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Simona Pierdominici, Maria Teresa Mariucci, Paola Montone. A study to constrain the geometry of an active fault in southern Italy through borehole breakouts and downhole logs.. *Journal of Geodynamics*, 2011, 52 (3-4), pp.279. 10.1016/j.jog.2011.02.006 . hal-00780027

HAL Id: hal-00780027

<https://hal.science/hal-00780027>

Submitted on 23 Jan 2013

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Accepted Manuscript

Title: A study to constrain the geometry of an active fault in southern Italy through borehole breakouts and downhole logs.

Authors: Simona Pierdominici, Maria Teresa Mariucci, Paola Montone

PII: S0264-3707(11)00042-1
DOI: doi:10.1016/j.jog.2011.02.006
Reference: GEOD 1049

To appear in: *Journal of Geodynamics*

Received date: 27-9-2010
Revised date: 15-2-2011
Accepted date: 19-2-2011

Please cite this article as: Pierdominici, S., Mariucci, M.T., Montone, P., A study to constrain the geometry of an active fault in southern Italy through borehole breakouts and downhole logs., *Journal of Geodynamics* (2010), doi:10.1016/j.jog.2011.02.006

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A study to constrain the geometry of an active fault in southern Italy through borehole breakouts and downhole logs.

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Submitted to: Journal of Geodynamics

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Abstract

Identification of an active fault and the local versus regional present-day stress field in the Irpinia region (southern Apennines) have been performed along a 5900m deep well (San Gregorio Magno 1) by a detailed breakout and geophysical log analysis. The selected area is characterized by diffuse low magnitude seismicity, although in historical times moderate to large earthquakes have repeatedly struck it. On 23rd November 1980 a strong earthquake ($M=6.9$) nucleated on a 38km-long normal fault, named Irpinia fault, producing the first unequivocal historical surface faulting ever documented in Italy. The analysis of stress-induced wellbore breakouts shows a direction of minimum horizontal stress $N18^{\circ}\pm24^{\circ}$, fairly consistent with the regional stress trend ($N44^{\circ}\pm20^{\circ}$). The small discrepancy between our result and the regional stress orientation might be related to the influence of local stress sources such as variations of the Irpinia fault plane orientation and the presence of differently oriented active shear zones. This paper shows for the first time a detailed analysis on the present-day stress along a well to identify the Irpinia fault at depth and constrain its geometry.

Key words: Borehole breakout, geophysical log, present-day stress field, seismogenic fault, southern Apennines, Italy.

1. Introduction

This paper is mainly devoted to the present-day stress field study performed in a high seismic hazard area of southern Italy (Cinti et al., 2004; Faenza and Pierdominici, 2007) in order to assess a methodology to identify and constrain active faults at depth along deep wells.

The present-day stress state can be assessed by different techniques, including the analysis of: (i) borehole breakouts, (ii) focal mechanism solutions, (iii) exposed active fault segments, (iv) well cores, and (v) crustal deformation and differential strain (Ding and Zhang, 1991; Zoback, 1992; Seto et al., 1998). Breakouts are used as indicators of the direction of maximum and minimum

horizontal stress (S_{Hmax} and S_{Hmin} , respectively) and correspond to observation points along deep wells (Bell and Gough, 1979; Zoback et al., 1985). Many studies have shown that the present-day stress orientation in a region is quite homogeneous and independent of the stratigraphy and depth (e.g. Plumb and Cox, 1987; Castillo and Zoback, 1994), whereas along a borehole the breakout orientations can change due to the presence of active faults (Barton and Zoback, 1994; Wu et al., 2007). As reported by several authors stress perturbations have been associated to open fractures and to active faults which have slipped recently (Bell et al., 1992; Shamir and Zoback, 1992; Barton and Zoback, 1994; Mariucci et al., 2002; Wu et al., 2007). Moreover, shear zones at depth usually show physical properties different from the nearby undamaged rock and downhole logs can record these features.

In this paper we have analysed the present-day stress along and around a deep well and tried to identify at depth some shear zones and the seismogenic fault, named Irpinia, located in the southern Apennines. This fault is related to the 1980 $M_s=6.9$ Irpinia earthquake, and represents the first unequivocal surface faulting ever documented in Italy. Its geometry is not well constrained by geophysical exploration and aftershock data analysis because this tectonic structure is relatively a young fault that has not yet developed enough cumulated vertical slip to be clearly resolved by seismic reflection profiles (Pantosti and Valensise, 1993; Improta et al., 2003; Cippitelli, 2007; Patacca, 2007; Figure 1). This paper shows for the first time a detailed analysis on the present-day stress nearby the seismogenic fault in the context of the overall setting. The Irpinia fault trace is located ~ 1.3 km westward from the well San Gregorio Magno 1 (herein named SGM1), and according to its geometry, the well should cut off it. If this is true, the main observation of Barton and Zoback, (1994) that stresses reorient close to faults should be verified. The idea is to study the present-day stress in the SGM1 well to identify the possible stress perturbations close to the Irpinia fault. Then, borehole breakouts, downhole log data and tectonic structures along the deep well SGM1 have been analysed.

