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Double-Difference relocation and focal mechanisms of Lucanian Apennine (southern Italy) seismicity.

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Introduction

The Lucanian Apennine belongs to the southern Apenninic chain which is located within the complex, articulated central Mediterranean plate boundary zone between the Eurasian and African plates. The geodynamic setting of this region is characterized by the NNW-SSE relative plate convergence between Eurasia and Africa. The tectonics of the Lucanian Apennine is accommodated by the collision between the Adria microplate and the Apenninic belt. Recent geodetic data suggest that the Adria is a microplate separated from the Eurasian and African plates, while its southern border is ambiguously defined. The eastward migration of the extension-compression system of the Apenninic chain is related to the subduction process of the Adria microplate lithosphere and the opening of the Tyrrhenian back arc basin. Since the Early Pleistocene, the active extension within the chain produced a broad and complex system of NW-trending normal faults and related basins. Seismological data and recent geodetic studies reveal that the Apenninic chain is undergoing a NE-trending extension, with seismic deformation rates higher in the southern portion. The southern Apenninic chain is one of the main seismically active regions of Italy (Fig.1). In the last four centuries, this area was characterized by moderate to strong events. Among the strongest earthquakes supported by historical records, the 1694 events (Me = 6.9) hit the Irpinia area and the 1857 Basilicata earthquake (Me = 6.9) hit the upper Val d'Agri and Vallo di Diano area, both with effects of the XI degree on the Mercalli–Cancani–Sieberg (MCS) scale. The least strong earthquake in this region hit the Irpinia area in 1980 (Ms = 6.9) with effects of the X degree MCS and normal mechanism of rupture.

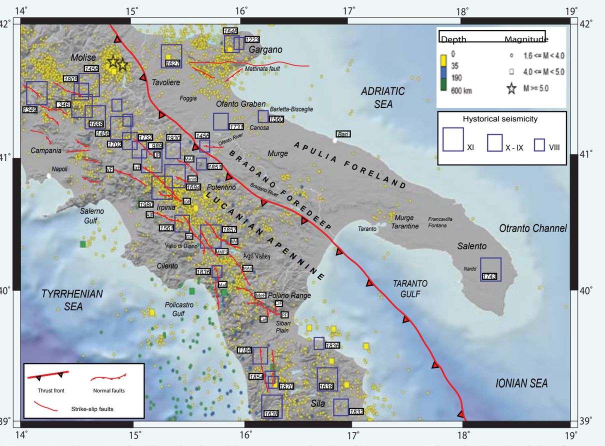

Fig.1: Southern Italy historical and instrumental seismicity map. Historical seismicity from the *Catalogo parametrico dei terremoti italiani* (CPTI Working Group, 2004). Instrumental seismicity from the *Seismicity map of Italy*, 2000-2007, INGV-CNT, Roma (*Castello et al.*, 2008). Active faults from *Galadini et al.* (2000), *Maschio et al.* (2005) and *Papanikolaou and Roberts* (2007) (from *Frepoli et al.*, 2010).

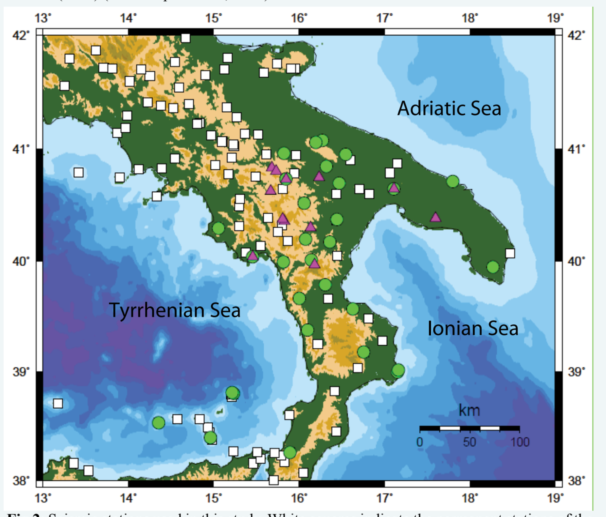

Fig.2: Seismic stations used in this study. White squares indicate the permanent stations of the Italian national network, green circles indicate the temporary stations deployed for the SAPTEX array (June 2001 – December 2004) and magenta triangles indicate the temporary stations deployed for the SeSCAL project (December 2007 – March 2009) (from *Frepoli et al.*, 2010).

Data and analysis

We studied the seismicity occurred in the period 2001-2008 analyzing a high-quality waveform dataset collected during two recent passive seismic experiments carried out in the study region (Fig. 2). The SAPTEX array (green circles in Fig.2) was a long-term tomography experiment lasted from June 2001 to December 2004 (*Cimini et al.*, 2006), while the SeSCAL array (magenta triangles in Fig.2) has operated in the period between December 2007 and March 2009. From the continuous recordings of the temporary stations we extracted over 15600 waveforms of events with local magnitude range 1.5 ≤ ML ≤ 4.1. These were hand-picked along with those recorded by the permanent stations of the Italian National Seismic Network (RSNC; white squares in Fig.2) obtaining a dataset of 15666 P- and 9228 S-arrival times. We located 566 events out of 1047 recorded earthquakes using the Hypoellipse code (*Lahr*, 1989), the 1D velocity model and Vp/Vs ratio of 1.83 computed for the study region by *Maggi et al.* (2009) (Table I). Taking into account the hypocentral distribution, we subdivided the studied region into 6 sub-areas (Fig. 3). We relocated the seismicity of each sub-area using the double-difference (DD) technique (HypoDD code, *Waldhauser and Ellsworth*, 2000; *Waldhauser*, 2001). This algorithm can be used when the hypocentral distance between two earthquakes is small compared to the source receiver distance and the scale length of velocity heterogeneity. Therefore the ray paths between the events and common station are similar and the difference in the travel times for two events recorded by the same station can be attributed only to the spatial offset between the events. We computed composite focal mechanisms using the FPFIT code (*Reasenberg and Oppenheimer*, 1985) only for the relocated events grouped in clusters characterized by a maximum of 2 km of distance between the hypocenters.

