Postseismic deformation and body forces shaping the Apennines and adjacent sedimentary basins in Umbria-Marche

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Abstract

The geodynamic complexity of the Apennines and adjacent sedimentary basins in Umbria-Marche (North-Central Italy) makes the dynamics of the present day deformation and its relationships with the seismicity less well understood. In this paper, we argue that, further to buoyancy forces, postseismic deformation of earthquakes taking place on the Apennines contributes to the regional deformation. We investigate the interaction between the normal faulting system responsible of the 1997 Umbria-Marche earthquake sequence (Colfiorito fault) and the low angle normal faulting system bordering the sedimentary basins, namely the Altotiberina fault. We set-up a 2D finite element model of the lithosphere-asthenosphere accounting for lateral heterogeneities and investigate how this heterogeneous structure is capable of localizing strain under the Umbria-Marche sedimentary basins, providing a way for the Colfiorito fault to influence the evolution of the Altotiberina fault. We show how the two different length and time scale processes, namely postseismic deformation and buoyancy, are complementary in shaping the Apennines and adjacent sedimentary basins. The high resolution deformation patterns modeled in this study can hardly be reproduced by a model accounting only for external forces such as a rotating or subducting or retreating Adria.

Key words *Viscoelastic relaxation – Aseismic slip – Body forces – Normal faults*

1. Introduction

The geodynamic complexity of the Apennines and adjacent sedimentary basins in Umbria-Marche (North-Central Italy) makes the dynamics of the present day deformation and its relationships with the seismicity less well understood. The recent 1997-1998 Umbria-Marche earthquake sequence clearly highlighted complex deformation processes both in its coseismic (*e.g.* Amato *et al.*, 1998; Zollo *et al.*, 1999; Salvi *et al.*, 2000; Chimera *et al.*, 2003) and postseismic (Riva *et al.*, 2000; Aoudia *et al.*, 2003; Riva *et al.*, 2007) phases. The Umbria-Marche crustal normal faulting seismic sequence, which consisted of three moderate earthquakes (26/09/97 at 00:33, M_W=5.7; 26/09/1997 at 09:40, M_W=6.1 and 14/10/1997 at 15:23, M_W=5.6), ruptured three distinct fault segments (*e.g.*, Galadini *et al.*, 1999; Meghraoui *et al.*, 1999; Barba and Basili, 2000). In the same region an earthquake occurred in the upper mantle, on March 28, 1998, M_W=5.2 (*e.g.*, Olivieri and Ekstrom, 1999; Chimera *et al.*, 20003) highlighting the importance of deep processes in the lithosphere. The lithosphere velocity models beneath Central Italy clearly highlighted the important lateral heterogeneity of the physical properties of the crust-uppermost mantle system along with pronounced variations of the

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geometry of both the crust-mantle and litho-sphere-asthenosphere boundaries (*e.g.* Agostinetti *et al.*, 2002; Chimera *et al.*, 2003; Mele and Sandvol, 2003). These models exhibit clear evidence of lithospheric roots without any continuous slab. This would imply that the slab has been eroded and no engine is actually left to drive relative subduction processes. Therefore our favorite model of the dynamics of the ongoing continental deformation is the one reported by Aoudia *et al.* (2007) that invokes body forces instead of external forces to satisfy the recent kinematics. Aoudia *et al.* (2007) have shown that the buoyancy forces resulting from the heterogeneous density distribution in the lithosphere govern the present day deformation within Central Italy and can explain regional coexisting contraction and extension at shallow depth and unusual distribution of sub-crustal earthquakes. Their modeled uppermost mantle flow supports the lithospheric delamination beneath the peninsula and provides a unifying background for petrologic and geochemical studies of recent magmatism and volcanism in Tuscany.

Further to the buoyancy forces already reported in Aoudia *et al.* (2007), this paper argues that postseismic deformation of earthquakes taking place on the Apennines contributes to the regional deformation. We investigate the interaction between the normal faulting system responsible for the 1997 Umbria-Marche earthquake sequence (Colfiorito fault, CF) and the low angle normal faulting system bordering the sedimentary basins, namely the Altotiberina fault (AF) (*e.g.* Boncio and Lavecchia, 2000; Chiaraluce *et al.*, 2007). By means of a half-space model we investigate the effect on the CF of prolonged slip on the AF. After that, we set-up a 2D finite element model of the lithosphere-asthenosphere accounting for lateral heterogeneities and investigate how this heterogeneous structure is capable of localizing strain under the Umbria-Marche sedimentary basins, providing a way for the CF to influence the evolution of the AF.

