several models, invoking mainly external forces (*1, 2, 3*)**,** have been formulated to explain the complex pattern of the regional deformations, observed by geophysical (*4, 5, 6*) and geological (*1, 6*) studies. Here we show that: (a) the structure of the crust and uppermost mantle in the central Apennines supports the concept of lithospheric delamination, and (b) the internal buoyancy forces are the driving mechanism for the observed deformations.

Twenty years ago an anomaly within the upper mantle in North-Central Italy was delineated on the basis of the analysis of seismic surface wave dispersion measurements (*7*). Since then, a large amount of data has been available. Deep seismic sounding profiles (*6, 8*), sample the crust from the Tyrrhenian to the Adriatic coast, while the upper mantle was imaged by regional P-wave seismic tomography (*3, 9*). To date, an integrated description of the structure and physical properties of the uppermost mantle and its transition to the crust is missing. To fill this gap we study the lithosphere-asthenosphere structure along a stripe from the Tyrrhenian to the Adriatic coast combining new tomographic inversions of surface waves with other pertinent data. We consider (i) a large number of new local and regional group velocity measurements sampling the Adriatic margin (Fig. 1a) and the Umbria-Marche geological Domain (UMD) (Fig. 1b); (ii) new and published (*10, 11*) phase and group velocity measurements sampling Italy and surroundings; and (iii) deep P-wave seismic sounding profiles crossing the whole Peninsula from the Tyrrhenian coast, via the UMD, to the Adriatic coast (*6, 8*).

We obtain locally averaged dispersion curves and the corresponding standard errors (Fig. 1c) in discrete points (*12*) of the study area and then proceed with their non-linear inversion (*13, 14*) that is independent from the starting model. The vertical resolving power of our surface waves data set is suitable for studies of the in-depth changes in the physical properties of the uppermost 250 km (Fig. 1d) of the Earth interior (*15*). Thus the data, as well as the methodology, provide a well-understood foundation for our work.

According to the resolution length (*16*) of the data used a sharp and well-developed low-velocity zone in the uppermost mantle (mantle wedge), from the Tyrrhenian dying out beneath the Apennines, separates the crust and the lithospheric mantle (lid). The crust and lid exhibit lateral variation in thickness (Fig. 2a): about 25 km and 30 km thick below the Tuscany Magmatic Complex (TMC) and about 35 km and 70 km below UMD, respectively. A lithospheric root, more than 120 km wide, between the TMC and UMD, reaches a depth of at least 130 km.

The model provides a new background for the still debated genesis of the TMC. Petrological and geochemical studies (*17*) revealed rocks rich in incompatible elements with crustal-like isotopic signatures consistent with a genesis in a sub-crustal anomalous mantle. This anomalous mantle may be associated with the identified mantle wedge and was probably metasomatized by an addition of subduction-related upper crustal material.

The sub-crustal earthquakes (*18*) cluster in the shallower part of the thick Adriatic lid and in the eastern part of the slab-like lithospheric root, while the part of the lithospheric root and thin lid to the west are almost aseismic (Fig. 2a). This is seen in many P-wave tomographic images indicating the presence of a high-velocity body of significantly larger volume than that delimited by the earthquakes foci (*3*). Based on geological, petrological and geochemical data (*1, 6*, *17*, *19*) the large lithospheric volume beneath the central Apennines can be interpreted as the remnant portions of the Adriatic west-dipping and old Alpine east-dipping slabs. Laterally varying physical properties of the lithosphere can be explained by lateral heat flow changes (*20*).

Therefore, the central Apennines crust-upper mantle image provides clear evidence of a low velocity uppermost mantle with a wedge-like geometry. The high velocity upper mantle underlying this low velocity layer is inferred to be lid material delaminated from the overlying crust.