Top of layer (km)	Velocity of model Test8 (km/s)
0	4.27
-2	5.52
-11	6.1
-23	6.5
-31	7.31
-45	7.9

Table 1: Lucanian Apennines velocity model computed with VELEST code (*Maggi et al.*, 2009).

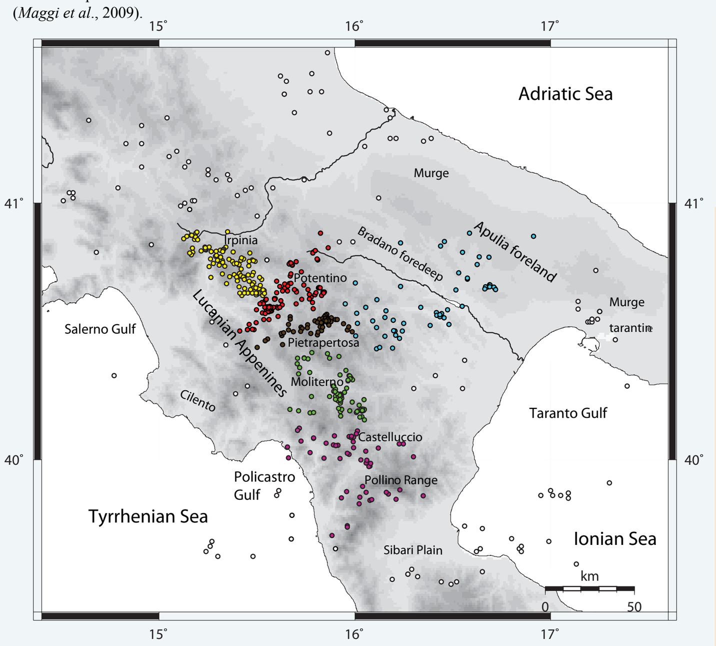

Fig.3: Map with the Hypoellipse location of the 566 earthquakes. Colours are indicating the six groups of events analyzed with HypoDD.

Group 1 (yellow)

This seismicity is located in the Irpinia region within an area stretching from 40.62º to 40.90º of latitude N and from 15.10º to 15.54º of longitude E (Fig.3). This group consists of 102 events located with Hypoellipse code. Event hypocentres are concentrated between 10 and 18 km of depth (Fig.4g, h). Hypocentral errors and rms are significantly reduced using the double-difference method (Fig.4). In this way hypocenters are more clustered (Fig.5). Analyzing the epicentral distribution we observe that the events are mainly located between the structures of the 1980 Irpinia earthquake (main fault and antithetic; Fig.5a, b). The HypoDD hypocenters show shallower depths in comparison with those obtained with Hypoellipse. Moreover, depth is increasing from NW to SE (Fig.5c, d, e, f).

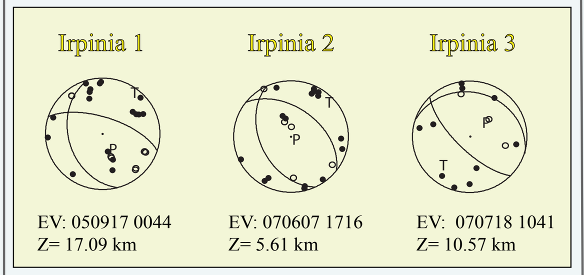

Fig.6: Composite focal mechanisms computed for three clusters located in the Irpinia area (see Fig.5b, d).

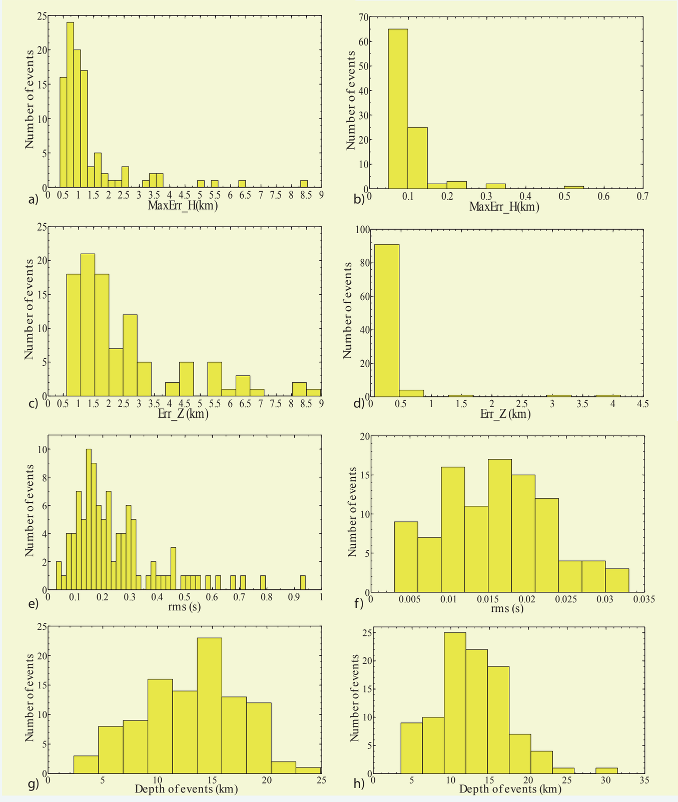

Fig.4: Rms (seconds), Maximum Horizontal (MaxErr_H) and vertical (Err_Z) errors (kilometres) and depth distribution of the 97 best earthquakes located using Hypoellipse (a, c, e, g) and HypoDD code (b, d, f, h).