2. Secular postseismic relaxation

When approaching the study of postseismic deformation in the area of the 1997 Colfiorito

earthquake, different mechanisms have to be taken into account (*e.g.* viscoelastic relaxation, afterslip, poroelastic relaxation…). Here, we are not interested in the details of present day relaxation (see, *e.g.*, Riva *et al.*, 2007): instead, we want to estimate the cumulative impact of viscoelastic relaxation due to repeated seismic events in the area. According to historical records (Boschi *et al.*, 2000), the largest events that occurred in the direct neighborhoods of the Colfiorito fault (CF) are the 1279 Camerino in the north and the 1328 Norcia in the south, with magnitudes 6.6 and 6.2 respectively.

We model the cumulative effect of those two earthquakes by means of a 50-km-long normal fault rupturing at a depth of 8 km and dipping 45 degrees to the SW, which approximately corresponds to an extension of the main fault of the 1997 sequence by 15 km to the north and 25 km to the south. The moment magnitude is equivalent to the cumulative effect of a 6.6 and 6.2 event ($M_0 = 6\times10^{18}$ Nm). The full relaxation of this fault is modeled by means of a normal modes approach (Sabadini and Vermeersen, 1997), with a stratified earth model comprising a 15-km elastic upper crust, a Moho at 30 km, a 20-km-thick mantle wedge and a homogeneous mantle. Since we discuss the fully relaxed model (*i.e.* at infinite time), the viscosity profile which controls the temporal variations of the relaxation process is here irrelevant, the key earth parameter being the thickness of the upper elastic layer.

Results for vertical relaxation are shown in fig. 1, where the thin solid lines describe the surface projection of the boundaries of the three main patches that represent the Altotiberina fault (AF) (Boncio and Lavecchia, 2000), starting at the surface in the SW and dipping towards the NE, and smaller open rectangles represent the surface projections of the three main faults of the 1997 sequence (from the north: the 9:40 event on 26 Sept., the 0:33 event on 26 Sept, and the Sellano event on 14 Oct.). We see how the whole area between the CF and the surface expression of the AF is dominated by subsidence: it is noteworthy; that in the same area we find deep sedimentary basins and most of the spread microseismicity observed in the Umbria-Marche Apennines (Deschamps *et al.*,
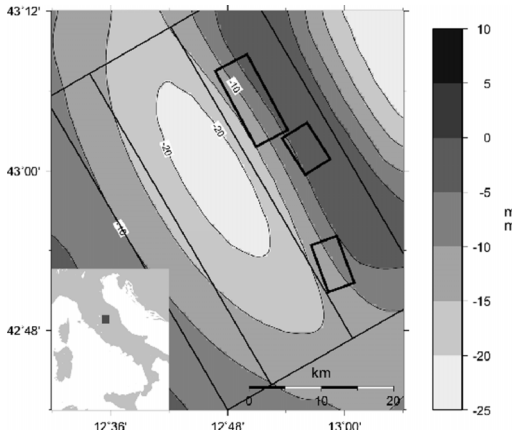
Fig. 1. Vertical postseismic relaxation due to slip on a 50-km-long normal fault, dipping 45 degrees to the SW and representing a prolongation of the largest shock of the 1997 sequence (northernmost open box). The three small open boxes represent the surface projections of largest shocks of the 1997 sequence, while the large boxes with bounded by thin lines represent the three segments of the Altotiberina fault.

1989). The maximum deformation amounts to about 22 mm, providing a secular rate of 0.03 mm/a if we assume a recurrence time of 700 a, as suggested by Pantosti *et al.* (1999) after interpreting the 1997 sequence as a reoccurrence of the 1279 earthquake. Since the upper crust has brittle properties, modeled vertical relaxation at the surface is representative of the displacement of the whole seismogenic layer. Therefore, we can project the vertical motion onto the AF to obtain average slip rates between 0.02 mm/a and 0.12 mm/a, which are much smaller than the value of 1 mm/a suggested by Chiaraluce *et al.* (2007) for the northern segment of the AF.

