Active stress field in central Italy: a revision of deep well data in the Umbria region

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Abstract
In this area the active stress field from borehole breakout analysis shows a prevalent NE-SW extension, perpendicular to the main tectonic structures, in agreement with stress inferred from earthquake focal mechanisms and with the strain velocity field. A detailed analysis of active stress data allows us to infer the influence of active structures on the local stress field orientations. San Donato 1 well shows a minimum horizontal stress orientation of N55±22°, in agreement with both the regional and local trends, the latter influenced by its vicinity to the Alto Tiberina Fault. Monte Civitello 1 well, in contrast, shows a quite different orientation, N12±29°, due to its more eastward location and to the structures that it crosses. Although the angular difference between the two directions is within the error, to estimate the regional active stress field many borehole data should be analysed or smoothing maps should be evaluated; in fact, each borehole dataset could be influenced by local stress conditions that in some cases can be different from the regional trend. The two breakout orientations perfectly depict the regional extension along the axis of the Apennines and also the rotation of minimum horizontal stress moving eastward to the area where compression is predominant.

Key words *active stress field - borehole breakout - Colfiorito - northern Apennines*

1. Introduction

This paper describes the regional present-day stress field and its local variations in the Umbria region. We discuss data already published relative to borehole breakout analysis performed in two deep wells (Monte Civitello 1 and San Donato 1) and show a new interpretation that also considers earthquake focal mechanisms and geological structures (fig. 1). Although these deep wells are not exactly placed inside the epicentral area of the September-October 1997 Colfiorito sequence, we believe that the available data can be realistically used to improve and define the active stress field in the region. The Monte Civitello 1 (MC1) and San Donato 1 (SD1) wells were previous analyzed within a more extensive work relative to the stress map of central Italy (Mariucci *et al.*, 1999) and afterwards the results were inserted in the Active Stress Map of Italy (Montone *et al.*, 2004). Now we have re-analyzed the wells in more detail using newly available data from downhole logs. The stress orientations inferred from these two wells have been also compared with the stratigraphic record and with the main fault structures intersected by the boreholes.

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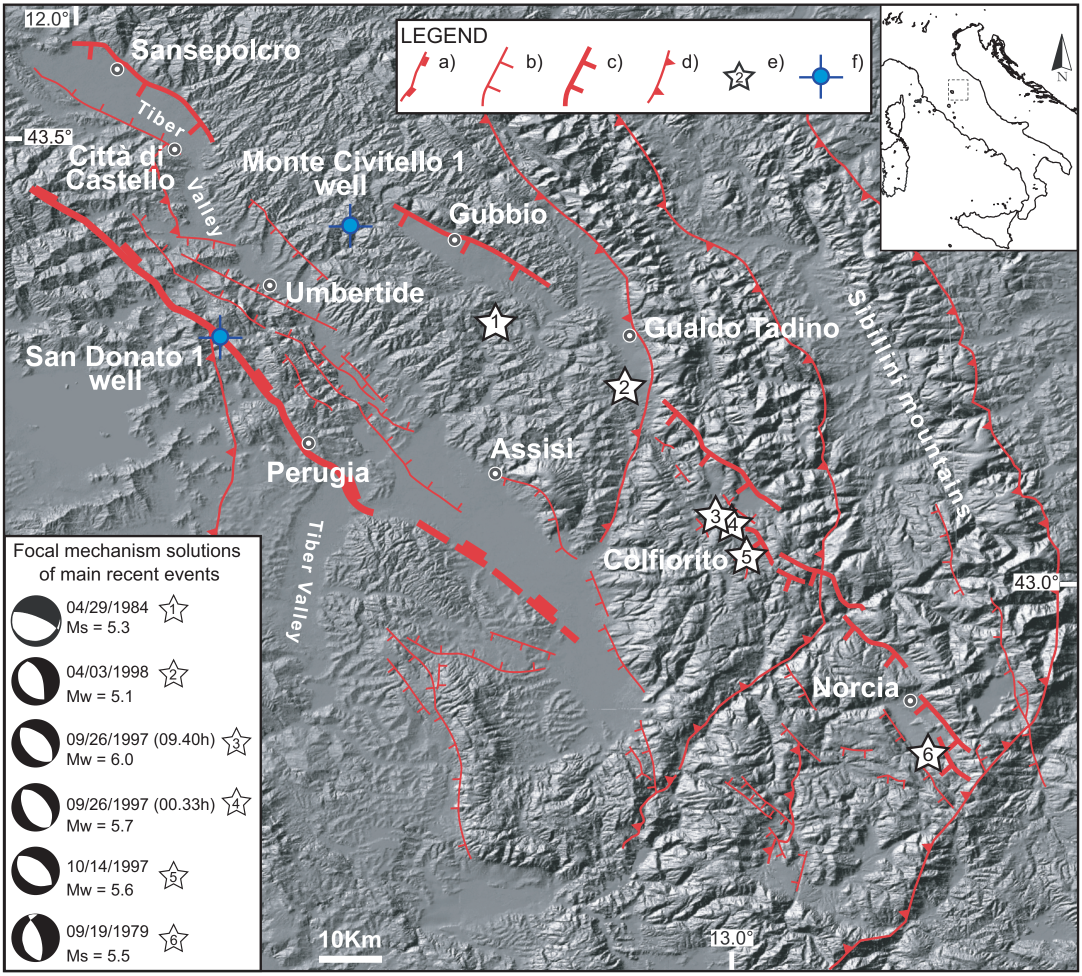