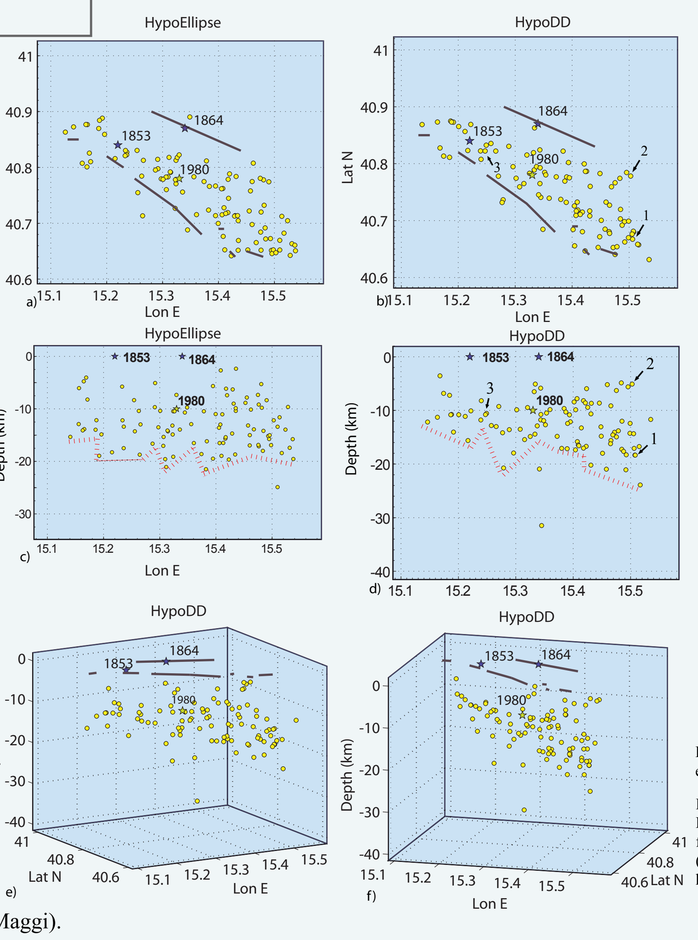

Fig.5 (left side): Map view of hypocentral distribution and W-E cross-sections of the 97 events located with Hypoellipse (a, c) and HypoDD code (b, d). 3D plots of events relocated with double-difference method (e, f). Red dotted line trace variation in seismogenic base. Brown lines: active structures observed in this area (DISS Working Group, 2009). Blue stars are epicentres of historical earthquakes and green stars are hypocentres. Numbers indicate clusters used to compute composite focal mechanisms.

Group 2 (red)

This group is located in the Potentino area (15.42-15.88 E, 40.5-40.9 N) and consists of 89 events located with Hypoellipse (Fig.3). 84 are the relocated earthquakes with HypoDD code. Most earthquakes are located within the 7-20 km depth range (Fig.7g, h). Hypocentral locations are improved with the double-difference method: vertical and horizontal errors and rms are reduced (Fig.7); hypocenters are more clustered (Fig.8). Analyzing the epicentral distribution we observe that the earthquakes are mainly located to the SW of the two Potentino sequences of 1990 and 1991 (Fig.8a, b). A small seismic sequence started with the event of April 18, 2002 (ML = 4.1), located at 12.4 km of depth beneath Savoia di Lucania, is placed to the SW of the grouped area (Fig.8a, b). Hypocentral depth of this sequence is ranging between 8 and 13 km (Fig.8c, d). Moreover, this cluster is slightly elongated in a NW-SE direction (Fig.8f).

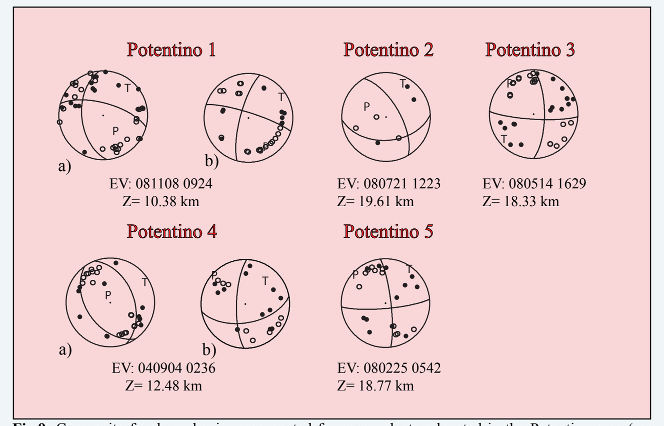

Fig.9: Composite focal mechanisms computed for seven clusters located in the Potentino area (see Fig.8b, d).

