Using Seismic Attributes in seismotectonic research: an application to the Norcia's Mw=6.5 earthquake (30th October 2016) in Central Italy.

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Abstract. In seismotectonic studies, seismic reflection data are a powerful tool to unravel the complex deep architecture of active faults. Such tectonic structures are usually mapped at surface through traditional geological surveying whilst seismic reflection data may help to trace their continuation from the near-surface down to hypocentral depth. In this study, we propose the application of the seismic attributes technique, commonly used in seismic reflection exploration by oil industry, to seismotectonic research for the first time. The study area is a geologically complex region of Central Italy, recently struck by a long-lasting seismic sequence including a Mw 6.5 main-shock. A seismic reflection data-set consisting of three vintage seismic profiles, currently the only available across the epicentral zone, constitutes a singular opportunity to attempt a seismic attribute analysis. ~~This analysis resulted in peculiar seismic signatures which generally correlate with the exposed surface geologic features, and also confirming the presence of other debated structures.~~ These results are critical, because provide information also on the relatively deep structural setting, mapping a prominent, high amplitude regional reflector ~~that marks~~ the top basement, interpreted as important rheological boundary. Complex patterns of high-angle discontinuities crossing the reflectors have ~~been also~~ identified. These dipping fabrics are interpreted as the expression of fault zones, belonging to the active normal fault systems responsible for the seismicity of the region. This work demonstrates that seismic attribute analysis, even if used on low-quality vintage 2D data, may contribute to improve the subsurface geological interpretation of areas characterized by high seismic potential.

1 Introduction

Studying the connections between the earthquakes and the faults to which they are associated is a primary assignment of seismotectonics (Allen et al., 1965; Schwartz and Coppersmith, 1984). Clearly, this is not an easy task: it is in fact generally complex to fill the gap between the exposed geology including the active "geological faults" mapped by the geologists and

the seismic features describing the geometry and kinematics of the seismic source at hypocentral depth ("seismological faults", e.g. Barchi & Mirabella, 2008).

In case of strong earthquakes, impressive topographic changes and surface ruptures are often reported (e.g. Press and Jackson, 1965; Wyss & Brune, 1967; Jibson et al., 2018; Yi et al., 2018; Civico et al, 2018). While many studies on the surface geology are generally performed, especially after important events, the recovery of deep information on the seismogenic structures is always a challenge, primarily due to the lack of high-resolution geophysical data and/or wells stratigraphy.

This fact generates uncertainties that may amplify the scientific debate and the number of models introduced by the geoscientists. Therefore, this process requires the use of appropriate geophysical data, aimed at recovering information on the deep geological architecture and, in particular, on the geometry of active faults.

Different geophysical methods (e.g. Gravimetry, Magnetics, Electric and Magnetotellurics, Ground Penetrating Radar) may contribute to define the stratigraphy and structural setting of the upper crust at different scales. But the seismic reflection is largely the most powerful tool producing high-resolution images fundamental to trace the actual geometry of active faults at surface (usually mapped and reconstructed in geological cross-sections), from the near surface down to hypocentral depths. However, the ex-novo acquisition of onshore deep reflection data, possibly 3D, is often hampered by environmental problems, complex logistics, and high costs. These issues seriously limit the possible, widespread use of this technique for scientific research. Significant exceptions are research projects for deep crustal investigations like BIRPS (Brewer et al., 1983), CoCORP (Cook et al., 1979), ECORS (Roure et al., 1989) and CROP (Barchi et al., 1998; Finetti et al., 2001), IBERSEIS (Simancas et al., 2003).

Such limitations can be partially overcome by considering old profiles (legacy data) acquired by the exploration industry. When collected in seismically active regions, such data may be used to connect the active faults mapped at the surface with the seismogenic sources depicted by seismological recordings (Boncio et al., 2000; Bonini et al., 2014; Carvalho et al., 2008; Beidinger et al., 2011; Maesano et al., 2015; Porreca et al., 2018). Vintage profiles can therefore significantly contribute to seismotectonic research, even if their location and orientation were not specifically designed with this aim. In addition, seismic technologies and acquisition/processing strategies of some decades ago, produced data with both relatively low signal/noise ratio (S/N) and resolution in comparison to modern data.