2. Geological-structural setting and regional seismicity

The southern Apennine belt is part of the Alpine orogens of the Mediterranean area, developing from the interaction between the converging Africa-Apulian and European plates since Late Cretaceous time, (e.g. D'Argenio et al., 1973; Dewey et al., 1989; Mazzoli and Helman, 1994 and references therein; Butler et al., 2004). The southern Apennines are a NE-verging fold-and-thrust belt that began to grow mainly since the lower Miocene (Bonardi et al., 1988; Patacca et al., 1990) due to deformation of the Adriatic subducting margin. The thrust belt is characterized by allochthonous units derived from both carbonate platform and pelagic basin successions (Apenninic Platform and Lagonegro Basin, respectively), which are stratigraphically overlain by Neogene foredeep and wedge-basin deposits (Miocene and Pliocene successions). These units are completely detached from their original substratum and transported onto the foreland sequence of the Apulian carbonate Platform (e.g. Doglioni et al., 1996; Mazzoli et al., 2004).

In the early Pliocene (Scandone et al., 2003), the entire pile of nappes overthrusts the Apulian carbonate platform giving rise to a complex duplex system (e.g., Mostardini and Merlini, 1996; Cello et al., 1987, 1989; Casero et al., 1988; Ascione et al., 2003; Patacca and Scandone, 2007). In this tectonic context, the thrust sheet emplacement moved following the opening of the Tyrrhenian back-arc basin (Patacca et al., 1990) as a consequence of the roll-back of the subducting Adriatic plate (Malinverno and Ryan, 1986; Doglioni, 1991). Only in the middle-late Pliocene, the Apulia Platform underwent shortening processes that created duplexing in the deep-seated carbonates and displacement of the overlying allochthonous sheets (Patacca and Scandone, 2007). The processes of thrusting and Adriatic-verging nappe transport have been active on the eastern side until the lower part of middle Pleistocene (Casero et al., 1988; Patacca et al., 1990; Roure et al., 1991; Cinque et al., 1993; Pieri et al., 1997; Patacca and Scandone, 2001), when the flexure-hinge retreat in the Adriatic plate suddenly stopped (Patacca and Scandone, 2007).

For further information on the geological and structural setting, the reader is referred to the wide existing literature (e.g., Casero et al., 1991; Patacca and Scandone, 1989; 2004; Lavecchia, 1988; Pescatore et al., 1999; Galadini et al., 2000; Giano et al., 2000; Lentini et al., 2002; Valensise and Pantosti, 2001; Schiattarella et al., 2003; Scrocca et al., 2007).

Concerning the seismicity, the southern Apennines are characterized by recent low magnitude seismic events, punctuated by large historical earthquakes that shook the area in the past (CPTI Working Group, 2004) (Figure 2). Strong historical events ($I_o=IX-X$) have been well documented since 1500: 1561-Vallo di Diano; 1694-Irpinia; 1826-Tito; 1831-Rivello; 1836-Lagonegro; 1851-Basilicata; 1857-Val d'Agri; 1930-Irpinia; 1980-Irpinia (Esposito et al., 1988; Marturano et al., 1988; Porfido et al., 1988; CPTI Working Group, 2004).

The instrumental seismicity, recorded by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) since 1981 is characterized by magnitudes generally lower than 4.0 (Castello et al., 2008). Only a few isolated seismic sequences hit the southern Apennines in the last years (Figure 2, Table 1). In 1990-1991 the Potenza area was shaken by a seismic sequence ($M_w=5.7$ and $M_w=5.2$) which occurred from about 2 to 25km depth with the mainshocks showing E-W dextral strike-slip mechanism (Azzara et al., 1993; Ekström, 1994; CPTI Working Group, 2004; Di Luccio et al., 2005); in 1996 the Irpinia area was hit by a seismic sequence characterized by normal faulting mechanisms with a mainshock ($M_w=5.1$) at 8km depth (Cocco et al., 1999; Cucci et al., 2004); in 1998 normal faulting earthquakes occurred in the north Pollino area with $M_w=5.6$ (Michetti et al., 2000; Pondrelli et al., 2002) and in 2002 the Melandro-Pergola basin was affected by $M_w=4.1$ earthquake at a depth of 9km (Cucci et al., 2004; Frepoli et al., 2005). The seismicity is mainly placed along the axial part of the belt, within the shallow crust, showing NE-SW T-axes with prevailing normal faulting focal mechanisms (Gasparini et al., 1985; Frepoli and Amato, 2000; Pondrelli et al., 2006; Maggi et al., 2009 among many others). As mentioned above, this trend is also coherent with the active stress field (Figure 2) inferred from geological and borehole breakout data (e.g., Amato et al., 1995; Montone et al., 2004).