The average slip rates we have computed are meant to represent the long term effect of the CF relaxation on the evolution of the AF. Therefore, we are not interested in a detailed description of the relaxation process, which would have to take into account additional factors such as time-variable relaxation and nearly-free shear stress conditions on the AF. Depending on the viscosity profile, deformation

rates in the first few years after each earthquake can easily reach values of several millimeters per year, as we discuss in a later section. Moreover, allowing the AF to slip under specific conditions would surely have an impact on the stress evolution within the upper crust that we have here modeled as a continuous elastic layer. However, the use of a more sophisticated model would not have a strong impact on the purpose of this section, *i.e.* showing that relaxation of the CF is capable to load the AF, but it cannot represent the primary loading mechanism.

3. Slip on the Altotiberina fault

Since it appears that the average rates of postseismic relaxation due to earthquakes in the Colfiorito area account for only a small fraction of the AF slip, here we explore the possibility of an opposite interaction, namely an active role of the AF in the evolution of the Umbria-Marche fault zone. For this purpose, we model co- and post-sesimic deformation due to a 50-km-long NE-dipping normal fault representing the AF. Following Boncio and Lavecchia (2000), we distinguish three fault patches along the dip, with the shallowest (0-4 km depth) and deepest (7-14 km depth) patches dipping 30° and the middle patch dipping 13°. We model the coseismic response by means of a half-space model (Feigl and Dupre, 1998) and viscoelastic relaxation as in the previous section.

Figure 2 shows the total (elastic plus full relaxation) vertical deformation due to 70 cm of slip on the AF, consistent with a rate of 1 mm/a (Chiaraluce *et al.*, 2007) during a 700-year seismic cycle (Pantosti *et al.*, 1999). The whole area under the AF is dominated by subsidence, with a maximum due to the elastic component where the AF intersects the free surface and a second maximum due to viscoelastic relaxation below the CF. The large subsidence below the CF reaches a value of about 35 cm, comparable with the average slip accommodated on the largest faults during the recent 1997 sequence (Zollo *et al.*, 1999), suggesting that the AF is capable of actively loading the CF throughout a seismic cycle.
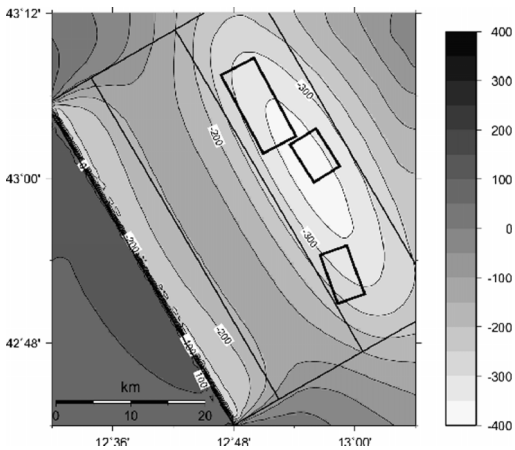
Fig. 2. Vertical deformation (elastic plus full relaxation) due to 70 cm of slip on the Altotiberina fault (AF). The large black boxes represent the three segments of the Altotiberina fault, dipping towards the NE with angles of 30°, 13° and 30° (shallow, middle and deep segment respectively). The three small boxes represent the surface projections of the largest shocks of the 1997 sequence.

4. Postseismic relaxation with a lateral heterogeneous lithosphere

The first part of our study focused on the average features of postseismic relaxation after earthquakes on the CF. The purpose of the present section is to discuss an improved postseismic relaxation model consistent with lateral crustal variations present in the Central Apennines.

By means of a 2D finite elements approach (Govers and Wortel, 1995), we model a SW-NE section through the Central Apennines extending for 250 km at each side of the CF, where the domain size has been chosen to minimize the effect of boundary conditions on the area of interest. Lateral variations are introduced according to the results published by Chimera *et al.* (2003). A large level of heterogeneity characterizes the topography of the Moho, which is located at a depth of 30 km under the CF area and at 38 km under the Adriatic Sea, whereas on the left side it presents a minimum of 28 km west of the AF and finally deepens to 33 km towards the Tuscan domain. According to Chimera *et al.* (2003), a