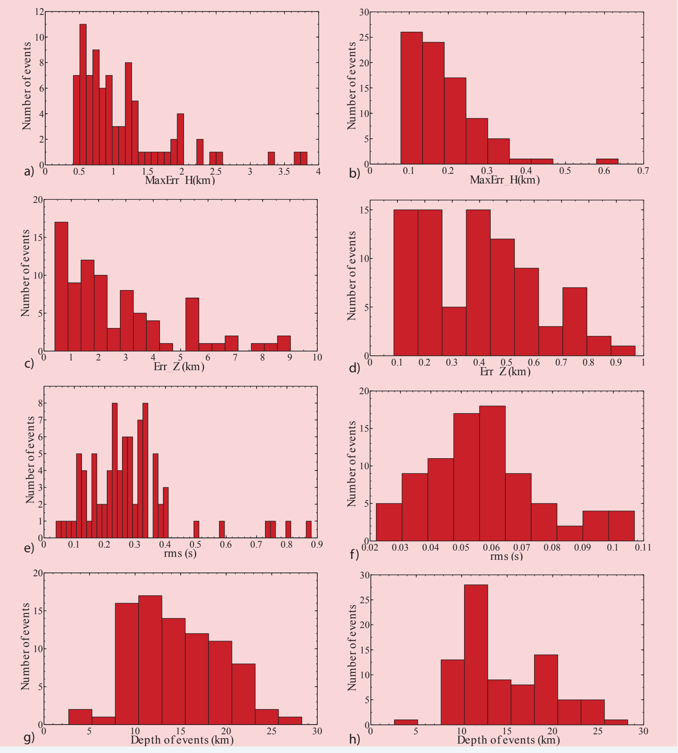

Fig.7: Rms residuals (seconds), horizontal and vertical errors (kilometres) and depth distribution of the 84 earthquakes located using Hypoellipse (a, c, e, g) and HypoDD code (b, d, f, h).

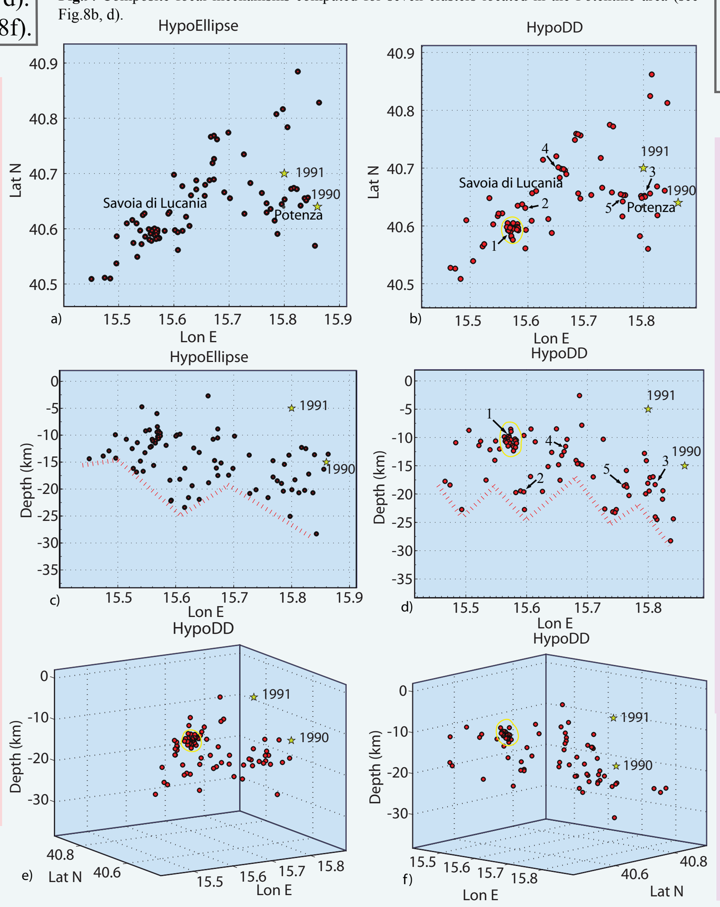

Fig.8: Map view of hypocentral distribution and W-E cross-sections of the 84 events located with Hypoellipse (a, c) and HypoDD code (b, d). 3D plots of events relocated with double-difference method (e, f). Green stars hypocentre of historical earthquakes. Red dotted line trace variation in seismogenic base. Yellow circle outlines the Savoia di Lucania cluster. Numbers indicate clusters used to compute composite focal mechanisms.

Group 3 (brown)

This group is located in the area between 40.44°-40.57°N of latitude and 15.50°-16.00°E of longitude named Abriola-Pietrapertosa and consists of 67 earthquakes (Fig.3). We relocated 64 events with the double-difference method improving the hypocentral locations (Fig.10, 11). Large part of earthquakes show hypocentral depths between 10 and 18 km (Fig.10g, h). These relocated events are elongated in a E-W direction (Fig.11a, b). A new result in this work is given by the seismic sequence of November 2008, which consists of 33 events (1.0 ≤ ML ≤ 2.9). The increased number of seismic stations in the study area, with the temporary array of the passive experiment SeSCAL, give us the occasion to relocate these events with good accuracy. This cluster is oriented along a NW-SE direction (Fig.11a, b) and shows a depth range of 10-17 km (Fig.11c, d).