2.1 The 1980 M6.9 Irpinia earthquake

In the last century, the most important and largest seismic event in the southern Apennines was the Irpinia earthquake that occurred on November 23, 1980 with $M_s=6.9$ (Boschi et al., 1993). It was one of the most disastrous events in Italy, causing the death of about 3000 people and the total destruction of 15 towns within a radius of nearly 50km. This earthquake nucleated at a depth of 10-12km (Westaway and Jackson, 1987) with a focal mechanism characterized by NW-SE normal faulting planes and by a moment tensor of 2.4×10^{19} Nm (Giardini, 1993) (Figure 3a). The aftershock distribution indicated that the area of the earthquake source was about $14 \times 40 \text{ km}^2$ providing also information on source geometry (Deschamps and King, 1980; Amato and Selvaggi, 1993) and on the relationship between crustal structure and faulting mechanism (Chiarabba and Amato, 1994; Improta et al., 2003). However, the 3D locations from local earthquake tomography did not allow constraining the fault geometry at depth accurately (Deschamps and King, 1984).

The Irpinia earthquake consists of three subevents, at 0s (the mainshock), at ~20s and ~40s from the mainshock (Bernard and Zollo, 1989). Associated to the 0s and 20s events, a 38km long rupture at the surface was partially recognized by Westaway and Jackson (1984) and then totally defined by Pantosti and Valensise (1990). Its mean strike is $N308^\circ$, with a 60° - 70° dip to the northeast with an average value of normal slip of 61cm along the fault (Pantosti et al., 1993) and a total vertical throw of about 50m in the last 150krs (Ascione et al., 2003; Improta et al., 2003). Pantosti and Valensise (1990, 1993) divided the 1980-surface rupture into 3 main segments on the basis of geological and geomorphological observations of the scarp, which is clearly linked to the coseismic deformation at depth. These 3 scarp strands are, from northwest to southeast: the Cervialto, the Marzano-Carpineta and the San Gregorio Magno (Figure 3a), separated by two surface faulting gaps (the Sele and the San Gregorio Magno gap). The first shock (at 0 sec) is associated both to the Marzano-Carpineta segment and to the Cervialto scarp (approximately 8-10 km long). The second event happened after 20s along a 8km San Gregorio Magno segment. Considering only seismological data, the last event

(40s) is supposed to be located on an antithetic, SW-dipping branch fault (Ofanto fault segment) (Improta et al., 2003) in front of the Cervialto and Marzano-Carpineta structures (Figure 3a); no evidence of surface rupture exists for this event.

3. San Gregorio Magno 1 well

3.1 Stratigraphy and structural outline

The SGM1 well is located at 797m elevation near the Marzano-Carpineta fault scarp (Figure 3b). It was drilled by British Gas RIMI in 1996-1997 down to a depth of 5900m with the goal of reaching a structural high in the Apulia carbonate Platform, which is generally a target of the oil industry in the southern Apennines, imaged by commercial and deep reflection profiles (Patacca and Scandone, 2007)) and gravity data modelling (Improta et al., 2003). The SGM1 well (Patacca, 2007) crossed three main tectonic units bounded by two thrust faults at 2280 m and 3377 m and different lithological units (Figure 4a).

According to Patacca (2007), the well penetrates 2280m of the Mesozoic carbonates of the Alburno-Cervati Unit (part of the Apenninic carbonate Platform succession), ~1100m of the Lagonegro Unit II (part of Lagonegro basinal succession) and ~2600m of the Apulian carbonate Platform. The first Unit is composed of: i) “lime breccias” (early Cretaceous-Jurassic), typical of slope environments and characterized by calcirudites and calcarenites, and ii) Dolomia Principale Formation (late Triassic), deposited in a tidal flat environment and characterized by dolomites and dolomitic limestones. The underlying Lagonegro Unit II, deposited in a deep-marine basin, consists of: i) the Galestri Formation (early Cretaceous), that is mainly formed of claystones and shales and subordinate calcilutites and calcarenites; ii) the Scisti Silicei Formation (Jurassic to Rhaetian), containing calcarenites and radiolarites and subordinate siliceous shales (2735-3070m), and in the lower part claystones and shales with subordinate calcarenites and calcilutites (3070-3200m); finally iii) the M. Facito Formation (early-middle Triassic), formed by shales, sandstones, siltstones and siliciclastic calcarenites, subordinate radiolarites and limestones. The deepest tectonic unit, the

