Regional and local stress field orientation inferred from quantitative analyses of extension joints: Case study from southern Italy

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outline

• Introduction
• Quaternary Framework
• Mesostructural Analysis
• Discussion
• Conclusion
Introduction

( Siculo-Calabrian Rift Zone, hereafter SCRZ)

more detailed information is needed!

Analyaze brittle extensional features affecting Quaternary deposits in eastern Sicily and southern Calabria in order to better constrain the tectonic behavior at a more local scale.
Quaternary Framework

-Tectonic Setting

- NNW-SSE–oriented convergence between Eurasia and Nubia plates.
- Two main processes dominate eastern Sicily and southern Calabria: the SCRZ activity and a regional tectonic uplift.
- The SCRZ began its activity
  1. in central Calabria ca. 700 ka B.P
  2. the southern Hyblean branch activated 450 ka B.P.
  3. in southern Calabria and northeastern Sicily, the rifting activity started only 250 and 125 ka B.P.
- SCRZ mean direction of extension (~N115E) and an opening velocity of 3.6 ±0.6 mm/a by analyzing fault and geodetic measurements.
- The overall tectonic setting is made and they involve crustal volumes with lateral dimensions up to few tens of kilometers and with activity rates highly variable in time.
Quaternary Framework

- Quaternary Deposits

- **Et**: Mount Etna Quaternary volcanic products
- **P-Q**: Pliocene-Pleistocene deposits;
- **Ap-Mag**: undifferentiated Mesozoic-Cenozoic units of the Apennines-Maghrebian chain;
- **Ibl. Volc**: Pliocene and Cretaceous volcanics of the Hyblean Plateau
- **Carb. Seq**: Mesozoic-Cenozoic carbonate foreland sequence of the Hyblean Plateau;
- **Ca-Pe**: Calabria-Peloritani metamorphic units.
Mesostructural Analysis—Inversion Methodology

• Focus on purely extensional fractures (no evidence of shear motion). This type of brittle tectonic features is known as “extension joints”

• A “extension joints” is here defined when a statistically significant number of extension fractures are parallel or grouped within a small dispersion of the mean orientation (±10), while an “orthogonal joint system” occurs when two joint sets form an angle of 90 ± 10

• “Extension joints” can suggest the orientation of the tectonic stress field. (assume $\sigma_1$ is vertical)

parallel with strike
perpendicular to strike

$\sigma_H$
$\sigma_h$

extensional direction
Mesostructural Analysis—Inversion Methodology

Let \( l: \sigma_x \) \( m: \sigma_y \) \( n: \sigma_z \)

\[ l_i x + m_i y + n_i z = 0, \quad i = 1 \sim N (N \geq 2) \quad \ldots \ldots (1) \]

\((l^2 + m^2 + n^2 = 1) \quad \quad (x^2 + y^2 + z^2 = 1)\)

Using a multiplier of Lagrange the function to minimize

\[ \sum_{1}^{N} (l_i x + m_i y + n_i z)^2 - K(x^2 + y^2 + z^2 - 1) = \min \quad \ldots \ldots (2) \]

Differentiating the function (2)

\[
\sum_{1}^{N} l_i (l_i x + m_i y + n_i z) - Kx = 0
\]

\[
\sum_{1}^{N} m_i (l_i x + m_i y + n_i z) - Ky = 0
\]

\[
\sum_{1}^{N} n_i (l_i x + m_i y + n_i z) - Kz = 0
\]

\[
\left( \sum_{1}^{N} l_i^2 - K \right) x + \left( \sum_{1}^{N} l_i m_i \right) y + \left( \sum_{1}^{N} l_i n_i \right) z = 0
\]

\[
\left( \sum_{1}^{N} m_i \right) x + \left( \sum_{1}^{N} m_i^2 - K \right) y + \left( \sum_{1}^{N} m_i n_i \right) z = 0 \quad \ldots \ldots (3)
\]

\[
\left( \sum_{1}^{N} n_i \right) x + \left( \sum_{1}^{N} m_i n_i \right) y + \left( \sum_{1}^{N} n_i^2 - K \right) z = 0
\]
Mesostructural Analysis-Inversion Methodology