To understand the present-day deformation of the region, we have attempted to fit simultaneously the observed stress data and the earthquake distribution with models of tectonic stress and mantle flow induced by gravity forces only (*21*). In the uppermost 50 km of the model, we use density values estimated from a high-resolution gravimetry survey (*22*) made along the study profile (Fig 2b). For the deeper structures we convert our S-wave velocity model into density taking into consideration temperature effects (*23*, *24*). The concordance between the gravity anomaly directly computed from our density model (no data fitting) and the observed Bouguer anomaly (Fig. 2b) is a measure of the reliability of our assumptions linked to the density estimates. Doing so, we fix the density and geometry of the crust-mantle structure, and the viscosity is the only variable parameter in our models. We consider three different models of viscosity (*21*) within a plausible range, consistent with the profile of the upper mantle viscosity (*25*). As shown in Fig. 3, the lateral variation in the viscosity of the lithosphere corresponds to the rather sharp heat flow difference (> 100 mW/m^2) observed in the area (*20*).

The negative buoyancy of the lid and the positive buoyancy of the mantle wedge cause the motion of the crust and mantle (Fig. 3). The downward motion due to the denser lid sinking in the mantle can be responsible for the subsidence of the Adriatic realm, and the upwelling predicted at the western part of the profile contributes to the tectonic uplift in Tuscany, where the horst-graben structure is observed (*1, 6*). Therefore, the predicted flow field is in agreement with the regional geological observations and at the same time it explains the delamination of the crust from the underlying mantle lithosphere and how the mantle wedge was emplaced. The young magmatism at the surface and the high heat flow values are in agreement with the computed upward flow field and suggest that this mantle wedge is partially molten mantle that feeds TMC. The ages of the TMC rocks ranging from 8-7 to 0.2 Ma (*17*), with a tendency to decrease from west to east, is in agreement with the predicted eastward flow in the mantle wedge.

Fig. 4 shows the state of tectonic stress in the central Apennine lithosphere resulting from our modeling. The maximum horizontal compressional stress is associated with the lid below UMD, in the depth range from 50 to 80 km. This finding is in good agreement with the compressional mechanisms of well-constrained fault-plane solutions (*18*). The sub-crustal seismicity distribution (see Fig. 2) correlates well with the region of high shear stress in the models. The puzzling location of the earthquake hypocenters, which does not correlate with the Wadati-Benioff seismic zone, can now be explained by the particular geometry and buoyancy of the delaminating lithosphere.

The predicted compressional regime at the eastern part of the study profile and the tension just below the UMD, where the 1997 normal faulting earthquake sequence took place, are in good agreement with observations (*4*, *5, 26*). Our stress models predict tension below the

Quaternary extensional sedimentary basins (Fig. 4) as well. The crust exhibits tension where the TMC outcrops and where the underlying mantle wedge and the asthenospheric low velocity layer are uprisen (Fig. 4). This localized uplift-subsidence type of motion is in agreement with a radial extension (*5*) in proximity of Quaternary vertical intrusions (*17*). Paleomagnetic data (*27*) and surface geology along with our model predictions suggest that buoyancy is the prevailing mechanism since, at least, Pleistocene times.

We have shown that buoyancy forces may govern the complex deformations associated with lithospheric delamination beneath the central Apennines. This result could also apply to other regions of delaminated lithosphere and unusual deformations such as the western Mediterranean (*28*) and southeastern Carpathians (*3, 29*).

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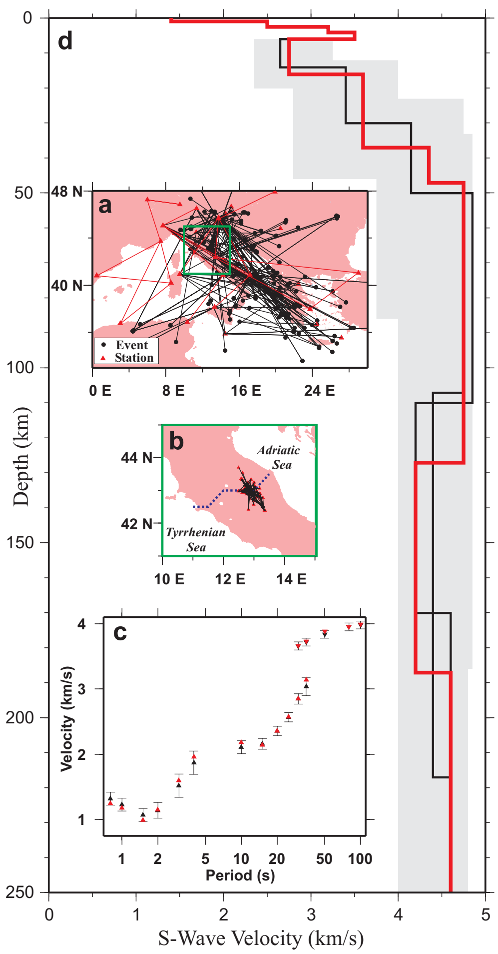
Figure Captions

