QUANTITATIVE FRACTURE CHARACTERIZATION IN THE DAMAGE ZONE OF THE VICTORIA FAULT, MALTA

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Main goals of the project

Digital Outcrop Model (DOM)

«ideal» scanline

fracture «maturity»

Barcode and P₁₀ plot of the damage zone

Does it affect the results?
Geological framework

- Pelagian platform: foreland of the Appennine-Sicilian-Maghrebian belt
- Two main extensional events:
  - **D1**: WNW-ESE extension (20-17 Ma): normal fault and Neptunian dikes,
  - **D2**: N-S extension (7-1.5 Ma) and formation of the coeval sets ENE-WSW and WNW-ESE.
Stratigraphy

<table>
<thead>
<tr>
<th>Ma</th>
<th>Age</th>
<th>Lithology</th>
<th>Member</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Maaanian</td>
<td>Gebel Imbark</td>
<td>Tal-Pitkal</td>
<td>Upper Coralline Limestone (75 - 100 m)</td>
</tr>
<tr>
<td></td>
<td>Tortonian</td>
<td>Mtarfa</td>
<td>Ghaluj Molel</td>
<td>Green sand (0 - 11 m)</td>
</tr>
<tr>
<td>11</td>
<td>Serravallian</td>
<td>Upper Globigerina (2 - 15 m)</td>
<td>UMCB</td>
<td>Blue Clay (10 - 100 m)</td>
</tr>
<tr>
<td>16</td>
<td>Langhian</td>
<td>Middle Globigerina (0 - 15 m)</td>
<td>UMCB</td>
<td>Globigerina Limestone</td>
</tr>
<tr>
<td>20</td>
<td>Burdigalian</td>
<td>Lower Globigerina (5 - 40 m)</td>
<td>LMCB</td>
<td>Lower Coralline Limestone (300 - 450 m)</td>
</tr>
<tr>
<td>23</td>
<td>Aquitanian</td>
<td>Lower Coralline Limestone (0 - 50 m)</td>
<td>LMCB</td>
<td>Xlendi (Ox): limestones with a top layer of echinoids Scutella subrotunda (called Scutella Bed),</td>
</tr>
<tr>
<td>28</td>
<td>Chattian</td>
<td>Xlendi</td>
<td>Attard</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td></td>
<td>Oligocene</td>
<td>Maghlaq</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

More details in Martinelli, Bistacchi, Balsamo & Meda, JSG, 2019

**Lower Globigerina (Mlg):** Planktonic foraminifers *Globigerina* with Neptunian dikes

**Xlendi (Ox):** Limestones with a top layer of echinoids *Scutella subrotunda* (called *Scutella Bed*).
Field analysis and drone photogrammetry

**PHASE 1**

1.1 Definition of 7 scanlines perpendicular to the Victoria Fault

1.2 Collect data: attitude of the discontinuities, openings and filling

1.3 Orientation and kinematic analysis

**PHASE 2**

2.1 Image acquisition (drone)

2.2 Photo alignment

2.3 Sparse and Dense point cloud

2.4 3D Mesh and texture building

2.5 DTM

2.6 Orthophoto

**Image acquisition (drone)**

**Photo alignment**

**Sparse point cloud**

**Dense point cloud**
Victoria Fault NE (1)

• The 4 sets of fractures, the Victoria Fault and the lithologies were traced on the orthophotos.

• Construction of an «ideal» scanline (Azimuth 122°), segmented, and perpendicular to the Victoria Fault (Azimut 212):

  24 scanlines  4 scanlines

→ calculate the intersections between fracture sets and scanlines
Two equivalent methods to calculate **progressive distances** along scanlines:

1. Pythagorean theorem and Terzaghi correction (1965)

2. Calculation of the distance from a point to a plane

\[
d(P, \pi) = \frac{|ax_P + by_P + cz_P + d|}{\sqrt{a^2 + b^2 + c^2}}
\]

→ statistical analysis of spacing
**Geological and structural field analysis**

- Orientation statistics of the master fault plane of the Victoria Fault:

  → results consistent with the N-S extensional phase (D2) of Martinelli et al. (2019)
Photogrammetry fracture analysis

- Orientation statistics of fractures traced on the orthophotos: 4 well-defined sets.