To improve the data quality and increase the accuracy of the interpretation, three main strategies can be usually considered: 1) collection of new reflection seismic data with modern technologies, optimizing feasibility studies on the base of available vintage datasets; 2) reprocessing of the old data from raw to new stacks using new and available powerful capabilities and developments and, 3) use post-stack processing techniques such as seismic attributes analysis. These approaches are currently all used by the O&G industry (e.g. in the re-assessment of known reservoirs) and are clearly characterized by different potential, costs and working time.

Some limitations characterize the first two approaches: the first is particularly demanding in terms of costs and logistic, and not practicable in zones where the use of dynamite or arrays of vibroseis trucks is forbidden or limited (e.g. National Parks

or urban areas). The second requires broad projects encompassing specialized teams, high-computation power and generally long processing times, the latter is dependent on the quality of the raw data. The third strategy, in the case of the attribute analysis exploits a well-known and mature technique. It has been used since early 80's by the O&G exploration industry (Chopra & Marfurt, 2005) for geometrical and petrophysical characterization of reservoirs (Chopra & Marfurt, 2008).

A seismic attribute is a quantity derived from seismic data (pre-stack and/or post-stack) that can be calculated on a single trace, on multiple traces, or volumes. This technique is commonly used to extract additional information that may be unclear in a traditional seismic image, therefore leading to a better interpretation of the data. Examples of applications on dense 3D seismic volumes produced spectacular results (Chopra & Marfurt, 2007; Marfurt et al., 2011; Hale, 2013; Barnes, 2016, Marfurt, 2018). Recent developments of approaches based on machine learning techniques are currently pushing it further to contribute towards an objective (automatic) interpretation of seismic data-sets (Wrona et al., 2018; Di & AlRegib, 2019; Naeini & Prindle, 2019). Therefore, among the three strategies, the attribute analysis is probably the easiest, cheapest and fastest to qualitatively emphasize the geophysical features and data properties of reflection seismic data sets in complex geological areas. Due to different well-known limitations and advantages existing between 2D vs 3D seismic data (these are extensively discussed by Torvela et al. (2013) and Hutchinson (2016), 2D seismic attribute analysis of post-stack data may be subjected to possible pitfalls and/or may not bring so impressive improvements in the seismic images. However, the main point is that inland, most of the sedimentary basins have actually been sampled by 2D grids of seismic profiles, or at least they have been probed by a few sparse 2D seismic lines. Hence, it is relevant to extract as much information as possible from these 2D surveys in areas not covered by 3D seismic surveys. Whilst in the hydrocarbon industry this process is useful even if mainly driven by a constant necessity to reduce the costs (Ha et al., 2019), in seismotectonic researches it is affected by even worse limitations previously aforementioned. Therefore, also slight improvements obtained on vintage 2D data may bring to new and unprecedent subsurface information in complex and active tectonic environments. We think that we might successfully export a similar approach in a seismotectonic study applying this type of analysis on an active seismic zone, covered only by a very limited number of 2D seismic lines. Based on such considerations, the selected study area is located in the central Apennines (Central Italy), a region between the southeastern part of the Umbria-Marche Apennines and the Laga Domain in the outer Northern Apennines (e.g. Barchi et al., 2001). This area presents ideal characteristics to test the proposed new approach. In fact, in the past, several seismic profiles were acquired at this location for hydrocarbon exploration, providing good constraints for subsurface geological interpretation (Bally et al., 1986; Barchi et al, 1991; Barchi et al., 1998; Ciaccio et al., 2005; Pauselli et al., 2006; Mirabella et al. 2008; Barchi et al., 2009; Bigi et al., 2011). After the last 2016-2017 seismic sequence, Porreca et al. (2018) have provided a new regional geological model based on the interpretation of vintage 2D seismic lines. In such a study, the authors remark important differences in the seismic data quality across the region. In fact, the eastern area that shows higher overall data quality, is located at the footwall of the Mount Sibillini thrust (MSt) and, includes (consists of) flyschoid units of the Laga foredeep Domain. It is noteworthy that the Mw 6.5 epicentral zone, is located on the MSt hanging-wall (Lavecchia, 1985). This is characterized by prevalent carbonate sequence and, its crossed by seismic sections with lower S/N ratio, that hampered the subsurface interpretation.