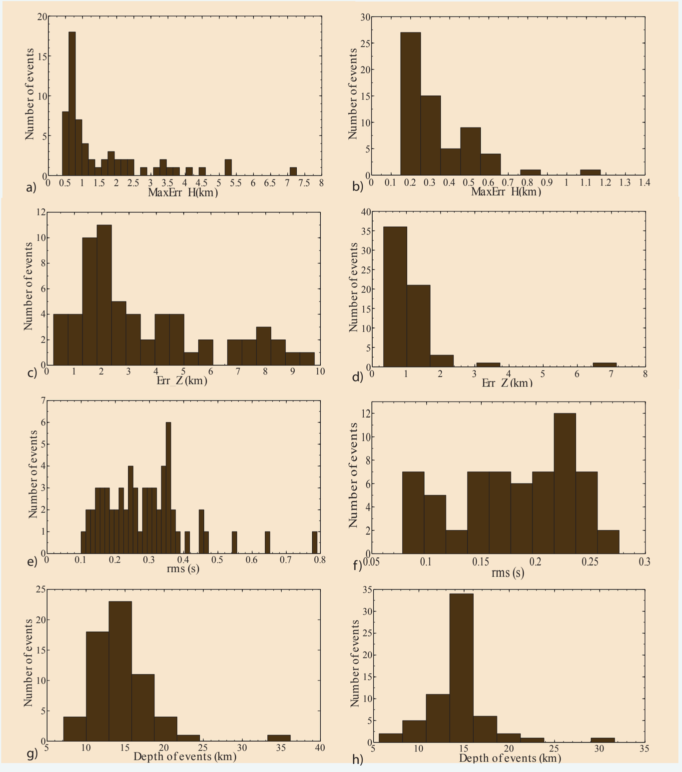

Fig.10: Rms residuals (seconds), maximum horizontal (MaxErr_H) and vertical (Err_Z) errors (kilometres) and depth distribution of the 64 earthquakes located with Hypoellipse (a, c, e, g) and HypoDD code (b, d, f, h).

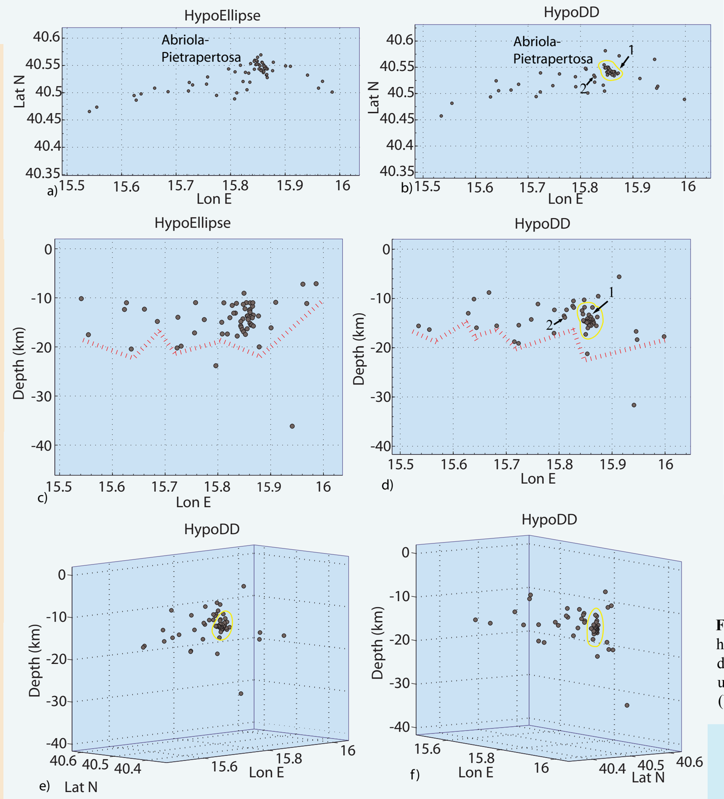

Fig.11: Map view of the hypocentral distribution and W-E cross-sections of the 64 events located with Hypoellipse (a, c) and HypoDD code (b, d). 3D plots of events relocated with double-difference method (e, f). Red dotted line trace variation in seismogenic base. Yellow circle outlines the cluster of the Abriola-Pietrapertosa sequence. Numbers indicate clusters used to compute composite focal mechanisms.

Group 5 (magenta)

Seismicity of this group is concentrated between 39.62°-40.14° N of latitude and 15.65°-16.36°E of longitude in the area of the Mercure Valley and the Pollino Range. It consists of 54 earthquakes (Fig.3). The microseismicity of this group is located in the same area of the small 1998 seismic sequence of Castelluccio. We relocated 50 events with the double-difference method improving hypocentral locations (Fig.16, 17). Hypocenters are more concentrated in the 10-15 km depth range (Fig.16g, h). There is a gap of microseismicity in the 23-32 km depth range (Fig.17). Few events are deeper than 30 km. This deep seismicity is located to the SW of the Pollino Range and could be related with the Southern Tyrrhenian Subduction Zone.

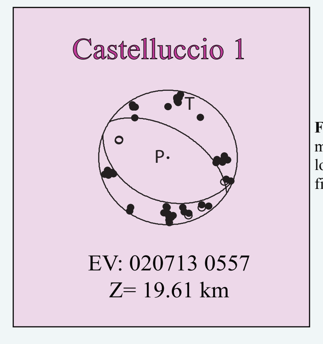

Fig.18 (left side): Composite focal mechanism computed for one cluster located in the Castelluccio area (see fig.17b,d).