Apulia, includes: “wildflysch” (middle Miocene to early Pliocene), siciliiclastic flysch deposits derived from the Apennines nappes deposited in foredeep basin; Gessoso Solifera Formation (Messinian) characterized by anhydrites and evaporitic limestones, typical of evaporitic carbonate ramp; “lime breccias” (upper Cretaceous) typical of slope environment consisting of calcarenites, calcilutites and calcirudites; “shallow-water carbonates” (Dogger-upper Cretaceous) deposited in a shelf environment. Besides the two thrusts, following the reconstruction of Patacca (2007), the well also encountered a system of SW-dipping normal faults at 440m and 3198m (Figure 4a). As the surface rupture of the Irpinia fault is located ~1.3km westward from the well, according to its geometry (N308° striking, 60°-70° northeast dipping), the borehole should intersect the fault within the depth range ~2300-3800m (Figure 4a). As a matter of fact, the fault has not been unequivocally recognized from the available data, either on stratigraphic logs or on seismic profiles. As mentioned in the introduction, one possible explanation is that the relatively young fault has not yet developed enough cumulated vertical slip to be clearly resolved by seismic reflection profiles (Pantosti and Valensise, 1993; Improta et al., 2003; Cippitelli, 2007; Patacca, 2007). For this reason we have jointly used different methods, including borehole breakouts and downhole logs, to identify the possible active shear zones and the Irpinia fault.

3.2 Borehole breakout data

Method

Borehole breakout analysis is an important tool for the evaluation of stress patterns in the uppermost crust (Bell and Gough, 1979; Zoback and Zoback, 1980, 1991; Zoback et al., 1985, 1989; Plumb and Cox, 1987). Breakouts fill the gap between data from earthquake focal mechanisms and surface measurements (e.g. active faults, extensional fractures and strain release measurements): they are the result of localized conjugate compressive shear failures that develop along deep wells in an anisotropic stress field with a triangular shape in cross-section. The shear planes are tangential to the circumference of the borehole and identify breakout zones parallel to the

direction of the S_{hmin} . The first breakout develops in the borehole very soon after the passage of the drill bit and continues to propagate along the axis of the borehole and into the formation (Bell and Gough, 1983). Mechanisms that explain the formation of these features have been extensively examined in the literature (Babcock, 1978; Bell and Gough, 1979; Zoback et al., 1985; Haimson and Heirrick, 1986; Zheng et al., 1989; Amadei and Stephansson, 1997).

Borehole breakouts are identified from four-arm caliper readings collected routinely with conventional dipmeter logging tools. Different borehole geometries are defined as: i) “in-gauge”, if the hole has the dimensions of the drill bit called bit size; ii) “breakout zone”, when one diameter is elongated and the orthogonal one has the bit size dimension; iii) “key seat”, when the drill-string wear causes a pear-shaped borehole with an artificial elongation at the low side of the well. It occurs when the borehole is highly deviated from vertical; iv) “washout”, an enlargement of the borehole in an “over-gauge hole” (Plumb and Hickmann, 1985). To obtain the average direction and standard deviation of the least horizontal stress in the well, the statistical method from Mardia (1972) has been applied in this study. Results are shown as rose diagrams scaled by length, and a quality factor is assigned to each well (from A=highest quality to E=lowest quality) according to the criteria used for the World Stress Map (Heidbach et al., 2008), first suggested by Zoback (1992).

Analysis

The breakout analysis of SGM1 well has been performed by four-arm caliper log data from 1200m to 5900m depth with two gaps (2645-2945m and 4775-4950m). The results of the investigation showed: a) key seats between 1200 and 2000 m; b) no breakout between 5585 and 5900 and c) breakouts between 2000 and 5585m.

The result of the entire well shows a cumulative breakout length of 675m with an average S_{hmin} orientation of $N18^\circ$ and a standard deviation of 24° (Figure 4h), with a data quality C (according to World Stress Map criteria; Heidbach et al., 2008).

A more detailed breakout analysis, considering all the data quality, has been performed for each lithological and tectonic unit to understand the scattering of breakout data (Figure 4d, f, g and Table 2). We have identified a breakout zone from 2000 to 2075m in the Dolomia Principale (belonging to the Alburno-Cervati tectonic unit) N348° oriented for a 75m total length. The Lagonegro II tectonic unit is characterized by a S_{hmin} orientation N38°±33° and a length of 365m with five breakout zones related to: the Galestri Fm. with S_{hmin} N310° oriented and a total length of 125m; the Scisti Silicei Fm. N41° and a total length of 165m, and the M. Facito Unit with S_{hmin} N33° trending and 75m long. The Apulia tectonic unit is characterized by a S_{hmin} orientation N7°±28° for a total length of 607m: in the Wildflysch S_{hmin} is N325° oriented (total length of 245m) and in the Shallow-water carbonate unit is N15° (total length of 362m) (Table 2). No breakouts have been found in the Gessoso Solifera and Lime Breccias units.