Fig. 1. Schematic structural map of the Umbria-Marche area (modified after Mirabella *et al.*, 2004). Legend: a) Alto Tiberina fault; b) normal fault; c) Umbria fault system; d) thrust; e) earthquake M>5.0; f) wells analysed in this study. Focal mechanism solutions and magnitude: 1) 1984 Gubbio earthquake (Haessler *et al.*, 1988); 2) 1998 Gualdo Tadino earthquake, and 3, 4, 5) 1997 Colfiorito sequence (Ekstrom *et al.*, 1998); 6) 1979 Norcia earthquake (Deschamps *et al.*, 1984).

Our methodology includes the identification of borehole breakouts in the downhole logs. Breakouts are enlargements that form on opposite sides of a borehole wall, and if the borehole axis is aligned with a principal stress axis then the breakouts are aligned along the direction of the minimum horizontal stress. It is generally accepted that breakouts derive from conjugate shear fractures which develop when a well is drilled in an anisotropic stress field (Bell and Gough, 1983; Zoback, 1992). Therefore, investigating breakouts and computing their average azimuth distribution allow us to get the orientation of the horizontal stress field around a well

(Bell and Gough, 1983; Plumb and Hickmann, 1985; Zoback *et al.*, 1985). We used four-arm caliper data to identify the borehole breakouts in our wells, and we assigned to each well a quality value, which is based on a combination of the breakout zone length, the standard deviation from the mean azimuth, the number of breakouts along the borehole, and the depth and lithology in which breakouts are detected.

Knowledge of the active stress field allows us to determine the behaviour of seismogenic structures and to define the seismotectonic zoning of a region. When the stress field in a region is well-known and faults are identified, it is possible to determine which of these faults are favourably oriented with respect to the stress field and which are more likely to slip in future earthquakes.

2. Seismotectonic context

This section provides an overview of information about the tectonic structure and the active stress field of the study area. We refer readers to the existing wide literature on this area and on the 1997 Colfiorito seismic sequence, as well as to the other papers in this volume and to a special issue of Journal of Seismology on Colfiorito earthquake (Amato and Cocco, 2000).