Fig. 1. Synoptic view of all dispersion profiles considered (a, b) with an example (c) of the locally averaged observed dispersion measurements (group ▲ and phase ▼ velocity; vertical bars represent measurement errors), compared with the group ▲ and phase ▼ velocity values computed for the selected solution of the inverse problem (solid broken red line) among other possible solutions (solid broken black lines) (d). The grey area in (d) delimits the portion of the parameter's space, sampled by the simultaneous non-linear inversion of phase and group velocity of Rayleigh waves. The study profile, blue dotted line in (b), from the Tyrrhenian to the Adriatic coastlines, crosses the UMD.

Fig. 2. (a) S-wave velocity image of the crust and upper mantle and the hypocentres (red ★, vertical bars indicate the depth error) recorded in the period 1965-1998 within a stripe 150 km wide along the study profile (blue dotted line in Fig. 1b). The section has been obtained juxtaposing eleven selected (see *14*, and Fig. 1) solutions of the inverse problem. In each of these solutions, a bold black segment indicates the average Moho depth. The topmost line presents the surface topography. (b) Observed (22, blue curve) versus model predicted (red) gravity anomaly.

Fig. 3. Viscosity used and flow field predicted (bottom panel). A reduction of the effective viscosity of the crust and mantle lithosphere at the left of the model correlates with the high heat flow observed in the region (*20*) (upper panel).

Fig. 4. Modeled tectonic shear stress and compressional axes (shown as ticks; tensional axes are perpendicular to the compressional ones). The horizontal and vertical ticks indicate thrusting and normal faulting, respectively.



d
Depth (km)
S-Wave Velocity (km/s)
a
48 N
40 N
0 E
8 E
16 E
24 E
Event
Station
b
44 N
42 N
10 E
12 E
14 E
Adriatic Sea
Tyrrhenian Sea
c
Velocity (km/s)
Period (s)

Fig. 1

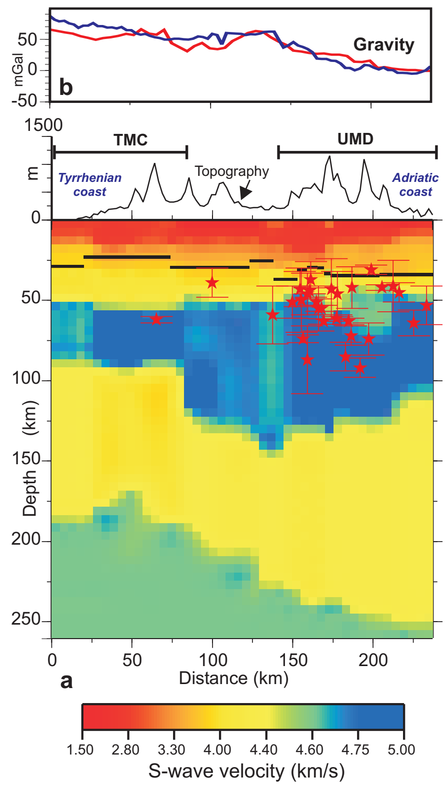

Gravity
mGal
50
0
-50
b
1500
m
0
TMC
UMD
Tyrrhenian coast
Topography
Adriatic coast
50
100
150
200
250
Depth (km)
0
50
100
150
200
Distance (km)
a
1.50
2.80
3.30
4.00
4.40
4.60
4.75
5.00
S-wave velocity (km/s)