As the regional stress field is well constrained in the area (S_{hmin} N44°±20°) (Montone et al., 1997; Montone et al., 2004), we believe it is possible to distinguish, along the well, anomalous stress directions departing from the regional trend and associate them with shear zones intersected by the drilling (Shamir and Zoback, 1992; Barton and Zoback, 1994; Wu et al., 2007). Barton and Zoback (1994) point out that the stress field rotates in proximity to an active fault due to small slip increments on the fault, possibly induced by the tectonic movement or due to an increase of pore pressure on the fault when drilling through it. With the purpose of identifying the Irpinia fault, the stress field detected from SGM1 has been compared to the regional stress orientation. Any deviation from the regional value has been considered as a local rotation of the stress field - if the breakout orientation deviates from the regional one more than 15° - and is shown as clockwise or anticlockwise rotation (Figure 4e). Along the SGM1 well, anomalously oriented breakouts occur in five intervals: 2000m-2650m, 3450m-3855m, 4350-4560m, around 4800m and around 5500m (Figure 4d-e).

As observed in other deep wells, when the breakout trend abruptly changes it is possible to identify faults and/or fracture zones otherwise difficult to recognize by seismic reflection data and drill

cutting analysis (Bell et al., 1992). We have distinguished four zones that separate different breakout orientations (Figure 4): from 2650m to 2950m (zone 1), 3275m to 3450m (zone 2), 3855m to 4320m (zone 3), and 5057m to 5460m (zone 4).

Considering the uncertainty of the fault geometry, three of the anomalous zones (zone 1, 2 and 3) are located around the area where the well is supposed to crosscut the Irpinia fault: in fact according to most authors (e.g., Boschi et al., 1981), the Irpinia fault has a dip between 60° to 70° corresponding to a depth of intersection with SGM1 approximately between 2300m to 3800m (Figure 4).

4. Breakout versus downhole geophysical data

The stress field along the SGM1 well has been studied using two approaches. First, we have analysed the borehole breakout data to obtain information on the present-day stress field. Second, we have used these data and the downhole logs to identify possible shear zones and the Irpinia fault itself. Shear zones at depth usually show physical properties different from the nearby undamaged rock and these features can be recorded by downhole logs. As by now observed in other drilled active faults (Wu et al., 2007; Wu et al., 2008) the shear zones correspond to the most significant changes in sonic and resistivity curves with respect to their average trend at depth.

Assuming the SGM1 well crossed the Irpinia fault we have analyzed three downhole curves (gamma ray, resistivity and sonic; Figure 5) in order to detect their anomalous physical properties with respect to overall value characterizing each lithology. For our analysis we have used an extremely detailed stratigraphic log (courtesy of Etta Patacca and Paolo Scandone) that allowed us to recognize and discard the anomalies related to the small-scale lithological variations and to the identified faults. In fact, according to this interpretation those faults are westward dipping, whereas the Irpinia fault dips toward east.

The remaining sectors showing significant changes in downhole logs are located at the following depths (Figure 5): around 2350m (sector A), around 3100m (sector B) with two small

areas, around 3800m (sector C), around 4300m (sector D) and around 4700m (sector E). Considering the Irpinia fault geometry (60° - 70° dipping) we can exclude the two deepest sectors (D and E). Particularly, in the sector A the sonic curve shows a decrease with respect its mean value (Figure 5) while the other curves do not seem to show any anomaly; in sector B we have identified two small zones showing anomalous peaks in all the curves (a decrease in gamma ray and sonic logs and an increase in resistivity, Figure 5). Finally, in sector C we have identified a well defined peak showing an increase in the sonic curve and a decrease in the resistivity curve trend (Figure 5). All these sectors correspond to washout zones (Figure 5b) that also support the presence of shear zones. In fact, when a borehole crosses a highly fractured area, the stress concentration enhances the effect of natural fractures that are mechanically weaker, and can easily produce collapse of the wellbore wall, detected as enlargements of the borehole size. Only sectors A and C are located within the previously identified five anomalous breakout intervals, whereas sector B is located where breakouts are consistent with the regional S_{hmin} orientation. As mentioned before, abrupt breakout rotations indicate the presence of active shear zones. For this reason we suggest that the Irpinia fault is located around 2350m (sector A) or around 3800m (sector C). In both zones we have more confident data revealing not only abrupt breakout rotations ($\sim$ NW-SE oriented) but also washout presence, geophysical log anomalies not directly connected to the lithology, and consistency with the fault dip deduced from focal mechanisms and surface data.