From seismological data the extension along the Apennines is very clear and oriented approximately perpendicular to the belt (Anderson and Jackson, 1987; Westaway, 1992; Pondrelli *et al.*, 1995; Selvaggi 1998; Gasperini *et al.*, 1999; Viti *et al.*, 2001), in agreement with the NW-SE active normal faults (*e.g.* Valensise and Pantosti, 2001 and references therein). This agrees with the analysis of the strain field where extension was measured on both a local scale by repeated GPS campaigns (D'Agostino *et al.*, 2001; Serpelloni *et al.*, 2001) and a larger spatial and temporal scale (Hunstad *et al.*, 2003). More recently, new data on the GPS velocity field for Italy and surrounding regions (Serpelloni *et al.*, 2005) indicate an ENE-WSW extension in this sector, concentrated in a relatively narrow belt about 80 km wide. In contrast, the Adriatic foredeep and the southern Tuscany-Latium volcanic area display low deformation rates. These results are also confirmed by borehole breakout analysis (Mariucci *et al.*, 1999; Montone *et al.*, 2004) where a predominant extensional active stress field with a NE-SW minimum horizontal stress (Shmin) direction characterizes the Apennine belt and the Tyrrhenian coastal region. At the same latitude, along the outer front of the belt and the Adriatic offshore, Shmin is oriented NW-SE related to a compressive and, secondarily, strike-slip stress field (Mariucci *et al.*, 1999; Montone *et al.*, 2004, Pondrelli and Morelli, 2008 this volume).

From a tectonic point of view, this region in geologically recent times was characterized by an inversion of the tectonic stress field: the compression acting during the Late Miocene was replaced by extension starting in the Late Pliocene-Quaternary (*e.g.*, Elter *et al.*, 1975; Lavecchia *et al.*, 1994). From a comparison of the recent tectonic evolution inferred from structural geology with the breakout results (Mariucci *et al.*, 1999), it was argued that the coeval extension-compression pair, characteristic of the post-Tortonian evolution of the Apennines, has been migrating from late Miocene in this sector of the mountain belt. Moreover, the striking correspondence between the active compression front and the region with evidence of a remnant subducted slab (Selvaggi and Amato, 1992; Lucente *et al.*, 1999) suggested that the migrating extension-compression pair is controlled by the progressive retreat of the slab (Mariucci *et al.*, 1999).

The kinematics of the Quaternary and active faults is mainly related to normal faulting that affected the area since the early Pleistocene and was controlled by a constant NE-trending extensional stress field. This feature is also well evidenced in Colfiorito seismic sequence data that show almost all the focal mechanisms consistent with a present-day NE-SW trending extensional stress field (Amato *et al.*, 1998; Ekstrom *et al.*, 1998; Chiaraluce *et al.*, 2003; 2005). The presence of important N-S shear zones in the area (Cello *et al.*, 2003) does not seem related to the recognized active stress, but the seismic sequence seems confined between at least two major N-S shear zones (Cinti *et al.*, 2000; Collettini *et al*., 2005). These shear zones could represent «structural barriers» to the development of the seismic rupture planes, and therefore they may have controlled the dimension of the seismogenic structure (Meghraoui *et al.*, 1999; Cinti *et al.*, 2000).

3. State of stress

As already mentioned, in the Colfiorito area we have only two wells (SD1 and MC1) in which to perform breakout analysis. In a previous paper, a preliminary analysis, executed within a wider work with the analysis of 86 deep wells, indicated that Shmin is oriented NNE-SSW and ENE-WSW for SD1 and MC1 wells, respectively (Mariucci *et al.*, 1999). These different orientations come from scattered data distributed along the logged intervals and do not seem to be simply related to the different tectonic units drilled by the wells. This large scatter was interpreted as due to the high degree of heterogeneity of the rocks in this region and to the great number of faults recognized in each well that might reorient the stress directions (Bell *et al.*, 1992; Barton and Zoback, 1994). In this work we will try to understand the relationships existing between breakout directions, stratigraphy and crossed faults.