<table>
<thead>
<tr>
<th>set</th>
<th>quantity</th>
<th>trend</th>
<th>plunge</th>
<th>kappa</th>
<th>mean length</th>
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</thead>
<tbody>
<tr>
<td>ENE-WSW</td>
<td>2988</td>
<td>64.1</td>
<td>0</td>
<td>1.5</td>
<td>0.3251</td>
</tr>
<tr>
<td>NE-SW</td>
<td>4039</td>
<td>35.5</td>
<td>0</td>
<td>2</td>
<td>0.4899</td>
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<tr>
<td>N-S</td>
<td>2100</td>
<td>1.5</td>
<td>0</td>
<td>1.6</td>
<td>0.3598</td>
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<tr>
<td>WNW-ESE</td>
<td>4058</td>
<td>147.4</td>
<td>0</td>
<td>1.2</td>
<td>0.1766</td>
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</table>
Fracture analysis: lengths

- Fracture length statistics for the 4 sets and for the terrestrial scanlines

### SET statistics

<table>
<thead>
<tr>
<th>SET</th>
<th>ENE-WNW</th>
<th>NE-SW</th>
<th>N-S</th>
<th>WNW-ESE</th>
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</thead>
<tbody>
<tr>
<td>Count</td>
<td>2988</td>
<td>4039</td>
<td>2100</td>
<td>4058</td>
</tr>
<tr>
<td>Minimum [m]</td>
<td>0.109</td>
<td>0.112</td>
<td>0.118</td>
<td>0.136</td>
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<tr>
<td>Maximum [m]</td>
<td>125.612</td>
<td>74.056</td>
<td>28.845</td>
<td>59.564</td>
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<tr>
<td>Mean [m]</td>
<td>6.222</td>
<td>3.996</td>
<td>2.309</td>
<td>3.268</td>
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<tr>
<td>Standard Deviation [m]</td>
<td>10.175</td>
<td>6.288</td>
<td>3.406</td>
<td>4.996</td>
</tr>
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</table>

→ negative exponentials
Statistical analysis of field scanlines (1):

Statistical analysis of the spacing (ex. scanline 1):

- K-S test for uniform spacing
- Barcode
- Spacing frequency
Statistical analysis of field scanlines (1)

Statistical analysis of the spacing (ex. scanline 1):

**Barcode**

K-S test for stationary spacing

**K-S test for GAUSSIA spacing distribution with x = 2.4079 and std.dev. = 0.8410: (corrected) -0.172 - 0.184 (non-corrected) p-value = 0.000

No evidence against H0 of no difference with GAUSSIA distribution. No evidence against a GAUSSIA spacing distribution is detected at 5% significance.

**K-S test for EXPONENTIAL spacing distribution with x = 0.7502 in range: 0.039 - 0.207 (corrected) -0.039 - 0.207 (non-corrected) p-value = 0.7782

No evidence against H0 of no difference with EXPONENTIAL distribution. No evidence against an EXPONENTIAL spacing distribution is detected at 5% significance.
### Statistical analysis of field scanlines (2)