20-km-thick layer of hot lithospheric material, called mantle wedge, underlies the Moho beneath the Tuscan magmatic complex and one large part of the Central Apennines. This layer dies out before reaching the Adriatic coast, where a colder thermal profile is expected is also observed by heat flow studies (Della Vedova *et al.*, 2000). In our model domain, the two end members are represented by the Tuscan magmatic domain on the left, with a thin lithospheric lid leading to high temperature and low viscosities, and the Adriatic domain at the right side, with a thick lithospheric lid and a consequent cold isotherm and high viscosities. In the middle of the domain, under the CF and AF, the presence of the hot mantle wedge induces low viscosities also in the lower crust, even if the area is located above thick lithospheric roots. We impose a laterally varying temperature profile consistent with the lithospheric structure and with the observed heat flow, and let the viscosity profile be controlled by empirical flow laws for rocks and by laboratory derived rheological parameters (*e.g.*, Ranalli, 1995) . Since we have a large choice of possible rheologies and stress conditions, we have introduced an additional constraint by looking for those combinations of rheology and stress that provide viscosities anywhere not lower than 10^{17} Pa s at the bottom of the lower crust and 10^{16} Pa s in the mantle wedge. A viscosity of 10^{17} Pa s at the bottom of the lower crust is consistent with laboratory rheological parameters for soft lower crustal materials (*e.g.* wet diorite in Hansen and Carter, 1982) under realistic conditions in regions of active tectonics, with a surface heat flow of 60-70 mW/m2 and a background stress of 10-100 MPa. In the mantle wedge, the presence of low viscosities is inferred from the very low seismic velocities (VS less than 4.2 km/s), suggesting that the wedge might represent a partially molten mantle (Chimera *et al.*, 2003; Aoudia *et al.*, 2007). With our approach, we aim to represent a plausible viscosity structure, where the choice of different parameters would influence the actual values, but not the relative horizontal viscosity variations, which represent our main point of interest.

Figure 3, shows the resulting postseismic strain rates one year after the Colfiorito main shock, where the horizontal axis is centered at
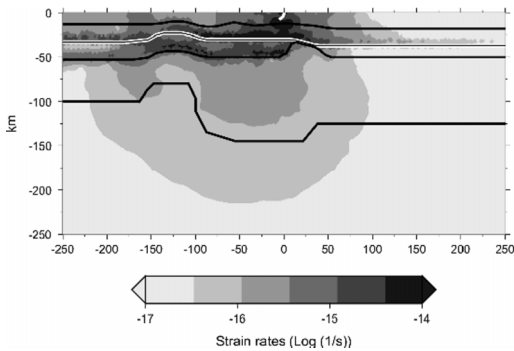
Fig. 3. 2D section through the Central Apennines, showing postseismic strain rates at 1 year after the earthquake. The Colfiorito Fault (CF) is represented by the small white segment in the center of the domain, and the Moho by the thin black line bounded in white.
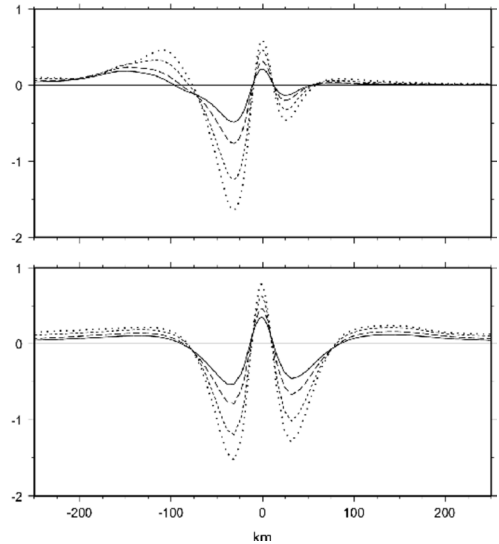

Fig. 4. Postseismic relaxation for the 2D approximation of the CF for both the lateral heterogeneous (top panel) and the homogeneous (bottom panel) model. The four lines depict vertical deformation at four different times after the earthquake: t = 1 a (solid), 2 a (long dashed), 5 a (short dashed) and 10 a (dotted).

the CF and the fault is represented by a small white segment. The two top layers represent the crust (upper and lower), the third layer the mantle wedge, followed by the rest of the lithosphere and by the asthenosphere. The Moho is indicated by a black line bounded in white. We can clearly see how the highest strain rates are localized in three distinct regions: in the first few kilometers around the fault, and in the bottom part of both the lower crust and the mantle wedge. The high strain rates in the upper crust are mainly due to the very large differential stresses induced by the earthquake, while localization of strain rates in the other layers is mainly controlled by the viscosity profile. The combined effect of viscosity jumps at the Moho and at the base of the mantle wedge due to changes in rheology, and lateral viscosity variations driven by the thermal structure, leads to the localization of postseismic relaxation in a confined region below the Umbria-Marche Apennines.