5. Discussion and conclusion

The stress analysis has allowed us to constrain the S_{hmin} orientation along the well ($N18^{\circ}\pm24^{\circ}$), suggesting that it is moderately consistent with the neighbouring regions (Figure 6). The slight difference between the regional stress field ($S_{hmin}=N44^{\circ}\pm20^{\circ}$) and the achieved SGM1 S_{hmin} is due to the presence of $\sim$ N-S S_{hmin} orientations in the deepest part of the well, mainly within the Apulia tectonic unit (Figure 4g and Figure 6). In Figure 6 breakouts are shown as rose diagrams instead of average S_{hmin} orientations; in fact we believe that the average S_{hmin} orientations are more appropriate

for regional tectonic reconstructions, whereas for local tectonic interpretations it is preferable to consider rose diagrams, where it is easier to resolve the contribution of possible different orientations within the same well.

Two main directions are observable not only in SGM1 but also in other breakout solutions (even of higher quality, A or B) along the belt and the foredeep. A ~N-S orientation has been recognized also in another deep well located in the northern part of the Irpinia area (Figure 6) and could be linked to the presence of ~E-W tectonic structures or to the changing trend of the NW-oriented faults. Actually, it is a common feature of a fault plane showing variable orientations that can correspond to slight deviations in the local principal stress orientations. The inferred S_{hmin} orientation is not exactly at 90° with respect to the $N308^\circ$ Irpinia fault mean direction, but it is fairly consistent with the “zig-zagging” trend of the fault (Pantosti and Valensise, 1993) and with the local tectonic structures displaying ~E-W directions (Caiazzo et al., 1992; Ascione et al., 2003). In detail, in this area there is interference between the $N150^\circ$ and $N110^\circ$ - 100° trends relative to the Marzano-Carpineta structure and Mt. Ognà fault respectively, both reactivated during the late Quaternary (Ascione et al., 2003).

Concerning seismological data, in correspondence of the Irpinia area a lot of earthquake focal mechanisms (Cocco et al., 1999; Cucci et al., 2004; Frepoli et al., 2005; Maggi et al., 2009) exhibit both normal faulting and strike slip mechanisms (Figure 6). Particularly, the fault plane solutions closer to the well clearly show ~N-S oriented T-axis, on ~E-W nodal planes (Figure 6 and Table 1, solutions from 20 to 23), which fit the deepest results of the breakout analysis.

Then, we hypothesize that the localized stress rotations along the SGM1 well probably result from slip on nearby faults indicating active deformation in the crust. Also the geophysical logs show significant anomalies in the physical properties in correspondence of two hypothesized major active shear zones: at 2350m (sector A) and around 3800m (sector C), depths where we suppose the Irpinia fault is located.

Then, we propose some possible hypotheses in terms of general geometry of the Irpinia fault, especially concerning its dip, segmentation or continuity (Figure 7). Starting from the information that the fault dips 60° at 10-12km depth, as inferred from the focal mechanism solution of the 1980 Irpinia earthquake, and taking into account the lower and upper bounds of the surface fault dip (60° and 70°) we obtain four different options. If the well crosses the fault in the sector A (i.e. the fault dip is around 60°) we can suppose: 1) a straight fault plane 60° dipping from surface to focal depth (red line in Figure 7); or 2) a fault plane changing dip from 70° at surface to 60° immediately below (blue line in Figure 7). Whereas, if sector C is the true hole-fault intersection (i.e. fault dip around 70°) we can have: 3) an irregular fault plane trend (like a “vertical segmentation”) with two dip changes, from 60° to 70° at few kilometres from the surface and from 70° to 60° around 10 km; or 4) a 70° dipping fault changing to 60° down to focal depth (yellow line in Figure 7). The first two hypotheses (numbers 1 and 2) differ only for the dip at surface and then can be considered as one hypothesis. Among these different hypotheses we believe that the number 3 is the less reliable considering its geometry and also it is very similar to the hypothesis number 4 at depth. Then we concentrate on the last hypothesis that agrees with the fault geometry proposed by Amato and Selvaggi (1993) based on the seismicity distribution and earthquake focal mechanisms. Occurrence of the fault in sector C is also consistent with the idea of stress decoupling due to the Irpinia fault, as supported by breakout orientations along the well that show a prevailing ~NNE-SSW direction (immediately below sector C) and ~NS in the deepest part of the well (4300-5600m; Figure 4, rose plot of column f). We believe that this sector has a slightly higher degree of probability, with respect to sector A, to be the real location of Irpinia fault along SGM1 well and then, the yellow line the most probable geometry of the fault (Figure 7).