99   Therefore, this contribution focuses on three low quality seismic cross-sections located close to the Mw 6.5 main-shock area,

100   aiming to exploit the use of seismic attributes to squeeze additional information. The main goal of this study is to obtain as

101   much information as possible on the geological structures responsible for the seismicity. Therefore, any improvement, that

102   for example can increase the resolution, the definition and/or the lateral continuity of the structural features is a very valuable

103   contribution. The current manuscript is an example of how can seismic attribute analysis contribute to seismotectonic

104   research as an innovative approach.

2 Geological framework and seismotectonics of the study area

106   During the 2016-2017, a wide part of Central Italy has been struck by a complex seismic sequence, characterized by multi-

107   fault ruptures occurred within few months (August 2016 – January 2017) similarly to previous seismic sequences in Central

108   Italy (e.g. L'Aquila and Colfiorito, Valoroso et al., 2013 and Chiaraluce et al., 2005). Nine earthquakes with M>5 and more

109   that 97'000 events in two years have been recorded at hypocentral depth not exceeding 12 km (Fig.1). The strongest

110   mainshock of Mw 6.5 occurred on 30th October 2016 (Chiaraluce et al., 2017; Chiarabba et al., 2018; Gruppo di Lavoro

111   Sequenza Centro Italia, 2019; Improta et al., 2019; ISIDe working group, 2019), generating impressive co-seismic ruptures

112   (Civico et al., 2018; Brozzetti et al., 2019).

113   The study area is located in the easternmost part of the Northern Apennines fold and thrust belt, including the Umbria-

114   Marche thrust and fold belt domain and Laga Formation. This is a geologically complex region, where in the past the

115   analysis of 2D seismic profiles have produced contrasting interpretation of the upper crust structural setting, e.g. thin vs.

116   thick-skinned tectonics, fault reactivation/inversion, basement depth (Bally et al., 1986; Barchi, 1991; Barchi et al., 2001;

117   Bigi et al., 2011; Calamita et al., 2012; Porreca et al., 2018). The Umbria-Marche fold and thrust belt was formed during the

118   Miocene compressive phase, and overthrusts the Laga foredeep sequence, through arc-shaped major thrusts, namely the M.

119   Sibillini thrust (MSt, Koopman, 1983; Lavecchia, 1985), with eastward convexity. The compressional structures were later

120   disrupted by the extensional faults since the Late Pliocene.

121   The Umbria-Marche domain involves the rocks of the sedimentary cover, represented by three main units:

122   1) on top, the Laga sequence consisting of siliciclastic turbidites belonging to the Laga foredeep and foreland Formation

123   (Milli et al., 2007; Bigi et al., 2011); it is made by alternating layers of sandstones, marls and evaporites (Late Messinian –

124   Lower Pliocene, up to 3000 m thick, average seismic velocity (v_{av})= 4000 m/s), mainly outcropping in the eastern sector of

125   the study area (i.e. at the footwall of the MSt).

126   2) in the middle, carbonate formations (Jurassic-Oligocene, about 2000 m thick, v_{av}= 5800 m/s) formed by pelagic

127   limestones (Mirabella et al., 2008) with subordinated marly levels overlying an early Jurassic carbonate platform (Calcare

128   Massiccio Fm.)

129   3) at the bottom, Late Triassic evaporites (1500–2500 m thick, v_{av}= 6400 m/s), consisting in alternated layers of anhydrites

130   and dolomites (Anidriti di Burano Fm. And and Raethavicula Contorta beds; Martinis & Pieri, 1964), never outcropping and

131 intercepted, only, by deep wells (Porreca et al., 2018 and references therein), representing the main ad deeper detachment of

132 the region.

133 An underlying basement of variable lithology (v_{av} = 5100 m/s) that never crops out (Vai, 2001), was intercepted by deep

134 wells (Bally et al., 1986; Minelli & Menichetti, 1990; Anelli et al., 1994; Patacca & Scandone, 2001) and, it is separated by

135 the aforementioned units by the aforementioned important regional decollement.

136 In a such complex structural setting, the Late Pliocene-Quaternary extensional tectonic phase, characterized by a prevalent

137 NE-SW stretching direction, produced NNW-SSE striking WSW-dipping normal faults. These faults were also responsible of

138 the tectono-sedimentary evolution of intra-mountain continental basins (Calamita et al., 1994; Cavinato and De Celles, 1999).