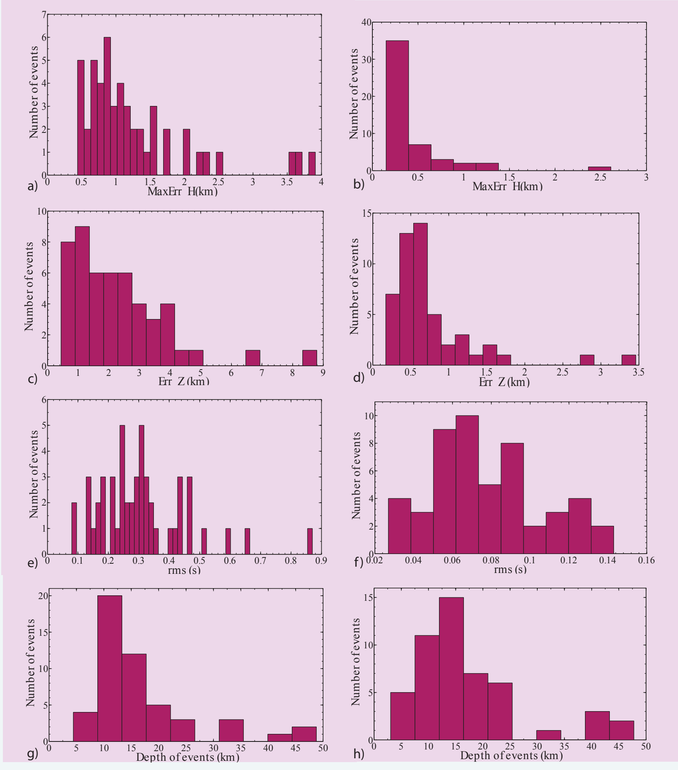

Fig.16: Rms residuals (seconds), maximum horizontal (MaxErr_H) and vertical (Err_Z) errors (kilometres) and depth distribution of the 50 earthquakes located using Hypoellipse (a, c, e, g) and HypoDD code (b, d, f, h).

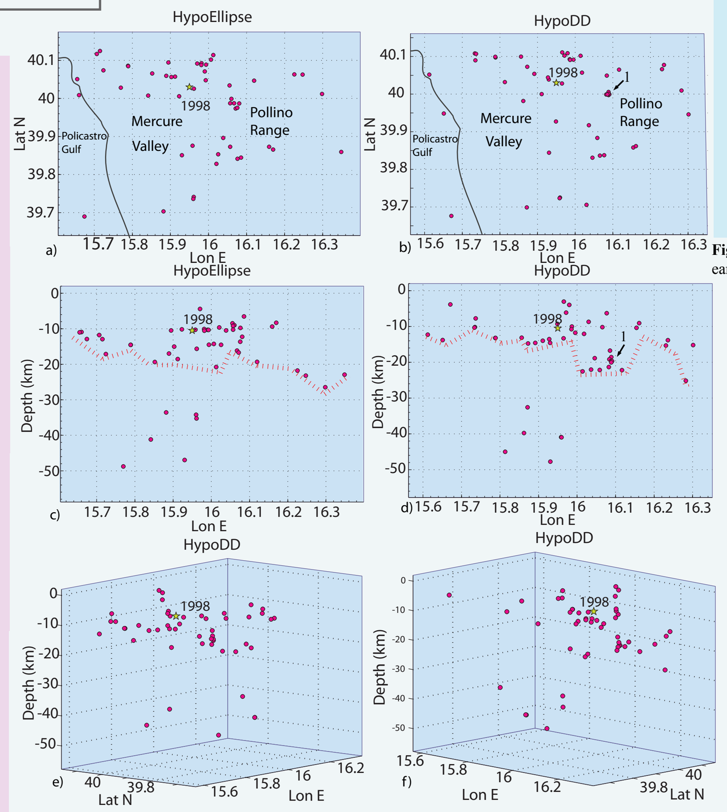

Fig.17: Map view of the hypocentral distribution and W-E cross-sections of the 50 events located with Hypoellipse (a, c) and HypoDD code (b, d). 3D plot of the events relocated with double-difference method (e, f). Red dotted line trace variation in seismogenic base. Grey line: coastline. Yellow star: epicentres of historical earthquakes. Numbers indicate clusters used to compute composite focal mechanisms.

Group 4 (green)

This seismicity is located within the area of Auletta Basin, Vallo di Diano and Val d'Agri (40.10°-40.43° N of latitude and 15.62°-16.10°E of longitude). It consists of 78 earthquakes (Fig.3). We relocated 74 events with the double-difference method improving hypocentral locations (Fig.13, 14). Events are mainly localized within the 9-15 km depth range (Fig.13g, h). Hypocenter are more clustered by using HypoDD code. We can identify one main cluster to the SE of the upper Val d'Agri active faults. This includes events of a significant swarm named Moliterno (February-December 2002; Fig.14b, d, e, f). The relocated events of the Moliterno swarm show hypocenter depths between 6 and 11 km. To the East and the NE of the Moliterno swarm the microseismicity is rather sporadic. It is worth to note that the upper Val d'Agri was hit by the strong 1857 earthquake with ground motion reached intensity XI in the localities of Montemurro, Grumento and Viggiano.

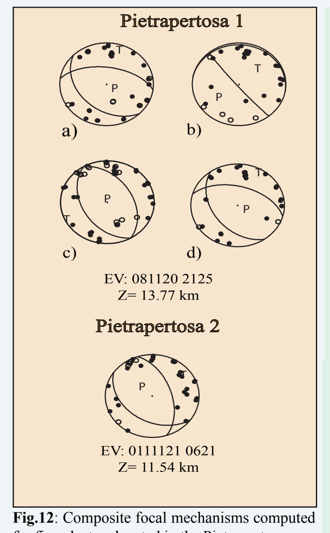

Fig.12: Composite focal mechanisms computed for five clusters located in the Pietrapertosa area (see Fig.11b,d).