The identification of fault geometry is an important factor for the characterization of the seismic behaviour and therefore the seismic hazard assessment of an area. The seismic behaviour of a fault can be considered both in space and in time. In the first case, the location and the geometry of the active faults influence the interactions with the surrounding faults that may accumulate stress or

initiate. This observation is consistent with substantial release of accumulated strain energy during earthquakes and a redistribution of stress in adjacent areas (e.g., Marzocchi et al., 2009). In the second case, the seismic behaviour of a fault is studied by examining the historical seismicity and the paleoseismological records to estimate recurrence intervals along different fault segments. In this paper, the most significant result is that using downhole log and borehole breakout data is possible to constrain the most likely location of an active fault at depth.

Acknowledgement

This work was partially funded by the Italian Ministry of University and Research in the framework of Project FIRB “Research and Development of New Technologies for Protection and Defense of Territory from Natural Risks”, W.P. C3 “Crustal Imaging in Italy”, coordinated by P. Montone. Many thanks are due to the reviewers for their precious suggestions which greatly improved the paper.

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Figure Captions

Figure 1. Above: schematic structural map (modified after Scrocca et al., 2007): 1. Main out of sequence thrust; 2. Buried Apenninic thrust front; 3. CROP-04 seismic line; 4. Wells. Below: part of CROP-04 cross-section (section A-A'; modified after Cippitelli, 2007 according to the stratigraphic description of Patacca, 2007 from c. to e. deposits). Legend: a. Castelgrande Sandstone (Miocene); b. Cilento Flysch and Liguride-Sicilide complex (Cretaceous-Paleogene); c. Apenninic carbonate Platform (Alburno-Cervati; late Triassic); d. Lagonegro II unit (early Triassic-early Cretaceous) e. Apulian carbonate Platform (Dogger-early Pliocene); f. Permo-Triassic substratum; g. Normal fault; h. Reverse fault-overthrust plane; i. Unconformity.

Figure 2. Regional overview of present-day stress data and seismicity. The black arrows indicate the S_{hmin} average orientation obtained by all the stress indicators. Historical seismicity from 217 B.C. to 1980 ($M \geq 5.5$; CPTI Working Group, 2004); instrumental seismicity from 1981 to present (INGV-CNT Seismic Bulletin <http://csi.rm.ingv.it>); fault plane solutions of the largest earthquakes (see Table 1 for references).

Figure 3. a) Map of the Irpinia Fault System and its segments breaking at 0s, 20s and 40s with the associated focal mechanism solutions. The stars represent the earthquake epicenters (modified from Pantosti and Valensise, 1990); b) zoom of the Marzano-Carpineta fault segment with the location of the San Gregorio Magno 1 well.

Figure 4. Breakout data along the San Gregorio Magno 1 well: a) synthetic stratigraphic log of the main lithological and tectonic units (Patacca, 2007); b) available data interval; c) breakout zones: the size of the black rectangle represents the length of the breakout data with the same direction; d) individual breakout azimuths; e) clockwise and anticlockwise breakout rotations with respect to the regional trend; f) and g) rose diagrams of breakout results for lithological and tectonic unit; h) total rose diagram. The light grey box represents the interval in which the borehole should intersect the Irpinia fault hypothesizing different fault dips (from 60° to 75°). Legend of a): 1. stratigraphic discontinuity; 2. normal fault; 3. thrust fault.

Figure 5. Geological and geophysical data of the San Gregorio Magno 1 well. a) Synthetic stratigraphic log of the main lithological and tectonic units (Patacca, 2007); b) washout zones; c) downhole logs; d) breakout azimuths; e) five boxes showing the magnification of the five selected sectors (in red the anomalous trend). The light grey boxes indicate possible shear zones (A, B, C, D and E sectors). See text for the explanation of zone 1, 2, 3 and 4.

Figure 6. Present-day stress data in southern Apennines. Breakouts are relative to SGM1 and wells from Montone et al., 2004. Focal mechanisms of main earthquakes and seismic sequences are shown (the numbers refer to Table 1, see References therein). Colours correspond to different types of focal solutions: brown, normal faulting with NE-SW extension; yellow, strike-slip faulting; orange, normal faulting with strike slip component and NE-SW to E-W extension; pink, normal faulting with strike slip component and N-S to NNE-SSW extension; violet, normal faulting with strike slip component and NW-SE extension.