139 The most evident Quaternary basins of this part of the Apennines are the Castelluccio di Norcia (CNb) and Norcia (Nb) basins,

140 located respectively at 1270 and 700 m a.s.l. They have been subjected to a lacustrine and fluvial sedimentation of hundreds

141 of meters characterized by fine clayey to coarse grained deposits (Blumetti et al., 1993; Coltorti and Farabollini, 1995).

142 The area is affected by historical and instrumental seismicity with frequent small to moderate magnitude earthquakes (4 <

143 Mw < 7, Boncio and Lavecchia, 2000; Rovida et al., 2016). The recent 2016-2017 seismic sequence has been caused by the

144 activation of a complex NNW-SSE trending fault system, characterized by prevalent high-angle WSW-dipping normal faults

145 (Lavecchia et al., 2016). More in detail, the easternmost fault system of the region recently activated is the NNW-SSE

146 trending "Monte Vettore fault system" (Vf). This was the responsible of the mainshock nucleation between the continental

147 Norcia (Nb) and Castelluccio di Norcia basins (CNb) (Fig. 1). Nb and CNb are two asymmetrical grabens, bordered by high-

148 angle WSW-dipping normal faults located on their eastern flanks. Both fault systems are thought to have high seismogenic

149 potential and able to generate earthquakes up to Mw 7.0 (e.g. Barchi et al., 2000; Basili et al., 2008; Rovida et al., 2016;

150 DISS Working Group, 2018).

151 The Nb master fault (Nottoria-Preci fault, Nf) is considered responsible of the 1979 earthquake (Deschamps et al., 1984;

152 Brozzetti & Lavecchia, 1994; Rovida et al., 2016) and possibly associated to multiple historical events (Galli et al., 2005;

153 Pauselli et al., 2010; Galli et al., 2018), including the 1703 (Me = 6.8, Rovida et al., 2016). The CNb master fault (Vf) and its

154 secondary splays activated during the 2016-2017 sequence (e.g. Wilkinson et al., 2017; Villani et al., 2018a) were already

155 known and mapped due to paleo-seismological and shallow geophysical evidences (Galadini & Galli, 2003; Galli et al.,

156 2008; Ercoli et al., 2013; Ercoli et al., 2014). However, despite of the large amount of surface data collected (Livio et al.,

157 2016; Pucci at al., 2017; Wilkinson et al., 2017; De Guidi et al., 2017; Brozzetti et al., 2019; Galli et al., 2018), the deep

158 extension of the Norcia and Castelluccio faults (particularly the Vf) ,and the overall complex structure of the area are still

159 debated (Lavecchia et al., 2016; Porreca et al., 2018; Bonini et al., 2019, Cheloni et al., 2019, Improta et al. 2019).

160 **3 Data**

161 We have performed the seismic attributes analysis on three W-E trending 2D seismic reflection profiles crossing the

162 epicentral area between the Umbria and Marche regions (Central Italy, Fig.1). Such 2D data are part of a much larger,

163 unpublished dataset including 97 seismic profiles and few boreholes, drilled for hydrocarbon exploration by ENI in the

164 period 1970-1998.

165 The data quality is extremely variable (medium/poor) with limited fold (generally < 60 traces / Common Mid-Point - CMP)

166 mainly due to environmental and logistical factors like: acquisition technologies, limited site access, complex tectonic

167 setting, and different (contrasting) outcropping lithologies like Carbonates and Quaternary sediments that resulted often in

168 low S/N recordings (e.g. Mazzotti et al., 2000, Mirabella et al., 2008).

169 The analysed lines include: NOR01 (stack, 14 km long), NOR02 (time-migrated, 20 km long, partially parallel to NOR01 on

170 the western sector), and CAS01 (stack, 16 km long), located more to the south (Fig. 1). NOR01 and CAS01 were acquired

171 using a Vibroseis source, whilst explosive was used for NOR02; all the lines are displayed in Two-Way-Travel-Time

172 (TWTT) limited to 4.5 s. The average frequency spectra display bandwidths ranging from few Hz up to 60-70 Hz, whilst

173 NOR02 extends up to 100 Hz. Assuming the average peak frequency of 20 Hz, a vertical resolution of ca. 80 m can be

174 estimated (average carbonate velocity = 6 km/s, parameters in Table 1s, supporting information). Some processing artefacts

175 (A) are visible in NOR01 as a straight horizontal signal at ca. 1 s (Fig. 2a), and two others sub-horizontal between 1-2 s in

176 CAS01 (Fig. 1s-a, supporting information). However, some seismic events and lineaments, related to geological structures of