Vertical postseismic relaxation is shown in fig. 4 for the first 10 years after the earthquake: the choice of representing this particular time-span is due to the fact that large portions of the lower crust and mantle wedge have viscosities lower than 10^{19} Pa s, meaning that they almost completely relax in the first few years. The upper panel shows viscoelastic relaxation for the

lateral heterogeneous model, while the bottom panel shows the same result for a lateral homogeneous model with the same structure as the region below the AF. For the case of the heterogeneous model, the deformation pattern is dominated by a large subsidence in a rather narrow region between 10 km and 75 km west of the CF, bounded by a narrow uplifting region around the CF and by a broader uplift further to the west. The large subsidence occurs where large sedimentary basins such as the Foligno basin are mapped. These sedimentary basins are bordered by low-angle normal faults. The effect of lateral heterogeneities is mainly visible in the eastern side: when approaching the colder Adriatic domain, we observe a drastic reduction in subsidence with respect to the homogeneous model. A further difference between the two models is visible towards the Tuscan domain, where the combined effect of the thinner crust and very warm geotherm leads to an amplification of the uplifting bulge. According to those

results, we think that a lateral heterogeneous lithospheric structure has the effect of localizing postseismic relaxation due to earthquakes in the Colfiorito area in a rather narrow region below the AF and the related sedimentary basins.

We have verified that our conclusions are not dependent on the adopted 2D approximation, because there is no substantial qualitative difference between relaxation of a 50-km-long fault, representative of multiple ruptures in the Colfiorito area between Camerino and Norcia, and that of an infinitely long fault. The key parameter controlling the wavelength of the relaxation signal, in fact, is represented by the thickness of the upper elastic layer, which is here about 15 km and therefore much shorter than the extended CF. By comparing relaxation in a vertically layered medium for finite faults of different length, we have further verified that the quantitative effect of the 2D approximation results in the amplification of the magnitudes of relaxation by about a factor of two, which is again not relevant for the purpose of this study.

5. Discussion and conclusions

Here elaborate further on the possibility of an interaction between the low-angle NE-dipping Altotiberina fault (AF) and the SW normal faulting structures responsible for the 1997 Colfiorito sequence. With loose constraints on the magnitude and location of historical earthquakes, as well as on their recurrence time, we have modeled a possible scenario of postseismic relaxation which appears to be consistent that the formation of major sedimentary basins at the western side of the Umbria-Marche faulting zone. The location of the postseismic relaxation signal favours the loading of the AF, even if the slip rates that we have obtained are rather small: however, uncertainties are very large because those values are directly dependent on the average earthquake magnitude and recurrence time.

On the other hand, after modeling the effect of slip on the AF, we have shown that the AF alone could be responsible for providing most of the load necessary to rupture the CF.

When we compare average postseismic relaxation rates due to the CF with slip rates on the AF, the latter appears to provide the dominating signal. However, for a realistic viscosity structure where the lower crust and the mantle wedge below the Umbria-Marche Apennines are characterized by low viscosities (in the range 10^{16}-10^{18} Pa s), about half of the total postseismic relaxation is likely to take place in the first 10 years after the earthquake. This means that, at least locally, the postseismic loading on the AF could easily exceed the average slip rates. In addition, the impact of stress relaxation on the evolution of the AF can be increased by the presence of large lateral heterogeneities in the lithospheric structure, which have the effect of concentrating postseismic relaxation below the AF.

In conclusion, a possible scenario for the interaction between the AF and the CF allows aseismic slip on the AF to effectively load the CF, while postseismic relaxation after each rupture event on the CF plays the role of a feedback process, reloading sections of the AF on short time-scales and potentially affecting the evolution of the AF itself.

From a regional perspective, the strain pattern retrieved from the 2D finite element modeling of the postseismic deformation mimics the modeled stress pattern that accounts only for buoyancy forces as reported by Aoudia *et al.* (2007) along the same section and using the same geometry of the crust upper mantle. In fact the realistic pattern of localized vertical deformation reported in fig. 4 compares fairly well with its equivalent part reported in Aoudia *et al.* (2007, fig. 3). This is evidence that the two different length and time scale processes, namely, postseismic deformation and buoyancy, are complementary in shaping the Apennines and adjacent sedimentary basins. The high resolution deformation patterns modeled in this study as well as the one reported in Aoudia *et al.* (2003) satisfying the ongoing observed and complex geodynamics across North Central Italy with emphasis to the Umbria-Marche region can hardly be reproduced by a model accounting only for external forces such as a rotating or subducting or retreating Adria.

Acknowledgements

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