Ultrashallow seismic imaging of the causative fault of the 1980, M6.9, southern Italy earthquake by pre-stack depth migration of dense wide-aperture data

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A two-step imaging procedure, including pre-stack depth migration (PSDM) and non-linear multiscale refraction tomography, was applied to dense wide-aperture data with the aim of imaging the causative fault of the 1980, M6.9, Irpinia normal faulting earthquake in a very complex geologic environment. PSDM is often ineffective for ultrashallow imaging (100 m of depth and less) of laterally heterogeneous media because of the difficulty in estimating a correct velocity model for migration. Dense wide-aperture profiling allowed us to build accurate velocity models across the fault zone by multiscale tomography and to record wide-angle reflections from steep reflectors. PSDM provided better imaging with respect to conventional post-stack depth migration, and improved definition of fault geometry and apparent cumulative displacement. Results indicate that this imaging strategy can be very effective for near-surface fault detection and characterization. Fault location and geometry are in agreement with paleoseismic data from two nearby trenches. The estimated vertical fault throw is only 29–38 m. This value, combined with the vertical slip rate determined by trench data, suggests a young age (97–127 kyr) of fault inception. Citation: Bruno, P. P., A. Castiello, and L. Improta (2010), Ultrashallow seismic imaging of the causative fault of the 1980, M6.9, southern Italy earthquake by pre-stack depth migration of dense wide-aperture data, Geophys. Res. Lett., 37, L19302, doi:10.1029/2010GL044721.

1. Introduction

The Southern Apennines range, with up to M7 earthquakes (Figure 1a), is among the areas with the highest seismic potential in the Mediterranean region. Active fault detection along the range is complicated by slow-slipping, recent (Middle–Upper Pleistocene) normal faults characterized by a small cumulative displacement, weakly expressed at the surface by short-term morpho-tectonic indicators (e.g. small scarps) [Pantosti and Valensise, 1990]. This is the case of Irpinia Fault (IF), source of the 4th largest Italian earthquake of last century (1980, Ms 6.9, Irpinia earthquake) [Pantosti and Valensise, 1990], which was recognized solely after the 1980 earthquake by coseismic scarps (Figure 1a). This example demonstrates that morphological and structural approaches alone can be insufficient for active fault detection and characterization, and that integration of geological with trench and high-resolution geophysical data is necessary. In particular, ultrashallow reflection seismology is very attractive for the potential benefits in terms of adding valuable information for hazard studies. Unfortunately, seismic reflection imaging of shallow fault–zones is often degraded by the presence of strong lateral velocity changes, which, together with steep-dip reflectors, clearly violate the flat-layered Earth assumption used for Common Depth Point (CDP) processing. This leads to the suppression of steep-dip energy on stacked records. Not surprisingly, post stack migration will contain the errors and the limited dip bandwidth of the CDP processing. Pre-stack depth migration (PSDM) can overcome these typical drawbacks of CDP processing [see Hole et al., 2001; Morozov and Levander, 2002; Bradford et al., 2006; Catchings et al., 2008, and references therein] because of its ability to focus reflectors in presence of complex velocity distributions [Versteeg, 1993]. PSDM is highly sensitive to the accuracy of the velocity model, which is critical to account for the seismic wave propagation and ray-path bending in the depth domain. It is well established that a correct Vp model of very heterogeneous structure is difficult to obtain when only near-vertical reflection acquisition geometries are available [see Operto et al., 2004, and references therein]. This occurs because small-aperture receiver/shot arrays preclude the recording of: (1) deep penetrating refracted and post-critical reflected waves (sensitive to the velocity structure); (2) reflections from steep dipping reflectors (i.e. faults). In theory, both those problems can be solved by dense wide-aperture profiling, which also allows the use of traveltome tomography to estimate the velocity model [see Hole et al., 2001; Operto et al., 2004; Catchings et al., 2008].