177 interest, are slightly visible and their display seems potentially improvable with a proper choice of seismic attributes type

178 and parameters. Therefore, we loaded the lines into the OpendTect (OdT) software, setting up a common seismic datum

179 equal to 500 m while adding some ancillary data, extracted by a complementary GIS (QGis software) project including:

180 regional fault patterns (from maps and Ithaca database), a regional DTM (Tarquini et al., 2007; Tarquini et al., 2012),

181 geological maps (Pierantoni et al., 2013; Carta Geologica Regionale 1:10'000 – Regione Marche, 2014; Carta Geologica

182 Regionale 1:10'000 – Regione Umbria, 2016), as well as mainshock earthquakes distribution belonging to the studied

183 seismic sequence (Iside database). The integration of such information in a pseudo-3D environment offered us a

184 multidisciplinary platform to clearly display the seismic lines and to link surface data and the deep geologic structures at

185 hypocentral depth.

4 Methods

187 The seismic reflection data interpretation is generally accomplished through the definition of specific signal characteristics

188 (seismic signature), supported by the geological knowledge of the study area. A standard seismic interpretation is affected by

189 a certain degree of uncertainty/subjectivity (particularly in case of poor data quality), because generally based on a

190 qualitative analysis of reflection amplitude, geometry and lateral continuity. Over the last years, the introduction of seismic

191 attributes and related automated/semi-automated procedures had an important role in reducing the subjectivity of seismic

192 interpretation, at first in 2D/3D seismic reflection data (Barnes 1996; Taner et al., 1979; Barnes, 1999; Chen and Sidney,

193 1997; Taner, 2001; Chopra and Marfurt, 2007; Chopra and Marfurt, 2008; Forte et al., 2016) and, more recently, also in

194 other reflection techniques like the Ground Penetrating Radar (GPR) (e.g. McClymont et al., 2008; Forte et al., 2012; Ercoli

195 et al., 2015, De Lima et al., 2018). In this work, we have tested several post-stack attributes on three 2D vintage seismic

6

196　lines, also using composite multi-attribute displays. Among those analysed, we selected the three attributes that resulted in

197　the best images, making possible to detect peculiar seismic signatures of regional seismogenic layers and fault zones. Details

198　about the calculated attributes are hereafter provided.

199

200　**"Energy" (E):** one of the RMS amplitude-based attributes, it is defined as the ratio between the squared sum of the

201　sample values in a specified time-gate and the number of samples in the gate (Taner, 1979, Chopra & Marfurt,

202　2005, Chopra & Marfurt, 2007). The Energy measures the reflectivity in a specified time-gate, so the higher the

203　Energy, the higher is the reflection amplitude. In comparison to the original seismic amplitude, it is independent of

204　the polarity of the seismic data being always positive, and in turn preventing the zero-crossing problems of the

205　seismic amplitude (Forte et al., 2012, Ercoli et al., 2015, Lima et al., 2018, Zhao et al., 2018). This attribute is

206　useful to emphasize the most reflective zones (e.g. characterization of acoustic properties of rocks). It may also

207　enhance sharp lateral variations in seismic events, highlighting discontinuities like fractures and faults. In this work,

208　we set a 20 ms time window (i.e. about the mean wavelet length), obtaining considerable improvements in the

209　visualization of higher acoustic impedance contrasts.

210　**"Energy gradient" (EG)**: it is the first derivative of the energy with respect to time (or depth). The algorithm

211　calculates the derivative in moving windows and returns the variation of the calculated energy as a function of time

212　or depth (Chopra & Marfurt, 2007; Forte et al., 2012). It is a simple and robust attribute, also useful for a detailed

213　semi-automatic mapping of horizons with a relative low level of subjectivity. The attribute acts as an edge detection

214　tool, effective in the mapping of the reflection patterns as well as the continuity of both steep discontinuities like

215　faults and fractures, and channels, particularly in slices of 3D data (Chopra & Marfurt, 2007). In this work, we have

216　used the same time window of the Energy, obtaining considerable improvements in the visualization not only of the

217　strong acoustic impedance reflectors but particularly in the faults imaged in the shallowest part of the seismic

218　sections.