**Purpose of the work**
- Terzaghi
- Geological framework

**Analysis methods**
- Results and data analysis

**Conclusions**
- Analysis

<table>
<thead>
<tr>
<th>Method</th>
<th>Lithology</th>
<th>Scanline</th>
<th>X_min</th>
<th>X_max</th>
<th>n. data</th>
<th>Trend test</th>
<th>Pattern test</th>
<th>Uniform dist. test</th>
<th>Poisson dist. test</th>
<th>Scan</th>
<th>Mean</th>
<th>Standard dev.</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>P&lt;sub&gt;0&lt;/sub&gt;</th>
<th>Spacing statistics</th>
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<tbody>
<tr>
<td>Terzaghi</td>
<td>mlg</td>
<td>1:00-15.50</td>
<td>0</td>
<td>15.5</td>
<td>62</td>
<td>no_trend</td>
<td>no_pattern</td>
<td>retained</td>
<td>retained</td>
<td>1a</td>
<td>0.2541</td>
<td>0.22785</td>
<td>3.3696</td>
<td>17.407</td>
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<td>Terzaghi</td>
<td>ox</td>
<td>1:15.5-17</td>
<td>15.5</td>
<td>27</td>
<td>13</td>
<td>no_trend</td>
<td>no_pattern</td>
<td>retained</td>
<td>retained</td>
<td>1b</td>
<td>0.38058</td>
<td>0.32897</td>
<td>0.55061</td>
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<td>Terzaghi</td>
<td>mlg</td>
<td>2:00-17.7</td>
<td>0</td>
<td>17.2</td>
<td>76</td>
<td>trend</td>
<td>no_pattern</td>
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<td>2</td>
<td>0.09108</td>
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<td>7.4887</td>
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<td>Terzaghi</td>
<td>ox</td>
<td>3:00-3.14</td>
<td>0</td>
<td>3</td>
<td>14</td>
<td>no_trend</td>
<td>no_pattern</td>
<td>retained</td>
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<td>3a</td>
<td>0.05528</td>
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<td>3:14-8.10</td>
<td>3.14</td>
<td>8.1</td>
<td>13</td>
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<td>no_pattern</td>
<td>retained</td>
<td>retained</td>
<td>3b</td>
<td>0.18335</td>
<td>0.13709</td>
<td>1.6582</td>
<td>4.964</td>
<td>5.4481</td>
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<tr>
<td>Terzaghi</td>
<td>ox</td>
<td>4:00-0.76</td>
<td>0</td>
<td>7.6</td>
<td>25</td>
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<td>no_pattern</td>
<td>retained</td>
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<td>4</td>
<td>0.19911</td>
<td>0.16236</td>
<td>0.83854</td>
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<td>5.0223</td>
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<tr>
<td>Terzaghi</td>
<td>mlg</td>
<td>5:00-1.60</td>
<td>0</td>
<td>16</td>
<td>24</td>
<td>no_trend</td>
<td>no_pattern</td>
<td>retained</td>
<td>retained</td>
<td>5a</td>
<td>0.05151</td>
<td>0.03338</td>
<td>0.60767</td>
<td>2.313</td>
<td>3.4129</td>
<td>0.05151</td>
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<tr>
<td>Terzaghi</td>
<td>ox</td>
<td>5:1-6.60</td>
<td>1.6</td>
<td>6.6</td>
<td>15</td>
<td>no_trend</td>
<td>no_pattern</td>
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<td>retained</td>
<td>5b</td>
<td>0.26464</td>
<td>0.10776</td>
<td>0.75436</td>
<td>2.6021</td>
<td>3.7813</td>
<td>rejected</td>
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<tr>
<td>Terzaghi</td>
<td>mlg</td>
<td>6:00-6.3</td>
<td>0</td>
<td>6.3</td>
<td>33</td>
<td>no_trend</td>
<td>no_pattern</td>
<td>retained</td>
<td>retained</td>
<td>6</td>
<td>0.13748</td>
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<td>0.13748</td>
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<tr>
<td>Terzaghi</td>
<td>mlg</td>
<td>7:00-5.8</td>
<td>0</td>
<td>5.8</td>
<td>30</td>
<td>trend</td>
<td>no_pattern</td>
<td>retained</td>
<td>retained</td>
<td>7</td>
<td>0.11047</td>
<td>0.07513</td>
<td>1.5068</td>
<td>5.3681</td>
<td>9.0524</td>
<td>rejected</td>
</tr>
</tbody>
</table>

Depending on the distance from the fault, we observe 3 distributions (from the closest) with different skewness:

- normal
- log-normal
- exponential
Statistical analysis of the scanline from photogrammetry (2)

- comparison between $P_{10}$ values and the barcode plot: main scanline and secondary scanlines

→ the main scanline is representative and consistent with smaller “check” scanlines
→ $P_{10}$ values are higher for Middle Globigerina than for Lower Coralline
→ width of the inner damage zone: 120 m
→ presence of fracture corridors at -200 and -400 m from the fault core (0 m) in the Middle Globigerina
Statistical analysis of the scanline from photogrammetry (3)

- comparison between $P_{10}$ values and the barcode plots of field scanlines with those from photogrammetry

  field scanlines have higher $P_{10}$ values

  but

  different detection **scale**:

  drone: 0.10 - 130 m  
  field: 0.01 - 1 m

→ the $P_{10}$ values must be accompanied with the scale of the observed fractures and resolution of the analysis!
Crosscutting and abutting relations between set A and B

→ both sets are coeval and belong to the deformation phase D2
Statistical analysis of the scanline from photogrammetry (4)

subdivision into 2 sets

- NE-SW and ENE-WSW
- N-S and WNW-ESE

→ set A: greater variability
→ set B: much more stable

main fractures sub-parallel to the Victoria Fault,
average spacing 0.98 m

secondary fractures, average spacing 3.17 m
Fracture network analysis (2)

deformation evolution based on spacing distributions (e.g. according to Rives et al. 1992):

- **negative exponential (initial phase)***
- **log-normal (intermediate phase)***
- **normal (final phase)***

- photogrammetry scanline: majority of log-normal
- field scanline: the three phases are observed according to the distance from the Victoria Fault

![Fracture spacing](image-url)
Fracture network analysis (3)

Analysis of the «maturity» stage of fracturing using the mode/mean ratio (Rives et al., 1992)

- values $\to$ 1 indicate saturation
- values $\to$ 0 poorly developed set
Conclusions (1)

Digital Outcrop Model (DOM)

4 sets of fracture:

- NE-SW medium spacing: 2.84 m
- NE-SW medium spacing: 0.81 m
- WNW-ENE medium spacing: 1.45 m
- NE-SW medium spacing: 1.10 m

→ always considering the survey scale
Conclusions (2)

«maturity» of the fault zone as described by fracture statistics

- **exponential distribution**
- **log-normal distribution**
- **normal distribution**

Increasing fracture saturation and fault zone maturity.
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References:
