SEismic Imaging of the Main Crater of the Proposed Sirente Meteorite Crater Field (Central Italy)

Patrizio Torrese, Dipartimento di Scienze della Terra e dell’Ambiente, Università di Pavia, Italy
Angelo Pio Rossi, Department of Physics and Earth Sciences, Jacobs University Bremen, Germany
Mario Luigi Rainone, Ce.R.S.-GEO, Università “G. d’Annunzio” di Chieti-Pescara, Italy
Patrizio Signanini, INGEO, Università “G. d’Annunzio” di Chieti-Pescara, Italy
Gian Gabriele Ori, IRSPS, Università “G. d’Annunzio” di Chieti-Pescara, Italy
Jens Ormø, Centro de Astrobiología (INTA-CSIC), Instituto Nacional de Tecnica Aeroespacial, Spain

Abstract

We present seismic imaging of the subsurface structure of the main crater of the proposed Sirente meteorite crater field (Abruzzo, Central Italy). The crater field has been suggested to have formed by a small meteorite impact and consists of a main, dominant crater (~120 m in diameter) and a group of much smaller craters (~10 m in diameter on average). The main crater has a prominent elevated rim. The crater field is found within lacustrine sediments overlying limestone. Two shallow reflection profiles with P waves were acquired across the structure when the small lake, which occupies the main crater, was ice-covered. Profile RFL 2 is 130 m long and crosses the main structure rim to rim. Profile RFL 1 is 78 m long and roughly transversal to profile RFL 2. Two CMP processing sequences were applied on raw data. A short processing sequence allowed recognition of the main features of the subsurface structure of the crater: a deep (53 m on average), rootless, bowl-shaped geometry, a deep-seated central uplift structure and three different seismic facies representing the infilling of the bowl-shaped basin. These include lateral onlap reflectors may be interpreted as an analogue to the “breccia lens” in craters formed on rocky targets, indicating the occurrence of collapse events (slumping) during the crater modification stage. A long processing sequence allowed a more detailed imaging of the bowl-shaped basin and the structures underlying and surrounding the crater, such as compaction of strata below the rim. The structural features interpreted from our survey are consistent with the impact hypothesis. Apparently, they do not support other proposed mechanisms of formation as the structure seems both rootless and deep.

Introduction

The Sirente crater field consists of a main dominant crater (~120 m in diameter) and a group of much smaller craters (~10 m in diameter on average) and is located in a small half-graben adjacent to the 2500 m high Sirente-Velino Massif (Abruzzo, Central Italy) (Figure 1). The main crater has a prominent elevated rim and is occupied by a small lake that occasionally freezes in winter, whereas, most of the field’s small craters lack elevated rims. The crater field is located in a part of the Sirente plain that is covered by lacustrine sediments (APAT, 2005). The basement below the lacustrine infill consists of limestone. The crater field has been suggested to have formed by a small meteorite impact (Ormø et al., 2002). Other interpretations of the crater field have also been suggested, including karst-related or anthropogenic processes (Ormø et al., 2002; Speranza et al., 2004; Stoppa, 2006).

Various geophysical methods have been used to investigate the internal structure of impact craters (e.g. Pilkington and Grieve, 1992), sinkholes and karst features (e.g. Carrière et al., 2013; Torrese et al., 2014, 2015; Van Schoor, 2002; Zhu et al., 2011). Nevertheless, the literature regarding
geophysical studies of small meteorite crater fields is scarce, in particular high-resolution seismic studies. Literature on seismic studies on karst features is also limited (e.g. Kindinger et al., 1994; Rainone et al., 2015; Torrese et al., 2012).

In order to better understand its origin, we designed and carried out a high resolution reflection seismic survey (Bachrach and Nur, 1998; Baker et al., 1999) and present the seismic imaging of the subsurface structure of the main crater.
**Table 1**: Long Processing Sequence (LPS) and Short Processing Sequence (SPS) applied on raw data in order to obtain the final two-way travel time cross-sections.