219　**Pseudo-relief (PR):** it is obtained in two steps: the energy attribute is first computed in a short time window, then

220　followed by the Hilbert transform (phase rotation of -90 degrees). The Pseudo-relief is considered very useful in 2D

221　seismic interpretation to generate "outcrop-like" images allowing an easier detection of both faults and horizons

222　(Bulhões, 1999; Barnes et al., 2011; Vernengo et al. 2017, Lima et al., 2018). In this work, considerable display

223　improvements have been obtained using the Pseudo-relief computed in a window of 20 ms. In comparison to the

224　standard amplitude, it better highlights the reflection patterns and thus the continuity/discontinuity of reflectors,

225　enhancing steep discontinuities and fault zones.

226　**5 Results**

227　The comparison between the original seismic lines and the images obtained after the attribute analysis allows to detect

228　considerable improvements in the visualization and interpretability of the geophysical features. In profiles NOR01, CAS01

229 and NOR02 (Figs 2, 3 and 4, respectively) we focus our analysis on three main types of geophysical features highlighted by

230 the attributes: sub-horizontal deep reflectors, low-angle and high-angle discontinuities.

231 Analysing in detail the line NOR01 (Fig. 2a, line location in the excerpt on the top), the most apparent low-angle

232 geophysical features are located in the eastern portion of the line between 2-3 s of the time window. The EN attribute in Fig.

233 2b clearly enhances a high-amplitude, gently W-dipping event at about 2.5 s (blue arrows). The EG and SR attributes of

234 NOR01 show clearly that this horizon (Figs. 2c, 2d, hereafter H) is characterized by a continuous package of reflectors (ca.

235 200 ms in TWT, ca. 8 km long), with common characteristics in terms of reflection strength and period.

236 A similar feature showing such a peculiar signature is visible also in CAS01, approximately at the same time interval (Fig.

237 3a, line location reported on the top insert). But in comparison to NOR01, it appears more discontinuous all along the

238 seismic profile, and in addition it is partially interfering with suspicious processing artefacts (highlighted with yellow dots,

239 labelled as "A", slightly undulated in Fig. 3a whilst horizontal in Fig. 2a ca. at 1 s). For those reasons, H is not particularly

240 clear in the standard amplitude line CAS01 (Fig. 3a), even if it is mainly visible on the westernmost side and beneath the

241 southern termination of Nb (ca. between 11-15 km). Despite a generalized high frequency noise content, H is better

242 enhanced in fig. 3b by EN attribute (blue arrows), and in particular by the EG and PR attributes (Figs. 3c and 3d), that

243 considerably help to better detect and mark its extension and geometry.

244 Regarding the most visible steep geophysical features detectable in these two seismic profiles, in NOR01 a high-angle E-

245 dipping lineament is defined by a clear high-angle discontinuity of the seismic signal, particularly enhanced in the eastern

246 sector (distance ca. 10 km) below the Nb (red arrows in fig. 2c and 2d). A very similar high-angle East-dipping discontinuity

247 can be noticed in the eastern sector of CAS01 (red arrows in Fig. 3c and 3d). Another main high-angle W-dipping lineament

248 is enhanced in Figs. 2c-2d of NOR01 (red arrows at the end of the line), that clearly divides two patterns of reflectors

249 showing different dip; this discontinuity propagates down to ca. 2.5 s and intercepts the aforementioned strong reflector H.

250 Between those two main alignments bounding the Nb, other similar but minor discontinuities can be also noticed crossing

251 and slightly disrupting the shallower reflectors: those high angle features are efficiently displayed by the EG and PR

252 attributes (Fig. 2c, 2d), whilst in the original line in Fig. 2a cannot be really appreciated.

253 The figure 4a display the original seismic line NOR02 characterized by similar geophysical features (location on the top

254 insert). The EN attribute in Fig. 4b again results efficient in enhancing sub-horizontal (blue arrows) and also gently dipping

255 deep events (green dots). On the western sector, the attributes in Figs. 4b and 4c show a pattern of relatively continuous and

256 gently W-dipping events between 0-2.5 s (0-5 km along the line). The most evident high-amplitude and continuous reflector

257 characterizes the central part of NOR02 at ca. 3.2–3.5 s (blue arrows in Figs. 4b, 4c, 4d), gently East-dipping and relatively

258 continuous for more than 8 km. This latter is intercepted by an important and well visible low-angle W-dipping discontinuity

259 (T, green dots in Figs. 4b, 4c and 4d). It crosses the entire profile, rising from about 4 s (West) to ca. 2 s (East), where it