In order to have solution, make the determinant of symmetric matrix(eq3) equal zero

\[-K^3 + NK^2 - AK + \Delta = 0 \quad \ldots \quad (4)\]

\[N = K_1 + K_2 + K_3 > 0\]
\[A = K_1 K_2 + K_2 K_3 + K_3 K_1 > 0\]
\[\Delta = K_1 K_2 K_3 > 0\]
\[K_3 > K_2 > K_1\]

We will get three value K (K_1, K_2, K_3) and R. In order to get three direction, put three value in eq(3)

\[X_r = \sum_{i=1}^{N} l_i m_i \sum_{i=1}^{N} m_i n_i - (\sum_{i=1}^{N} m_i^2 - K_r) \sum_{i=1}^{N} l_i n_i \quad r=1, 2, 3 \quad \ldots \ldots \quad (5)\]
\[Y_r = \sum_{i=1}^{N} l_i m_i \sum_{i=1}^{N} l_i n_i - (\sum_{i=1}^{N} l_i^2 - K_r) \sum_{i=1}^{N} m_i n_i \]
\[Z_r = \left(\sum_{i=1}^{N} m_i^2 - K_r\right) \left(\sum_{i=1}^{N} m_i^2 - K_r\right) - (\sum_{i=1}^{N} l_i m_i)^2 \]
\[R = \frac{(K_2 - K_3)}{(K_1 - K_3)} \quad \ldots \ldots \quad (6)\]
Mesostructural Analysis-
Orthogonal Joint Pattern (fracture grid-lock system)

\[ \sigma_2 \approx \sigma_3 \]
Mesostructural Analysis—Structural Stations

- Investigate calcarenite sediments and cemented deposits, **avoiding** clayish and loose matrix-supported clastic sediments.
- Examine 13 different localities here presenting data from 16 structural stations.
- The surveyed joints are commonly characterized by **subvertical setting**, roughly perpendicular to bedding.
- At all stations, we first ensured that the displacement vector of the fractures indicates prevailing opening.

1. along-strike persistence
2. the amount of opening
3. the possible infilling of each fracture
4. minimum of 20–30 measurement of the fractures orientation
**Mesostructural Analysis - Structural Stations**

- At the same site, the joints belonging to these *secondary sets* often show different development.

whether they could be the effects of different phases of fracturing associated with different remote stress fields, or instead they have been originated by a unique stress field.

### Table 1. Surveyed Structural Stations and Corresponding Results Obtained from the Inversion Technique [Caputo and Caputo, 1989]\(^a\)