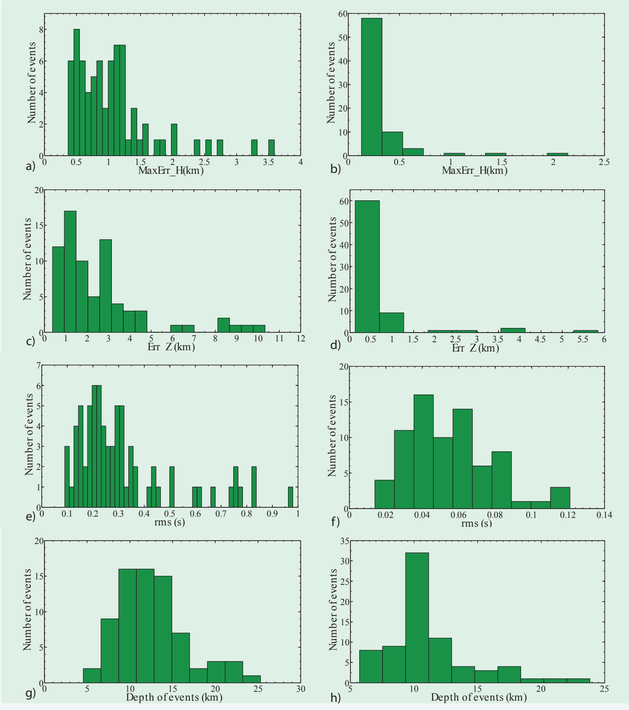

Fig.13 (right side): Rms residuals (seconds), horizontal and vertical errors (kilometres) and depth distribution of the 74 earthquakes located using Hypoellipse (a, c, e, g) and HypoDD code (b, d, f, h).

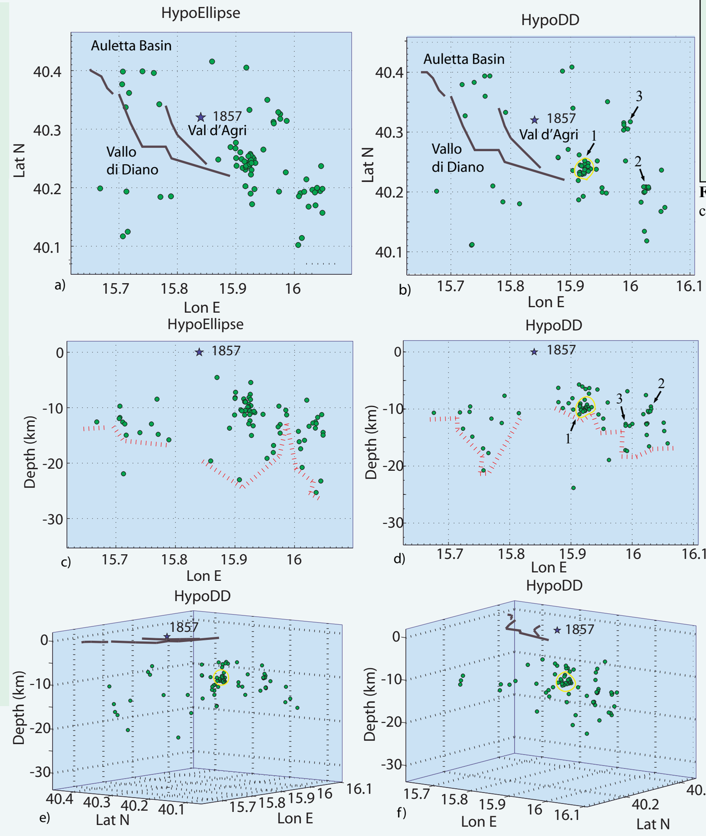

Fig.14 (left side): Map view of the hypocentral distribution and W-E cross-sections of the 74 events located with Hypoellipse (a, c) and HypoDD code (b, d). 3D plots of events relocated with double-difference method (e, f). Red dotted line trace variation in seismogenic base. Brown line shows the active structures observed in this area (DISS Working Group, 2009). Blue star: epicentres of historical earthquakes. Yellow circle outlines cluster of the Moliterno sequence. Numbers indicate clusters used to compute composite focal mechanisms.

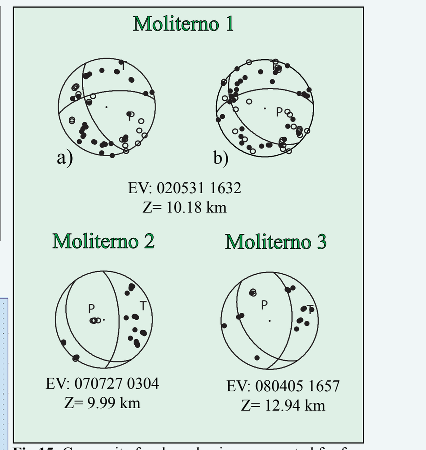

Fig.15: Composite focal mechanisms computed for four clusters located in the Moliterno area (see Fig.14b,d).

Group 6 (blue)

Seismicity of this group is located in the area of the Bradano Foredeep and the Apulia Foreland (40.40°-40.90° N of latitude, 16.00°-16.88°E of longitude). It consists of 56 earthquakes (Fig.3). This area is characterized by a more sparse seismicity. From historical records we know that this area was not hit by strong earthquakes. We relocated 54 events with the double-difference method improving the hypocentral locations (Fig.19, 20). Most of the microseismicity is located in the Bradano foredeep area. To the west, close to the eastern margin of the chain, the seismicity shows hypocentral depths between 9 and 30 km, while in the eastern part of the Bradano foredeep it is characterized by deeper events (9-40 km depth range) (Fig.20). We observe a cluster of shallow events (around 5-8 km of depth) to the east of Matera city. The deep crustal seismicity in the Bradano Foredeep and the Apulia Foreland area indicates the westward flexure of the Adria plate beneath the Apenninic belt.