260 intercepts one of the high amplitude events on the eastern end of the seismic line (18-20 km). Here again the attribute

261 analysis results extremely efficient to clearly detect such geophysical features otherwise poorly visible on the original line

262 NOR02 in Fig. 4a.

263 The most important result provided by the EG and PR attributes is a much clear visualization of the reflection patterns of

264 NOR02, aiding an easier detection of high-angle discontinuities, at different scales. In fact, a main high-angle E-dipping

265 discontinuity (red arrows) delimits the NOR02 western sector (ca. 1 km of distance along the line at surface); another steep

266 W-dipping alignment (red arrows) clearly cuts and slightly disrupt the set of reflectors below the Nb (0-2.5 s, ca. 4-5 km). In

267 addition, smaller discontinuities pervasively cross-cut the set of reflectors between 1-4 km bounded by such two main

268 features, producing a densely fragmented reflectors pattern in the middle portion. Another steep E-dipping feature is visible

269 at higher depth (red arrows at 1-3 s, ca. 7-9 km) beneath the topographic relief separating Nb by CNb: it seems to end up on

270 the deep surface T and in addition it doesn't reach the shallower portion of the seismic line. This discontinuity is subparallel

271 to a similar structure displayed in a more central portion of NOR02 (western side of CNb highlighted by red arrows at 10-12

272 km). The Figs. 4c and 4d show here sets of reflectors sharply interrupted, fragmented and displaced in a narrow zone. The

273 same seismic pattern is present in the western side of CNb, but it is due to some west-dipping discontinuities located

274 between 14-16 km. These features highlight an asymmetric "V-shape" fabric characterized by very short and fragmented

275 reflectors bounded by those two steep features of opposite dip. The deep continuation of such a main W-dipping alignment

276 also seems to truncate and disrupt both the gently-dipping discontinuity T and the deep reflector H: at approximately 3.2 s, it

277 appears interrupted laterally on its western side (Figs. 4c and 4d).

278 The results of this work produced has globally improved the interpretability of the original dataset. In particular, the data

279 integration in a 3D environment and the use of multi-attribute displays clarified the deep geometries of the main reflectors

280 and of the geophysical discontinuities, later interpreted on the light of the known and debated tectonic structures on the study

281 area. This is particularly clear in Fig. 5a, in which we report the seismic line NOR02 after the combined plot of the PR

282 attribute ("similarity" palette) with superimposed the EG attribute ("energy" palette), overlapped using ODT software (depth

283 conversion with V_{Pav} = 6000 m/s, vertical scale 2x). The reflectors characteristics and the discontinuities are clearly visible at

284 different levels of detail, and the two boxes (blue and black colours, respectively) highlight on the two most representative

285 seismic facies described before. The blue box of Fig.5a is reported in Fig. 5b and 5c by displaying a comparison of the H

286 signature in the original line and a plot of the EN attribute superimposed on the PR attribute. On the two other inserts in Figs.

287 5d and 5e, the same comparison of the data included in the black box is proposed. Fig.4d shows the scarce detectability of

288 the dense pattern of steep discontinuities in the original seismic profile (SA). The Fig.5e displays the enhancement obtained

289 plotting the PR attribute ("similarity palette") in transparency on the seismic line in amplitude (SA).

290 An analogous visualization is proposed in Fig. 6a for the seismic line NOR01. The comparison between the multi-display of

291 attributes PR and EG (blue box in Fig. 6a), the original line (Fig. 6b) and the EN+PR plot (Fig.6c) shows the improved

292 signature of the strong reflector H. The black box again reports the original line NOR01 and the version PR+SA, clearly

293 boosting the visualization of the high-angle discontinuities.

294 Such results therefore ensure an easier and more accurate interpretation of the subsurface geological structures; those are

295 connected with the surface geology and related to the hypocentre location of the main seismic events, that will be discussed

296 more in detail within the following chapter.

6 New constraints on the deep geological structure reconstruction

Due to the lack of 3D seismic volumes and of a regular grid of 2D seismic profiles in the area, the geological meaning of the results provided by the attributes analysis have been constrained by integrating all the other available literature data. We have therefore integrated geological and structural maps (Koopman, 1983; Centamore et al., 1993; Pierantoni et al., 2013), high-resolution topographic data (Tarquini et al., 2007 and 2012), mainshocks hypocentral data (Chiaraluce et al., 2017) and co-seismic surface ruptures data (Civico et al., 2018; Villani et al., 2018; Brozzetti et al., 2019).