3.1. *Monte Civitello 1 breakout analysis*

A detailed analysis has been performed on Monte Civitello 1 well logs. The borehole, drilled by AGIP in 1988-89, is 5600 m deep with a deviation from vertical less than 7°. The stratigraphy of the well is composed of: Miocene flysch («Marnoso Arenacea» fm) in the interval 0-1076 m; the Umbria-Marche Meso-Cenozoic pelagic sequence (1076-2220 m); the Umbria-Marche platform carbonates (2220-2841 m); the triassic evaporites («Anidriti di Burano» fm; Martinis and Pieri, 1964) from 2841 to 5600 m (fig. 2a). The well is located close to the Gubbio tectonic structure in the north-western sector of the Gubbio basin (fig. 1). It intersects several faults between 300 m and 1500 m, whereas only two main fault structures are recognized in its deepest part. These latter features could be the Gubbio fault and the Alto Tiberina fault. A previous analysis of this well (Mariucci *et al.*, 1999) gave a minimum horizontal stress direction of N11±29° for a total breakout length of 1431 m, with overall low data quality (equal to D).

In this paper we re-analyzed the breakout data comparing them with the available geophysical logs (sonic, gamma ray, resistivity, dip strata), which previously were not considered, and the stratigraphy and structural setting of this area. We have taken into account the depth interval between 248 and 5559 m, and found breakouts from 500 to 5541m. The complete analysis, including all of the breakout zones, shows a Shmin N12±29° with a total breakout length of 1397m and D data quality (fig. 2c). The breakout zones are present throughtout the well showing a long deep interval with the same breakout orientations, whereas in the shallow part systematic breakout rotations close to the faults can be observed (fig. 2, see inset). For this reason we analysed the breakout data split into four different stratigraphic intervals (fig. 2b). In the Umbria Miocene turbidites the analysis (data from 500 down to 1060m) shows a Shmin N59±29° for 252 m total length of breakout zones, to which we assigned a D data quality. In the data interval between 1209 and 2103 m, within the pelagic formations, the analysis shows a Shmin N344±36° for a total length of 323 m of breakouts with a D quality. The rose plot for the interval between 2234 and 2794 m (carbonate platform units) points out a Shmin N10±4°, with a length of breakouts of 113 m and B quality. The last rose plot from the «Burano» Triassic evaporite formation (data from 2870 to 5541 m) shows a Shmin N9±18° for a total length of 709 m, with B quality. These diagrams highlight the strong difference between the shallow and the deeper part of the well. In fact, while in the deeper formations («Burano» and carbonate platform units) Shmin orientations are well constrained around a N-S direction, with a low standard deviation (about 11°) and a very high total length of breakout zones (822 m), in the upper part of the hole (turbidites and pelagic sequences) a high degree of scattering of breakout orientations is