Fig. 2

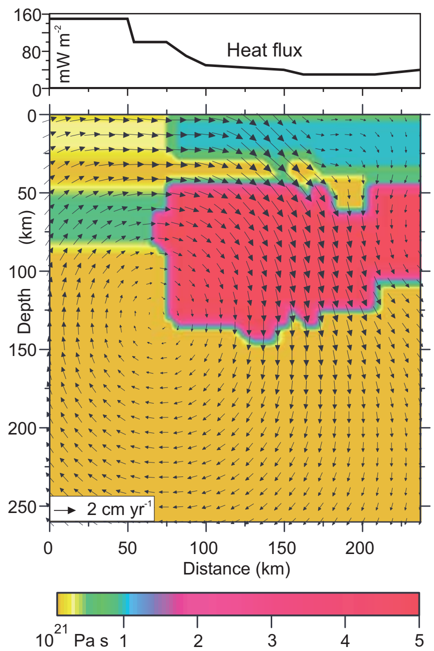

160
80
0
mW m-2
Heat flux
0
50
100
150
200
250
Depth (km)
2 cm yr-1
0
50
100
150
200
Distance (km)
10^21 Pa s
1
2
3
4
5

Fig. 3

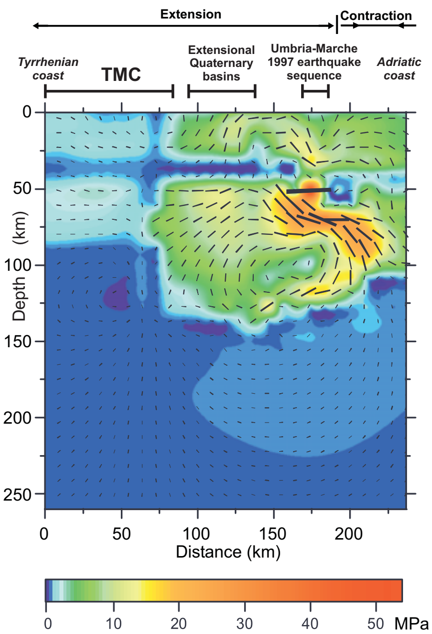

Extension
Contraction
Tyrrhenian coast
TMC
Extensional Quaternary basins
Umbria-Marche 1997 earthquake sequence
Adriatic coast
Depth (km)
Distance (km)
MPa

Fig. 4

SUPPORTING MATERIALS

Crust-upper mantle structure

In our non-linear inversion the unknown independent parameters are S-wave velocities and thickness of layers. We do not choose the solutions of the inverse problem corresponding to the minimum root mean square (rms), since they are the most affected by the presence of possible systematic errors (*1*). From the set of solutions, we accept the solution (Fig. 1d) corresponding to the rms closest to the average value, which was computed from all solutions, and hence reduce the projection of possible systematic errors into the structural model. If alternatively a median of all solutions in a set is used as representative, the resulting picture is not significantly different from Fig. 1d.

The non-linear inversion of the Umbria-Marche local dispersion measurements, spanning the period range from 0.8s to 4s, provides the ranges of S-wave velocity (*V*s) and thickness for each stratigraphic unit, identified in the pertinent part of the deep seismic soundings, that give us P-wave velocity (*V*p) and density. We thus estimate the *V*p/*V*s ratio for each stratigraphic unit. Fixing the upper crust parameters we resolve the deeper structure from the Tyrrhenian to the Adriatic coast, inverting the longer period dispersion measurements, reaching periods above 100s.

Setup of numerical models

The image of the crust and upper mantle structure beneath the central Apennines is the geometry used for the numerical models. Slow viscous flow and tectonic (deviatoric) stress are found from the momentum conservation (Stokes equation), continuity and state equations, employing the

Eulerian finite-element method (with an approximation of unknowns by bicubic splines). Additional details on our methods can be found in (*2*) and *(3*).

To avoid boundary effects, the modeled cross-section has been extended by 200 km in the horizontal and vertical directions. We prescribe free slip conditions at the boundaries of the extended model, and we incorporate surface topography over the cross-section with stress free conditions at this surface. The model domain is divided into 98x94 elements in the horizontal and vertical directions.

We consider three models of viscosity: model *a* is shown in Fig. 3; in models *b* and *c* the viscosity of the mantle wedge is one order of magnitude lower than that in model *a*. In model *c*, the effective viscosity of the crust beneath the Umbria-Marche region is three times higher than that in model *a*. We show that a larger viscosity contrast between the lid and the mantle wedge does not affect strongly the stress field (see Fig. S1*a*, 1*b*). The higher effective viscosity of the crust, the larger shear stress is (Fig. S1*c*).