<table>
<thead>
<tr>
<th>Processing step</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operation</strong></td>
<td>data import, record conversion from SEG2 to processing format</td>
<td>pre-processing editing</td>
<td>geometry input</td>
<td>AGC</td>
<td>F-K filtering</td>
<td>AGC</td>
</tr>
<tr>
<td>LPS</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Processing step</strong></td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>band-pass frequency filtering</td>
<td>spike deconvolution</td>
<td>band-pass frequency filtering</td>
<td>CDP sorting</td>
<td>elevation static</td>
<td>NMO</td>
</tr>
<tr>
<td>LPS</td>
<td>44-54 ≤f (Hz)≤ 195-205</td>
<td>√</td>
<td>44-54 ≤f (Hz)≤ 195-205</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Processing step</strong></td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>stack</td>
<td>AGC</td>
<td>dip filtering</td>
<td>predictive deconvolution</td>
<td>band-pass frequency filtering</td>
<td>predictive deconvolution</td>
</tr>
<tr>
<td>LPS</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Processing step</strong></td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>band-pass frequency filtering</td>
<td>AGC</td>
<td>dip filtering</td>
<td>band-pass frequency filtering</td>
<td>trace mix</td>
<td>post-processing editing</td>
</tr>
<tr>
<td>LPS</td>
<td>44-54 ≤f (Hz)≤ 195-205</td>
<td>√</td>
<td></td>
<td>44-54 ≤f (Hz)≤ 115-125</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>SPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Material and Methods**

Two P wave shallow reflection profiles (Figure 1) were acquired during winters 2003 and 2005 across the structure when the small lake, which occupies the main crater, was ice-covered. Profile RFL 2 is 130 m long and crosses the main structure rim to rim. Profile RFL 1 is 78 m long and roughly transversal to profile RFL 2. An off-end spread geometry with 12 channels was used with a station and
Figure 2: Two-way time stack cross-section of RFL 2, obtained by applying the Short Processing Sequence (SPS) on raw data.

geophone spacing of 2 m, a source spacing of 2 m and an offset distance of 6 m. Stacking was favored by keeping the arrays short, and given the low depth of investigation a 600% coverage was enough to get a good signal-to-noise ratio. A 24 channels StrataView (by Geometrics) seismometer was used to collect seismic data by performing a roll along sequence with 12 active channels. A heavy metal plate hammered with a 5 kg hammer was used for the generation of compressional waves. The presence of water below the ice cover prevented the use of shear waves (Rainone et al., 2009; Rainone and Torrese, 2007) showing higher resolution than compressional waves (Luzi et al., 2010; Signanini and Torrese, 2004). Vertical stacking enhanced the signal-to-noise ratio by summing a few hammer blows for each shot. Each receiver string was comprised of three 10 Hz vertical geophones arranged along a line that is parallel to the profile in order to obtain an analog filtering of surface waves.

Visual Sunt 12 Pro (by W-GeoSoft) interfacing with Seismic Unix modules (Cohen and Stockwell, 1999) and Seistrix-2 (by Interpex Ltd.) were used to process seismic data. Two CMP (Common-Mid-Point) processing sequences (Table 1) were applied on raw data in order to obtain the final two-way travel time cross-sections: a Short Processing Sequence (SPS) and a Long Processing Sequence (LPS), including F-K and dip filtering to remove ground roll, direct and head waves and strong diffraction hyperbolas affecting the seismic signal. Together with the FK spectrum assessment, a velocity analysis based on the dispersion of Rayleigh waves was performed on selected frequency
Figure 3: Two-way time stack cross-section of RFL 2, obtained by applying the Long Processing Sequence (LPS) on raw data with a line drawing interpretation.

filtered CMP gathers to verify that no surface waves affected the stack cross-sections. The NMO (Normal-Move-Out) velocity model used for stacking was obtained by running a constant velocity scan on the sorted CMP gathers. The interval velocity model (Figure 4) used for time to depth conversion was computed from the stacking velocity model using the DIX formula (Dix, 1955).
The Short Processing Sequence (SPS) allowed the analysis of the main features of the subsurface structure of the crater (Figure 2): a deep (53 m on average) rootless, bowl-shaped geometry typical for exogenic craters (i.e. impact and explosion craters, cf. Melosh, 1989 and references therein), a deep-seated central uplift structure typical of larger, complex impact craters, but known from craters as small as the Sirente main crater when developed in poorly consolidated targets (cf. Jones, 1977; Quaide and Oberbeck, 1968; Roddy, 1976), three different seismic facies representing the infilling of the bowl-shaped basin in which lateral onlap reflectors may be interpreted as an analogue to the “breccia lens” formed at larger natural impact craters in rock, indicating the occurrence of collapse events (slumping) during the crater modification stage. The latter facies is well exposed in the RFL 2 profile.