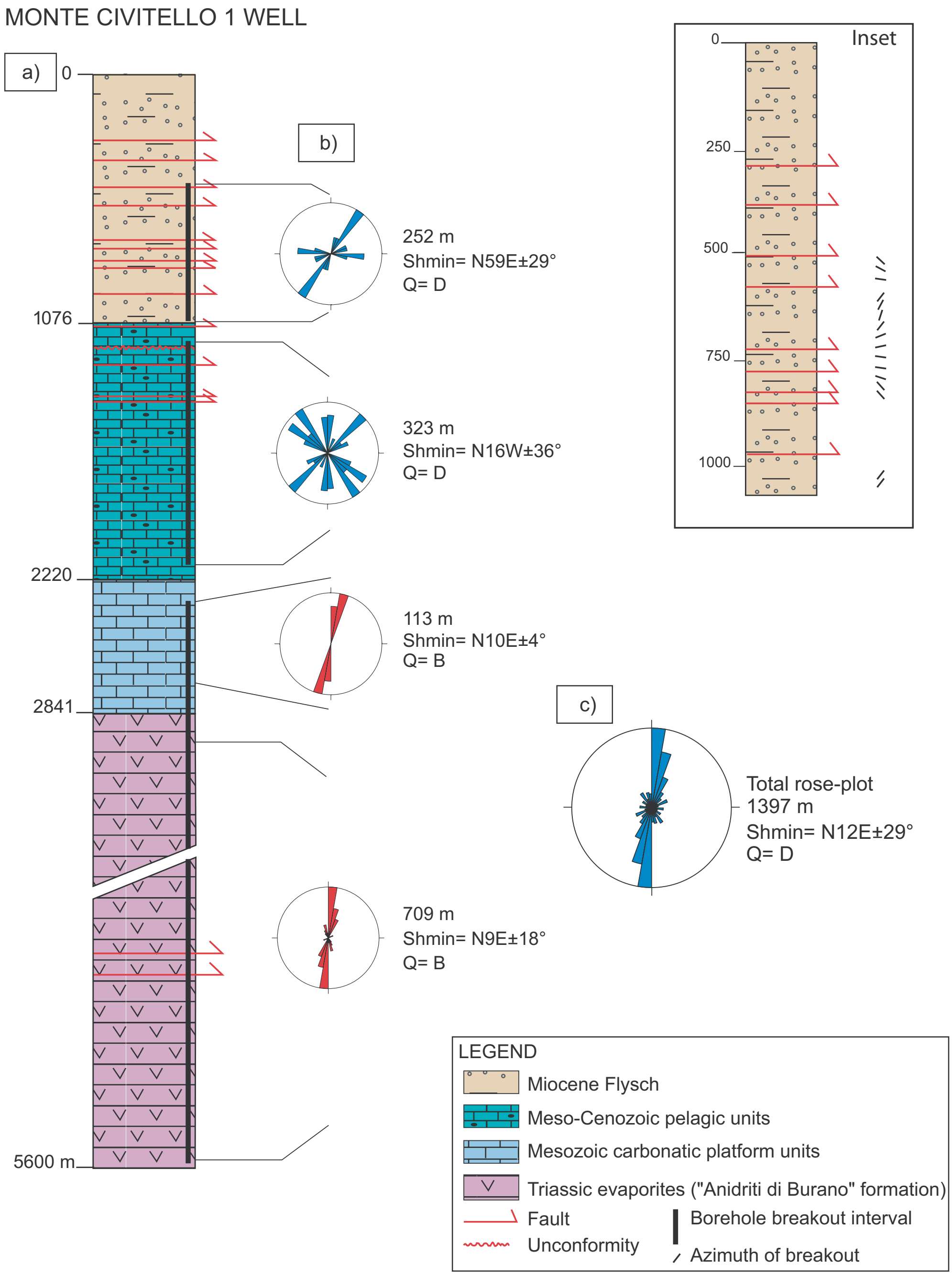

Fig. 2a-c. Monte Civitello 1 well analysis: a) stratigraphic sketch; b) Shmin from breakout data for different units; c) Shmin from all breakout data. Beside each rose plot: breakout length, Shmin orientation and standard deviation, quality assigned to the result. In the inset details on the Shmin breakout orientations for the first 1000 m.

evident, with standard deviation values greater than 30° for a total length of 575 m.

A possible explanation of these non-homogeneous orientations is related to the stratigraphic sequences characterized by thin layers of marls, sandstones and clays that could affect the breakout orientations. Otherwise the scattered orientations can be due to the presence of the above-mentioned faults that cross the well in the range between 300 and 1500 m. As it is possible to observe in the inset of fig. 2, this last explanation seems to be the most convincing. Breakout orientations seem to rotate in proximity to the faults, tending to reorient in the perpendicular direction with respect to the main Shmin trend (Bell *et al.*, 1992; Barton and Zoback, 1994).

Taking into account that: i) the faults seem to reorient the stress in the shallow part of the well, ii) the result achieved from the total analysis is mainly influenced by the deeper part of the well (about 60%), and iii) bedding does not affect breakout orientations, Shmin inferred from this well can be a reliable estimate of the regional stress direction, even though its quality (D) usually is not used in stress maps.