Figure 7. - The cross-section (modified from Cippitelli, 2007) shows the three hypotheses of the Irpinia fault trend. If the SGM1 well crosses the Irpinia fault at 2350m: i) a straight fault plane 60° dipping from surface to focal depth (red fault); ii) a fault plane changing dip from 70° at surface to 60° in the upper kilometer (blue fault). If the SGM1 well crosses the Irpinia fault at 3800m: iii) a 70° dipping fault changing to 60° down to focal depth (yellow fault). The red star represents the mainshock at 0s and the grey area around it indicates the associated error in vertical and horizontal location of about 3km and 1km respectively (Bernard and Zollo, 1989). Legend: a. Castelgrande Sandstone (Miocene); b. Cilento Flysch and Liguride-Sicilide complex (Cretaceous-Paleogene); c. Apenninic carbonate Platform (Alburno-Cervati; late Triassic); d. Lagonegro II unit; (early Triassic-early Cretaceous) e. Apulian carbonate Platform (Dogger-early Pliocene); f. Permo-Triassic substratum; g. Normal fault; h. Reverse fault-overthrust plane; i. Unconformity.

Research highlights

- Horizontal stress orientations in the well are consistent with the regional trend.
- Anomalous stress orientations reveal local stress sources
- faults cause log anomalies in a well
- fault-well intersection at depth can be defined
- downhole logs help in defining fault geometry at depth

Figure 1

Figure 2

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Table 1

Earthquake focal mechanism data (the events are ordered according to figure 6).

Event Number	Event Date (yyyy/mm/dd)	Origin Time	Lat, deg	Lon, deg	Depth (km)	Magnitude	Strike	Dip	Rake	References
1	19801123	18:34	40.724	15.373	10-12	6.9	135	60	-80	a
2	20020102	02:17	40.779	15.417	15.4	2.8	140	75	-80	b
3	20060314	03:15	40.818	15.326	10.5	2.7	155	50	-60	b
4	20060915	17:55	40.766	15.384	16.2	2.4	70	85	-170	b
5	20040224	05:21	40.715	15.407	16.5	3.8	135	25	-90	b
6	20020504	09:41	40.611	15.537	15.8	2.3	160	45	-50	b
7	20061201	15:38	40.775	15.460	15.0	2.7	130	40	-120	b
8	20060717	16:56	40.774	15.490	8.4	2.5	125	40	-90	b
9	20060926	16:29	40.722	15.455	7.8	3.0	80	75	-110	b
10	19900505	07:21	40.775	15.766	15.0	5.7	184	73	13	c
11	19910526	12:26	40.730	15.765	11.0	5.2	183	71	-9	c
12	20020505	06:40	40.373	15.373	21.6	1.9	155	50	-150	b
13	19980909	11:28	40.150	15.947	9.0	5.6	139	29	-83	d
14	20020419	18:06	40.595	15.568	6.0	4.1	170	50	-50	b
15	20020418	21:00	40.588	15.569	10.3	3.0	200	75	-10	b
16	20020418	21:36	40.583	15.573	9.6	2.2	200	80	-10	b
17	20020418	22:58	40.583	15.571	9.5	2.7	100	80	150	b
18	20020526	10:19	40.549	15.534	11.4	2.6	140	45	-70	b
19	19960304	13:04	40.670	15.420	10.0	4.9	111	15	-126	f
20	19960304	13:04	40.670	15.420	8.0	5.1	297	74	-70	e
21	19960717	09:45	40.670	15.400	10.5	3.5	35	55	-140	f
22	19960822	06:47	40.670	15.390	10.0	3.0	115	45	-40	f
23	19960716	12:46	40.670	15.380	12.2	3.4	45	45	-130	f
24	20011209	12:15	40.795	15.287	16.6	3.3	130	20	-80	b

References: a) Boschi et al., 1981; b) Maggi et al., 2009; c) Ekström, 1994; d) Pondrelli et al., 2002; e) Cocco et al., 1999; f) Cucci et al., 2004.

Table 2

Summary of breakout data results of the SGM1 well for each lithological and tectonic unit

Tectonic Unit	Lithological Unit	Depth Units		Breakout Interval		Shmin (°)	standard deviation (°)	Breakout length (m)	Breakout zone number
		Top	Bottom	Top	Bottom				
Alburno-Cervati		40	2280	2000	2075	348	0	75	1
	Dolomia Principale	440	2280	2000	2075	348	0	75	1
Lagonegro II		2280	3377	2325	3275	038	33	365	5
	Galestri	2280	2735	2325	2650	310	14	125	2
	Scisti Silicei	2735	3198	2960	3198	041	7	165	2
	Monte Facito	3198	3377	3200	3275	033	0	75	1
Apulia		3377	5901	3450	5580	007	28	607	14
	Wildflysch	3377	3977	3450	3990	325	15	245	4
	Shallow-Water Carbonates	4085	5901	4090	5580	015	21	362	10