<table>
<thead>
<tr>
<th>ID</th>
<th>Long. (°E)</th>
<th>Lat. (°N)</th>
<th>Location</th>
<th>Lithology and Formation</th>
<th>Age</th>
<th>Data Num.</th>
<th>(\sigma_1) Azimuth/Plunge</th>
<th>(\sigma_2) Azimuth/Plunge</th>
<th>(\sigma_3) Azimuth/Plunge</th>
<th>(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01</td>
<td>15.669</td>
<td>38.207</td>
<td>Campo Calabro</td>
<td>Sandy marls (Vito Superiore Fm)</td>
<td>Early Pleistocene</td>
<td>31</td>
<td>296/88</td>
<td>45/1</td>
<td>135/2</td>
<td>0.31</td>
</tr>
<tr>
<td>C02</td>
<td>15.674</td>
<td>38.208</td>
<td>Campo Calabro</td>
<td>Sandy marls (Vito Superiore Fm)</td>
<td>Early Pleistocene</td>
<td>44</td>
<td>252/85</td>
<td>150/1</td>
<td>60/5</td>
<td>0.92</td>
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<tr>
<td>C03</td>
<td>15.686</td>
<td>38.210</td>
<td>Campo Calabro</td>
<td>Sandy marls (Vito Superiore Fm)</td>
<td>Early Pleistocene</td>
<td>22</td>
<td>243/87</td>
<td>340/0</td>
<td>70/3</td>
<td>0.95</td>
</tr>
<tr>
<td>C04</td>
<td>15.690</td>
<td>38.212</td>
<td>Campo Calabro</td>
<td>Sandy marls (Vito Superiore Fm)</td>
<td>Early Pleistocene</td>
<td>23</td>
<td>342/78</td>
<td>181/11</td>
<td>90/4</td>
<td>0.88</td>
</tr>
<tr>
<td>C05</td>
<td>15.723</td>
<td>38.122</td>
<td>Terreli</td>
<td>Sandy calcarenites with intercalation of silt (Vinco Fm)</td>
<td>Early Pleistocene</td>
<td>15</td>
<td>42/76</td>
<td>253/12</td>
<td>161/7</td>
<td>0.96</td>
</tr>
<tr>
<td>C06</td>
<td>15.723</td>
<td>38.113</td>
<td>Vinco</td>
<td>Sandy calcarenites with intercalation of silt (Vinco Fm)</td>
<td>Early Pleistocene</td>
<td>20</td>
<td>352/84</td>
<td>247/2</td>
<td>157/6</td>
<td>0.77</td>
</tr>
<tr>
<td>C07</td>
<td>15.736</td>
<td>38.120</td>
<td>Campi</td>
<td>Sandy calcarenites with intercalation of silt (Vinco Fm)</td>
<td>Early Pleistocene</td>
<td>57</td>
<td>100/86</td>
<td>248/3</td>
<td>338/2</td>
<td>0.84</td>
</tr>
<tr>
<td>C08</td>
<td>15.712</td>
<td>38.078</td>
<td>Pozzi</td>
<td>Marine calcarenites</td>
<td>Early Pleistocene</td>
<td>16</td>
<td>313/76</td>
<td>75/8</td>
<td>167/12</td>
<td>0.96</td>
</tr>
<tr>
<td>S01</td>
<td>15.235</td>
<td>37.802</td>
<td>Serra S. Biagio</td>
<td>Marine calcarenites and marly clays</td>
<td>Late Early Pleistocene–Early Middle Pleistocene</td>
<td>41</td>
<td>266/87</td>
<td>64/3</td>
<td>154/2</td>
<td>0.73</td>
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<tr>
<td>S02</td>
<td>15.478</td>
<td>38.071</td>
<td>Monte Vecchio</td>
<td>Marine calcarenites</td>
<td>Middle Pleistocene</td>
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<td>207/79</td>
<td>21/11</td>
<td>112/1</td>
<td>0.86</td>
</tr>
<tr>
<td>S03</td>
<td>15.103</td>
<td>36.802</td>
<td>Vendicarn</td>
<td>Bioelastic calcarenites</td>
<td>Middle-Late Pleistocene</td>
<td>42</td>
<td>135/89</td>
<td>277/1</td>
<td>7/1</td>
<td>0.47</td>
</tr>
<tr>
<td>S04</td>
<td>15.210</td>
<td>36.955</td>
<td>Punta del Cane</td>
<td>Marine calcarenites</td>
<td>Early Pleistocene</td>
<td>62</td>
<td>142/82</td>
<td>21/4</td>
<td>291/7</td>
<td>0.78</td>
</tr>
<tr>
<td>S05</td>
<td>15.110</td>
<td>36.823</td>
<td>Calabroscie-Pantano piccolo</td>
<td>Bioelastic calcarenites</td>
<td>Middle-Late Pleistocene</td>
<td>42</td>
<td>257/86</td>
<td>118/3</td>
<td>28/3</td>
<td>0.42</td>
</tr>
<tr>
<td>S07</td>
<td>15.131</td>
<td>37.309</td>
<td>Castelfuceo</td>
<td>Marine calcarenites</td>
<td>Early Pleistocene</td>
<td>59</td>
<td>46/88</td>
<td>312/0</td>
<td>222/2</td>
<td>0.98</td>
</tr>
<tr>
<td>S08</td>
<td>15.062</td>
<td>37.409</td>
<td>S. Denticio</td>
<td>Sandstone and polygenic conglomerate</td>
<td>Early Pleistocene</td>
<td>45</td>
<td>237/87</td>
<td>22/3</td>
<td>112/2</td>
<td>0.50</td>
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<tr>
<td>S09</td>
<td>15.167</td>
<td>37.561</td>
<td>Isola Lachea</td>
<td>Marine calcarenites</td>
<td>Middle-Late Pleistocene</td>
<td>51</td>
<td>243/83</td>
<td>110/4</td>
<td>20/5</td>
<td>0.81</td>
</tr>
</tbody>
</table>