3.2. *San Donato 1 breakout analysis*

A detailed analysis has been performed on SD1 well logs. The borehole, 4763 m deep and with a deviation from vertical less than 4° was drilled by SNIA-BPD in 1983-84 and is located about 20 km south-west of the MC1 well (fig. 1). It is in a peculiar position with respect to one of the major features of northern Apennines: it is very close to the Alto Tiberina fault. Indeed, this low angle normal fault is crossed at 326 m depth by SD1, juxtaposing the «Marnoso Arenacea» Miocene turbidite sequence directly on the «Anidriti di Burano» Triassic sequence down to 3030 m. From 3030 m to 4485 m the well penetrates metamorphic basement («Verrucano» fm) which lies, with a tectonic contact, on «Anidriti di Burano» unit, where the borehole ends without crossing any Umbria-Marche marine unit, unlike MC1 (fig. 3a).

SD1 was previously analyzed (Mariucci *et al.*, 1999) giving a resulting Shmin orientation of N77±23° with a data quality equal to C (medium quality). No correlation between breakout orientations and stratigraphy had been found, and the breakout orientations were distributed along the well showing a prevalent mean orientation about ENE-WSW and secondarily NE-SW.

Now we have had the chance to reanalyze this well comparing the available geophysical logs, previously not considered (gamma ray, resistivity) with the stratigraphy and with the structural setting of this area. We analysed the interval between 466 and 4062 m where we found breakout zones from 1550 to 4022 m. The first part of the logged interval does not show breakout zones, and the well deviation from the vertical often is too low (less than 0.5°) and not suitable to obtain reliable breakout orientations. The comparison with gamma ray, resistivity and stratigraphy allowed us to constrain the Shmin orientation in the whole borehole: N55±22° with C data quality for a total length of breakout zones equal to 547 m (fig. 3c). We have performed the breakout analysis for each main stratigraphic interval separately (fig. 3b) showing good qualities (B) and roughly the same Shmin orientation. The analysis in the deep Triassic evaporites (breakouts from 1550 down to 2055 m) shows a Shmin N38±18° for a total breakout length of 176 m. This result is in agreement with the Shmin orientation N63±20° relative to the «Verrucano» metamorphic basement, although it shows a slight difference of about 20°, within the error of the results. The latter analysis identified breakout zones between 3128 and 4022 m, for a total breakout length of 371 m.

4. Discussion and Conclusions

The Shmin orientation inferred from MC1, about N-S, differs strongly from the regional Shmin trend, about NE-SW (Montone *et al.*, 2004), and suggests the influence of active structures consistent with this stress orientation, such as E-W normal faults or strike slip faults perpendicular to the belt or N-S faults. The former interpretation can be related to a bend of NW-SE normal faults, as recognized on the Gubbio fault both at the surface and at

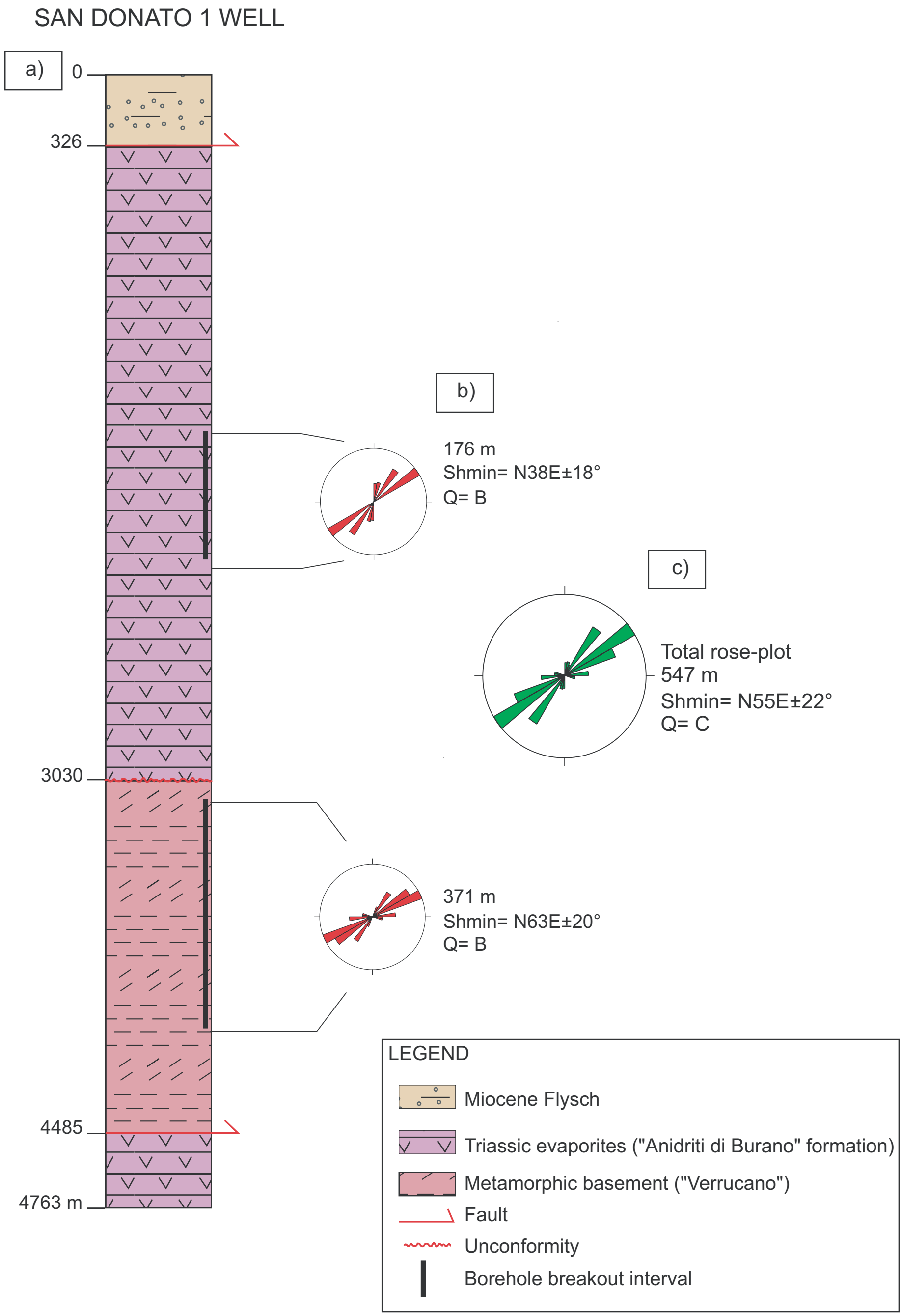

Fig. 3a-c. San Donato 1 well analysis: a) stratigraphic sketch; b) Shmin from breakout data for different units; c) Shmin from all breakout data. Beside each rose plot: breakout length, Shmin orientation and standard deviation, quality assigned to the result.

depth (Mirabella *et al.*, 2004 and references therein). It can be argued that a similar structure could also be present in the area of the MC1 well. This interpretation is also supported by the focal mechanism of 1984 Gubbio earthquake computed by Haessler *et al.* (1988), where the fault plane dipping toward south is about E-W oriented. Although the mainshock occurred at the southern edge of the sequence (Collettini *et al.*, 2003), most of the seismic events are located in a narrow belt corresponding to the bend area of the Gubbio fault (Mirabella *et al.*, 2004), suggesting that the rupture may have occurred on the E-W oriented portion of the fault plane. This is in agreement with the Haessler *et al.* (1988) fault plane solution and with a Shmin about N-S oriented, as inferred from our data. A fault with a bend can represent the remnant of a segmented structure evolved to form a single fault (*e.g.* Cartwright *et al.*, 1995 and references therein). The second hypothesis is that the stress orientation could be due to the presence of a transfer fault that separates two NW-SE oriented structures (Barchi *et al.*, 1998). In the northern Apennines there are some seismic events characterized by T-axes about N-S that would support our breakout data (fig. 4).