Fig. S1. Tectonic shear stress and compressional axes (ticks) predicted by three models of viscosity (a), (b) and (c) (see text) along the studied profile (tensional axes are perpendicular to the compressional ones). The horizontal and vertical ticks indicate thrusting and normal faulting, respectively.

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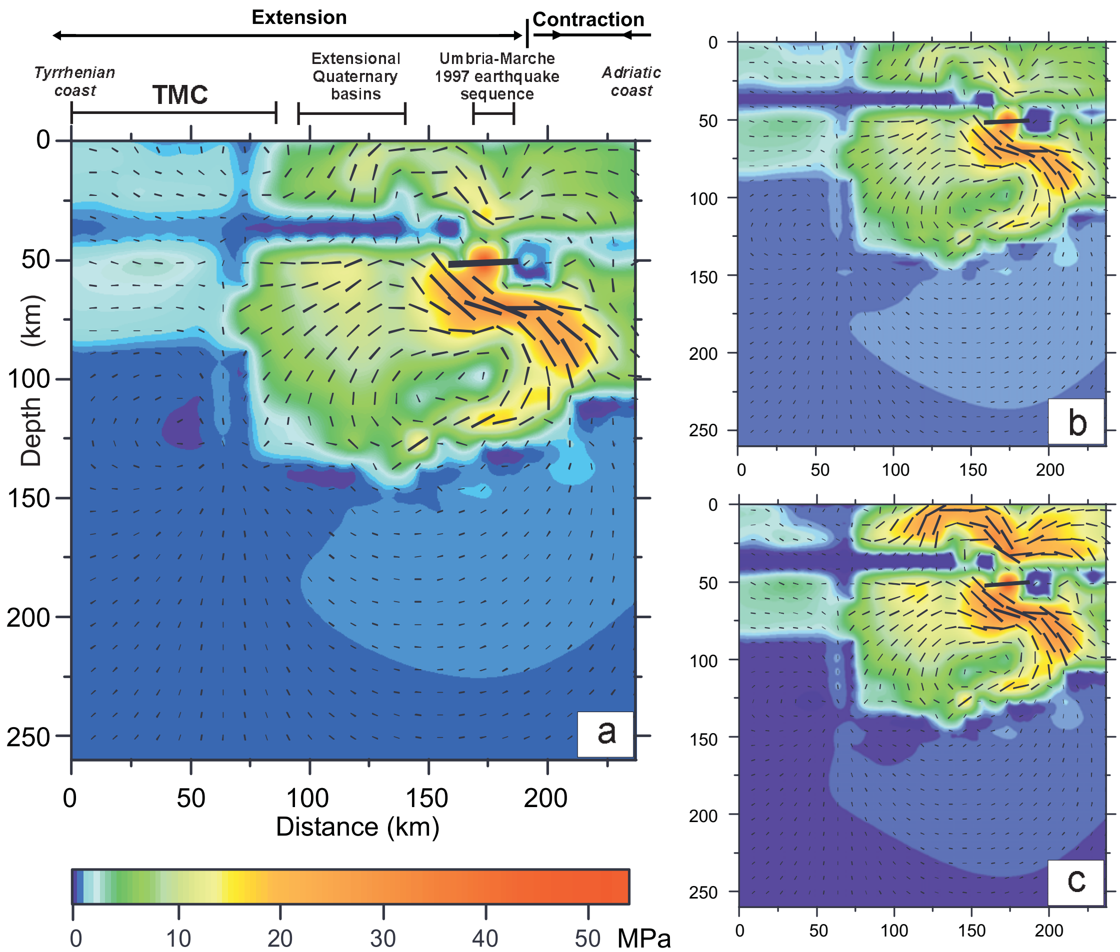

Extension
Contraction
Tyrrhenian coast
TMC
Extensional Quaternary basins
Umbria-Marche 1997 earthquake sequence
Adriatic coast
Depth (km)
Distance (km)
a
b
c
MPa

Fig. S1