In this study, we investigate the ultrashallow structure of the IF in a extremely complex location using a 256 m long, dense geophone array and a two-step imaging procedure that combines multiscale refraction tomography and PSDM. The seismic profile was acquired across the 1980 scarp, at “Pantano di San Gregorio Magno” (hereinafter referred to as “Pantano”: Figures 1b–1c). This Quaternary intermontane basin is filled by lacustrine sediments, passing laterally into carbonate alluvial fans and slope debris, which rest upon Mesozoic limestone [Aiello et al., 2006] (Figure 1b). The basin opening and evolution was mainly controlled, since Middle Pleistocene, by WNW–ESE trending range-bounding normal faults. The basin was affected by surface faulting during the 1980 earthquake. This event resulted from the rupture of three main normal fault segments (e.g. Irpinia Fault) [Pantosti and Valensise, 1990] that strike 310°–320° and dip 60–70° NE. Three main strands, separated by two...
gaps, formed an overall 38-km-long, NW-trending fault scarp up to 1 m high (Figure 1a). The Pantano scarp belongs to the southernmost IF strand. The scarp investigated in this study starts from the middle of the basin, runs southwestward across Pantano for about 1 km with increasing throw (from 0 to 50 cm), irrespective of the nearby range-bounding faults (Figure 1b) [Pantosti and Valensise, 1990]. It continues along the northern flank of a limestone ridge for about 2 km. Two trenches (Figure 1c) [D’Addezio et al., 1991] show that at least four 1980-type paleoearthquakes occurred along this section of the IF during the last 19 kyr. Consistency between timing of paleoevents, recognized on different IF sections [Pantosti et al., 1993], suggests that the 1980 earthquake is characteristic and that IF represents a major seismogenic source of the Southern Apennines.

2. Seismic Data Acquisition

[4] The seismic profile is situated at the eastern margin of the basin and strikes NNE-SSW, nearly perpendicular (106°) to the fault scarp intercepted at 180–190 m (Figure 1c). The data were recorded above lacustrine and colluvial deposits, with the limestone bedrock exposed ~50 m southwestward (Figure 1c). Fault imaging is challenging because the fault displaces, with a steep dip (~70°, D’Addezio et al., 1991), unconsolidated and clastic deposits above an articulated limestone substratum. Using a “target oriented” acquisition layout we were able to sample the deep part (~100 m) of the fault zone with maximum fold and offset range (Figure S1 in the auxiliary material). We used a dense geophone spread ~3 times larger than the presumed depth of the basin substratum (50–100 m). Seventy-three buffalo gun shots were recorded by a 168-channel, 40-Hz geophone array with a 1.5 m spacing between individual sensors. The average shot spacing was 4 m. Data sampling was 125 µs. This field setup allowed to record not only near-vertical to large-

Figure 1. (a) Seismicity of the Southern Apennines with sketch map of the central Mediterranean area and location of the Apennine range. 1 - Instrumental seismicity (1981–2002; depth: 0–30 km); 2 - Historical earthquakes (M > 6); 3 - Focal mechanism of M > 5 events (a ~ 1980 M6.9; b ~ 1996 M5.1; c ~ 1990 M5.7; d ~ 1998 M5.6); 4 - Fault scarps of the 1980 Irpinia earthquake. The transparent box encloses the area in Figure 1b. (b) Geological sketch of Pantano basin. 1 - Mesozoic limestones, 2 - Pliocene sands and conglomerates, 3 - Alluvial fan deposits (Middle Pleistocene - Holocene), 4 - Slope debris (Middle Pleistocene - Holocene), 5 - Lacustrine and colluvial deposits (Upper Pleistocene - Holocene), 6 - Basin-bounding normal faults, 7 - Quaternary normal fault, 8 - 1980 scarp (Irpinia Fault). The yellow box encloses the area showed in Figure 1c. Well location is also reported. (c) Aerial photo of the survey area showing the trace of the seismic profile with numbered CDP positions (yellow), the trenches (blue) and the 1980 scarp (red).

offset - high-amplitude post-critical reflections but also deep penetrating refracted and turning waves, which are suitable for first-arrival traveltime tomography (Figure 2).

3. Data Processing and Estimation of Velocity Models

Figure S2 (auxiliary material) shows the data processing flow. To evaluate the improvement of PSDM with respect to conventional processing (Figure 3), both post-stack depth migrated and PSDM images were produced. CDP processing included near-surface static corrections computed by tomographic velocities. Conversely, PSDM data were depth migrated from topography using the common offset domain Kirchhoff migration algorithm. Migration from topography improves static corrections with respect to simple datum statics, which are based on vertical ray-path assumption. PSDM processing includes two main parts: (1) estimation of a proper Vp model and (2) PSDM runs [Versteeg, 1993].

An ensemble of smooth Vp models was determined by a multiscale, non-linear refraction tomography algorithm, effective to image complex shallow structures [Im improta et al., 2003, and references therein]. We inverted 9060 first breaks, handpicked on 62 selected records. The multiscale strategy consists of a series of inversion runs performed by progressively thickening the velocity grid (i.e. increasing the spatial resolution) [see Lutter and Nowack, 1990]. For each run the minimum cost function model is found by a combined global random (Monte Carlo) and local (Simplex) search, that does not require a starting model. The improvement in spatial resolution is achieved, run by run, at the cost of a progressive decrease in resolution depth, which is assessed by a posteriori checkerboard tests (Figure S4a and S4b in the auxiliary material). Both the long- and the short-wavelength Vp models (Figures 4a and 4b) show a velocity pattern compatible with a NE-dipping normal fault.

A smoothed Vp model is required for achieving the best PSDM imaging results, because ray-based migration algorithms break down when velocities change too rapidly over short distances. To find the best compromise between model smoothing and performance of PSDM in terms of quality and details of the reflectivity image, we performed several migration tests by using Vp images at different spatial resolution obtained by multiscale tomography. We assessed migration results for each Vp model analyzing both the Common Image Gathers (CIG) and the related PSDM sections (Figure S3 in the auxiliary material). The best migration run was achieved using a long-wavelength Vp model (Figure 4a). This model allows reflection imaging of the fault.
zone down to the basin substratum (~100 m depth), while maintaining metrical resolution (Figure 3c).

4. Comparison of Imaging Results and Interpretation

[8] PSDM provides better results compared to the related post-stack depth migration (Figures 3b and 3c). In detail, post-stack migration fails to image the shallow structure (i.e. < 20 m depth), which is contaminated by source-generated noise and migration artifacts. In presence of large lateral Vp variations, such as across locations 140–240 (see Figures 4a and 4b), post-stack migration yields a very poor reflectivity image down to 70 m deep. The comparison between Figures 3a–b and Figure 3c also reveals that CDP processing leads to the suppression of steep-dip energy (between position 140–180 in Figure 3).

[9] The PSDM section shows a NE-dipping fault, located at 140–190 m. Its surface projection matches the 1980 co-seismic scarp and faulted deposits exposed in the trenches (Figures 4c–4d). IF is detected by: (1) an abrupt change in the reflection configuration across the fault zone down to 50 m deep; (2) clear reflection truncations in the 30–100 m depth range; (3) a steep-dipping reflector, evident across the fault zone at ~40–80 m deep. We associate the top of the limestone basement to low-frequency high-amplitude events above a reflection free region. In the fault hanging-wall, the basement shows a concave shape, reaching a maximum depth of ~110 m, and rapidly rises northward. Above the basement, we observe a low-reflectivity region (Unit 2), which is in turn covered by a stack of high-amplitude and continuous reflectors (Unit 3). In the fault foot-wall, the basement is imaged at ~60 m deep and rises at the southwestern ending of the profile. Above it, a continuous reflector, ~45 m deep, allows us to discriminate two Units. The lower Unit, ~20 m thick, can be related to Unit 2 in the hanging-wall. The upper Unit (Unit 4), up to 45 m thick, consists of low-amplitude/complex fill, and considerably differs from Unit 3 imaged in the fault hanging-wall. The fault dip, corrected for the angle between fault strike and seismic profile (i.e. 106°) is between 61° and 66°, in close agreement with a 70°–dipping fault plane exposed in the trenches [D’Addezio et al., 1991]. Along the section, we identify some minor splays. The basement displacement, measured across the fault-zone and corrected for the profile strike, yields a cumulative throw of only 29–38 m. Throw measurement is complicated by the fact that IF seems to dislocate a substratum with an articulated morphology (e.g. a paleo-valley), which might pre-date IF inception.

[10] The geologic interpretation of the PSDM image is aided by complementary Vp models. In the fault hanging-wall, the top of Unit 2 matches a high-Vp region (Vp > 2500 m/s, Figure 4a), whereas Unit 3 corresponds to low-Vp values (Vp < 1500 m/s; Figure 4b). In particular, very-low (Vp < 1000 m/s) bodies approximately delineate the fault-zone. In the footwall, we observe a lateral Vp increase in correspondence of Units 2 and 4 (Figure 4a).

[11] Based on velocity and PSDM images, we interpret Unit 2 as Middle Pleistocene dense/cemented carbonate slope debris and alluvial fans covering the Mesozoic limestones, while Unit 3 can be reasonably interpreted as Upper Pleistocene - Holocene lacustrine deposits. The very-low Vp bodies can be tentatively interpreted as colluvial packages deposited in the fault zone. This interpretation is supported by trench data: in the downthrown side of the fault, slip along IF caused the formation of colluvial bodies with abundant weathered pyroclastites (Figure 4d) [D’Addezio et al., 1991]. Unit 4 can be related to coarser deposits (presumably Upper Pleistocene - Holocene carbonate slope debris), which crop out along the southern edge of the basin, in the upthrown side of the IF (Figures 1b–1c).

[12] Tilting and growth of lacustrine strata (Unit 3) towards the fault indicate sin-sedimentary activity. The abrupt thickening of Unit 2 in the downthrown side of the fault (~20 m) suggests that IF partially controlled the deposition of this Unit. By combining the total vertical slip (29–38 m) inferred by PSDM with a 0.3 mm/yr vertical slip rate reported by D’Addezio et al. [1991], and assuming that this rate is representative of the entire IF history, we speculate estimate a 97–127 kyr age for fault inception (Middle–Upper Pleistocene).

5. Conclusions

[13] This study presents the first detailed seismic image of the ultrashallow (i.e. ≤ 100 m deep) structure of IF, the
causative fault of the 1980 (Ms 6.9) Irpinia earthquake, and provides valuable information on fault geometry and cumulative displacement. The exploration strategy was based on dense wide-aperture profiling and on a two-step imaging procedure, which, in presence of large lateral heterogeneity, allows: (1) the estimation of a reliable, smooth Vp model by multiscale non-linear refraction tomography, and (2) to correctly focus reflectors by PSDM. This strategy, was crucial to successful imaging of IF. Indeed, the comparison between the outcomes of PSDM and conventional CDP processing show that the latter results are hampered by structural complexity across the fault zone.

Results demonstrate that the investigated segment of the IF produced no more than 29–38 m of throw, probably starting from latest Middle Pleistocene–early Upper Pleistocene. This small value of cumulative deformation is in agreement with the outcomes of a shallow refraction survey carried out on the central segment of the IF [Impromita et al., 2003] and with morpho-tectonic data [Ascione et al., 2003]. Thus, IF is a relatively young and slow-sliping structure that has not yet developed mature geomorphic features, despite its significant seismogenic potential. Local geomorphic surveys and well data (Figure 1b) indicate that sedimentation rate essentially counterbalanced fault-induced subsidence at
Pantano [Aiello et al., 2006]. However, our imaging of the basin structure suggests that the investigated segment of the IF, sited in the middle of the basin, is responsible for only part of the accommodation space created by faulting. This fact implies that nearby extensional faults [Aiello et al., 2006], not investigated by our profile, were active in recent times.

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References