After the detailed revision of the whole SD1 well dataset (digital and paper dipmeter logs, stratigraphy, gamma ray and resistivity) we believe that the Shmin orientation N55E±22° is more reliable than the previous result that gave a Shmin orientation N77±23°. The Shmin

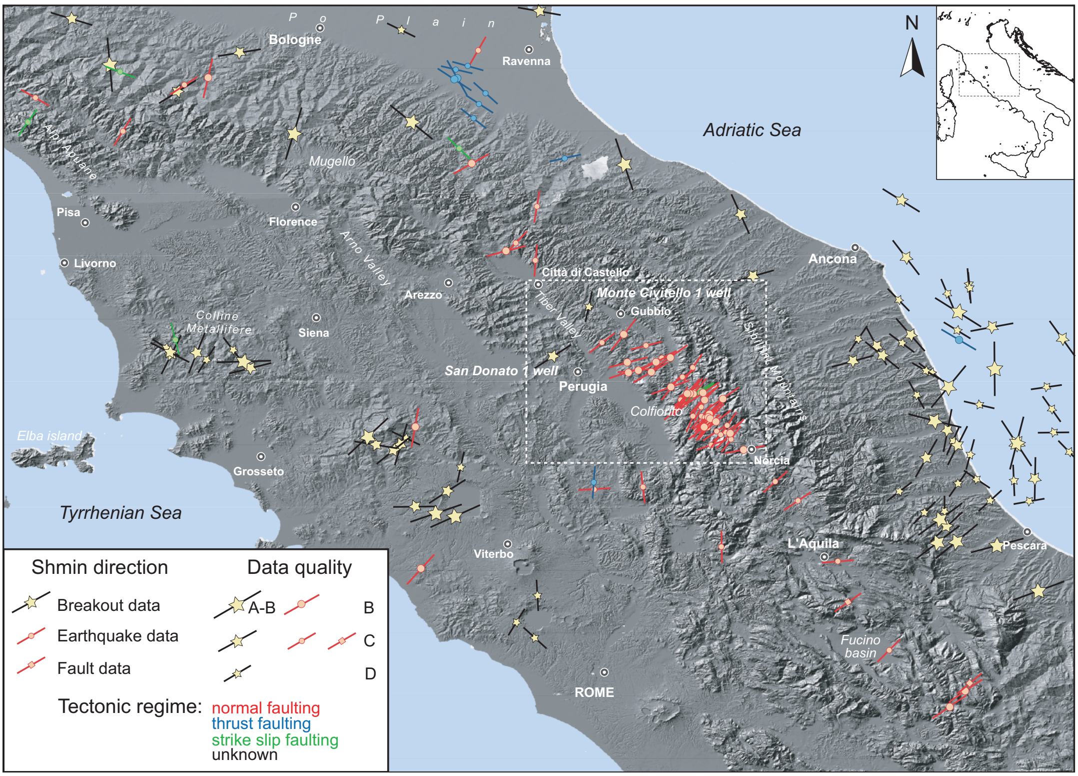

Fig. 4. Active stress map of central Italy (Shmin direction) with all data quality (modified after Montone *et al.*, 2004). The dashed square is the area of fig. 1.

N55E±22° is much more in agreement with data by earthquake focal mechanisms in this area, even if slightly rotated toward an E-W direction. We believe that this difference can be due to the location of the well, very close to the Alto Tiberina Fault that has a mean direction about NNW-SSE. In this case the presence of an important tectonic feature slightly rotates the active stress field in the direction of the minimum horizontal stress inside a very strong extensional stress regime. An extensional tectonic regime in this area was also confirmed by the estimate from borehole breakout occurrence at depth in SD1 (Mariucci and Müller, 2003).

The main lesson learned is that a detailed analysis in a single well or in two wells in the same area can give strong indications of the local stress variations. However, we wish to emphasize that only two data points cannot adequately depict the regional stress field, and more data are needed or smoothed maps should be built with other information in order to get a reliable and well-constrained mean orientation of a large area.

Notwithstanding the slightly different Shmin orientations in the two boreholes, within the error, both results give information about the regional active stress field. Indeed, a rotation of Shmin toward the foredeep, from NE-SW to NNE-SSW, is coherent in an intermediate area linking the extensional belt with the outer front of the Apennines, where compression is still active and Shmin trend is NW-SE (fig. 4).

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