The Long Processing Sequence (LPS) provided a more detailed imaging of the bowl-shaped basin and structures underlying and surrounding the crater (Figure 3), such as NNE dipping bedrock strata and a compaction-fissure-like feature below the rim (cf. Jones, 1977). Compaction instead of volume-expansion (i.e. down-warping instead of structural uplift below the rim ejecta) is known from explosion craters in porous, unconsolidated targets (see discussion in Ormø et al. 2002). Diffraction hyperbolas affecting the section would be related to the presence of large blocks that likely are derived from rock-falls and avalanches during the deposition of the lacustrine sediments (Ormø et al., 2002).
Comparison between the interpreted cross-sections of RFL 2 profile achieved by applying LPS and SPS shows only slight differences (Figure 4). The structural features shown by RFL 2 profile (Figures 2, 3) are consistent with those shown by the roughly transversal RFL 1 profile.

The interval velocity model (Figure 4) achieved by the NMO velocity analysis is consistent with the velocity model achieved by the refraction seismic profile RFL (Figure 1): poorly consolidated sediments and soft lacustrine sediments filling the crater show a 1170 (RFR) - 1380 (RFL 2) m/s average P wave velocity; limestone bedrock shows a 4200 (RFL 2) – 4230 (RFR) m/s average P wave velocity. Reflection and refraction surveys show the bottom of the bowl-shaped basin at 51 (RFR) – 53 (RFL 2) m of depths, on average, which is consistent with the resistivity imaging revealed by ERT surveys carried out by Speranza et al. (2009) across the main crater. Likewise, the upturned target strata at the wall of the crater just below the inner part of the elevated crater rim (Figures 3 and 4) show similarities with the ERT models by Speranza et al. (2009, Figure 4). This upwards movement of material is inconsistent with the gravity-driven movements of material during karst doline formation, and is instead in strong analogy with the overturning of strata below impact crater rims (cf. Melosh 1989 and references therein).

Conclusions

The structural features interpreted from our survey are consistent with the hypothesis of a small impact crater in a low-strength target, with a relatively shallow apparent crater. These features include a rootless, bowl-shaped subsurface structure of the main crater with a central peak-like feature as well as compaction features below the rim. In addition, a well-developed “breccia lens” consisting of material relocated during the strong collapse of a cavity in incompetent material, is suggesting an impact origin.

The main alternative modes of formation of the Sirente main crater, i.e. anthropogenic cattle pond or karst doline, do not seem to be supported by the seismic data in that the structure is too deep to have been dug out by humans in this highly unstable material, as well as that it is lacking a downwards continuation typical for the underground removal of material during karst development. However, in the absence of shock-metamorphic and/or geochemical evidence of impact, a karst origin or other alternative causes of formation cannot categorically be ruled out.

References

APAT, 2005, Foglio N 368 "Avezzano" della Carta Geologica d'Italia a scala 1:50.000 e note illustrative, Servizio Geologico d'Italia, Istituto Poligrafico e Zecca dello Stato, Roma, Italy.


Torrese P., Rainone M.L., Signanini P., Greco P., Colantonio F., Porel G., Nauleau B., Paquet D., Mari J.L., 2014, 3D ERT imaging of the fractured-karst aquifer underlying the experimental site of

Acknowledgements

The research has been performed with the permit of the Ente Parco Regionale Sirente-Velino. A special thank goes to the Secinaro community and the Sirente-Velino park staff. The research has been financed by Agenzia Spaziale Italiana and the Italian Ministry of University and Research. The authors wish to thank Antonio Baliva, Gaetano Di Achille, Goro Komatsu, Raffaele Madonna and Paolo Sammartino for the precious collaboration.