*\(R\) is the ratio: \((\sigma_2 - \sigma_3)/ (\sigma_1 - \sigma_3)\).*
Discussion-section I
Discussion-section II

- Nizzeti fault
- Acireale fault
- Piedimonte Fault
- Taormina fault

Legend:
- Holocene fault
- Strike slip fault
- Plio-Pleistocene fault
- Mt. Etna
- Ionian Sea
- Catania
- Catania Plain
- Primico Heck
- 37.5°N
- 15°E
Discussion-section III
Discussion—stress field perturbation

• The occurrence of major tectonic structures can perturb the first-order stress field, causing second-order reorientations of the principal stress axes.
• At S03 and S06, it has been observed that the influence of the faults on the stress field is wider in regions with small differential horizontal stresses.
Discussion-stress trajectories

- Have good agreement with (1) GPS data, (2) earthquake focal mechanisms, (3) kinematics inversion of Quaternary fault planes, (4) borehole breakout analyses.
- Within the investigated area, it is reasonable to merge geologically and geodetically derived stress information since a unique tectonic event has acted in this area in recent times, and it is still active at present.
- In order to remain conservative, we just compare the principal stress directions and not their magnitudes.
- Compiling 113 data from different approach, there is a good agreement between the surface deformation pattern and the focal mechanisms, indicating, once again, that the general WNW-ESE extension affecting and generating the SCRZ is the consequence and effect of a single geodynamic process acting at the crustal scale.
Discussion - stress trajectories

• In the zones where the data density is higher, it is possible to draw closely spaced trajectories, which permit to highlight the local stress deflections reflecting the interference between major tectonic structures and the first-order stress field.

• The trajectories confirm the left-lateral slip component of the eastern part of Sant’Eufemia Fault and suggest a right-lateral component for the Armo Fault.
Conclusion

1. The analysis of extension joint sets based on the inversion technique proposed by Caputo and Caputo [1989] or other approaches allowed to constrain the tectonic setting and better define the geodynamic evolution in several Mediterranean regions [Caputo and Pavlides, 1993; Arlegui and Simon, 2001; Arlegui et al., 2005, 2006; Di Bucci et al., 2011].

2. The present study, focusing on joint sets and fracture grid-lock systems, allows to document the existence of an extensional tectonic regime whose activity is younger than Middle Pleistocene.

3. The obtained stress orientations are in good agreement with the regional direction of extension (WNW-ESE)
   (I) inversion of slickensides data on fault planes of the SCRZ [Monaco et al., 1997; Monaco and Tortorici, 2000; Catalano et al., 2008, 2010],
   (II) focal mechanisms [Neri et al., 2003, 2005; D'Amico et al., 2010]
   (III) Geodetic measurements [D’Agostino and Selvaggi, 2004; Mattia et al., 2009, 2012]
   (VI) borehole breakout data [Ragg et al., 1999; Montone et al., 2012].
conclusion

4. There is a good overlap between our results and the smoothed stress map of the whole Italian peninsula [Pierdominici and Heidbach, 2012]

5. Data contribute to make denser the Italian stress directional catalogue for this region [Montone et al., 2012].

6. This sector has been recognized to have great variability for the horizontal stress directions [Pierdominici and Heidbach, 2012]

7. As suggested by the presented stress tensor inversions, in some sites, local stress deflections and stress swaps systematically occur in zones characterized by two overlapping fault segments or close to their tips [Kattenhorn et al., 2000].
Thanks for listening