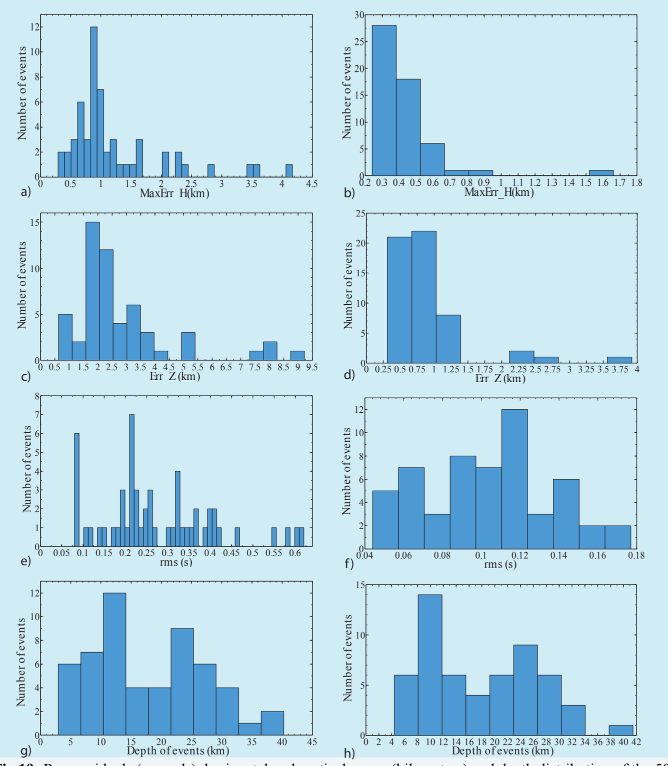

Fig.19: Rms residuals (seconds), horizontal and vertical errors (kilometres) and depth distribution of the 50 earthquakes located with Hypoellipse (a, c, e, g) and HypoDD code (b, d, f, h).

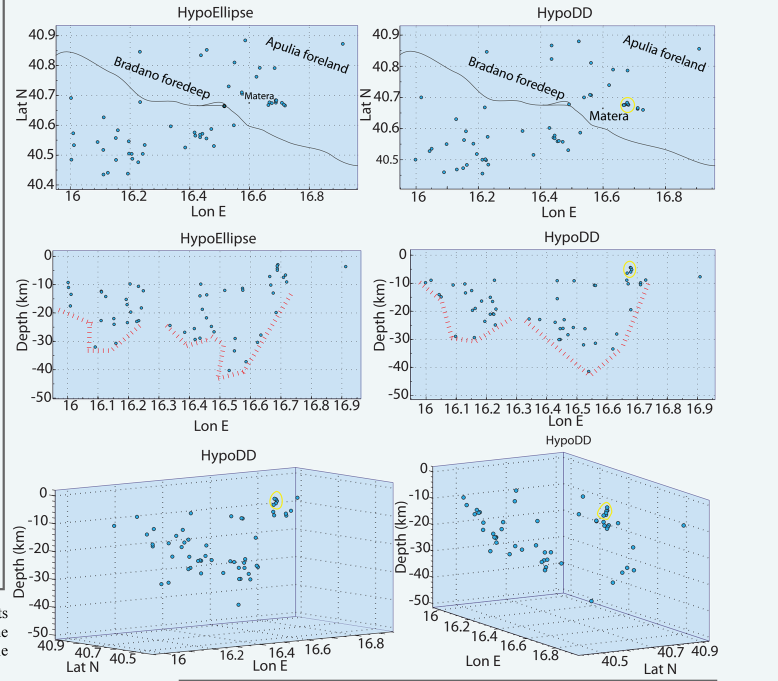

Fig.20 (right side): Map view of hypocentral distribution and W-E cross-sections of the 50 events located with HypoEllipse (a, c) and HypoDD code (b, d). 3D plots of the events relocated with the double-difference method (e, f). Red dotted line trace variation in seismogenic base. Yellow circle outlines the cluster of Matera.

Conclusions

The accurate earthquake relocations performed with the double-difference method in this study allow us to retrieve a very detailed picture of the microseismicity in the area of the Lucanian Apennine. Earthquakes are mostly located along the Apenninic chain and overlaps the area characterized by the great active normal faults of the Southern Apennines (Group1, Group2). The studied microseismicity beneath the chain could be explained with the post-seismic relaxation process related to the 1980 strong Irpinia earthquake (Group1), the 1990 and 1991 Potentino sequences (Group2) and the 1998 Castelluccio sequence (Group 5). The seismicity beneath the outer margin of the chain, in the Bradano Foredeep area (Group 6), is more scattered. The depth of the seismogenic layer is around 20 km beneath the Apenninic chain and between 30 and 40 km below the outer margin of the chain and the Apulia Foreland. This eastward deepening indicates a deeper boundary between the brittle and ductile crust beneath the external margin of the Lucanian Apennine and the foredeep, compared to that beneath the chain itself. This increasing seismogenic layer depth is associated with the westward flexural bending of the Adriatic continental lithosphere beneath the Apenninic chain. The available composite focal mechanisms computed in this study suggest that the whole Southern Apennines are characterized by a NE-trending extensional stress regime in agreement with previous studies. The more constrained locations of microseismicity examined in this study is a further contribution to the comprehension of the seismogenesis and state of stress of a tectonically complex region as the Southern Apennines characterized by a very high seismic hazard. Moreover, the scarce microseismicity observed in some sectors along the Apenninic chain could be related with active fault segments presently locked where possible large earthquakes might be expected in the future.

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