In fig. 7, a 3D overview of the study region summarizes the data analysed across the area surrounding the Mw 6.5 mainshock (30th October 2016), plotted together with other three strong seismic events in the Northern sector. The two seismic images in Figs. 7b and 7c have been obtained by using again a multi-attributes visualization, in this case overlapping the PR and EN attributes in transparency with the original seismic lines NOR01 and NOR02. The black boxes centred on the NB and CNb basins have been magnified above and display the limits of the bounding faults (black dashed lines) and the main important reflectors detected in depth. In the Figs. 7d and 7e, we propose a detailed interpretation of the geophysical features displayed by the attribute images, together with the location of the focal mechanisms of the principal mainshocks.

The deep, high-amplitude reflector (H, blue arrows and dashed line) highlighted to the West of Nb in NOR01 (at 2.5 s, in Figs. 2d and 7d and in Figs. 3d of CAS01), presents an attribute signature similar to the one deeper visible in NOR02 beneath CNb (3.2 s, in Figs. 4b and 7e). This set of reflectors are interpreted as a high acoustic impedance contrast, possibly related to an important velocity inversion occurring between the Triassic Evaporites (anhydrites and dolostones, Vp ≈ 6 km/s, e.g. Trippetta et al., 2010) and the underlying acoustic Basement (metasedimentary rocks, Vp ≈ 5 km/s, sensu Bally et al., 1986). Similar, prominent reflections were detected in adjacent regions of the Umbria-Marche Apennines (e.g. Mirabella et al., 2008) confirming its regional importance, particularly because it represents a lithological control marking a seismicity cutoff (Porreca et al., 2018; Mancinelli et al., 2019).

The continuity of the deep reflector H is interrupted in the western edge by the low-angle west-dipping T discontinuity crossing NOR02 (Figs. 4d and 7e), not identified by Porreca et al. (2018). We interpret this discontinuity as the evidence of a deep thrust emerging in the easternmost sector of the region.

The steep discontinuities highlighted by the attribute analysis are here interpreted as the seismic signature at depth of complex normal faults mapped at the surface. More in detail, the most evident seismic discontinuity is marked by an E-dipping fault in NOR01, bordering westward the Nb (Figs. 2d and 7d). The latter does not have a clear surface expression and therefore its presence is still debated in literature (Blumetti et al., 1993; Pizzi et al., 2002; Galadini et al., 2018; Galli et al., 2018): its location and geometry in NOR01 perfectly match the supposed position at surface. Therefore, it may represent the evidence of the antithetic normal fault of Norcia (aNf), belonging to a conjugate tectonic system (Brozzetti & Lavecchia, 1994; Lavecchia et al., 1994) and suggested by morphological evidences (Blumetti et al., 1990) and paleoseismological records (Borre et al., 2003). It is a synthetic (W-dipping) high-angle, normal fault bordering the eastern flank of Nb ("Nottoria-Preci fault" – Nf, Calamita et al., 1982; Blumetti et al., 1993; Calamita & Pizzi, 1994). The Nf in NOR02 is

10

330   evident by a downward propagation of steep alignments (red arrows, Figs. 2c, 2d and 7d), that generates sharp lateral

331   truncations of the gently W-dipping reflectors. This area is also fragmented by several minor strands parallel to the main

332   faults (Figs. 7d). In addition, another similar structure is visible slightly eastward (Figs.4c, 4d red arrows between 7-9 km,

333   ca. 1-3 s and westernmost dashed black line in Fig. 7e). It is not reaching the shallower portion of the seismic line, but it is

334   clearly visible in depth down to the discontinuity T. This feature might be interpreted as a parallel E-dipping fault, moreover

335   suggested by several authors to be connected with an aftershock (Mw5.4), that "ruptured a buried antithetic normal fault on

336   eastern side of Nb, parallel to the western bounding fault of CNb" (Chiaraluce et al., 2017, Porreca et al., 2018 and Improta

337   et al., 2019).

338   The central sector of NOR02 including CNb, was described as a "triangle-shaped zone" by Porreca et al. (2018), who remark

339   a generalized difficulty to detect the accurate position of the normal faults. The multi-attribute visualization shows a clear

340   reflection fabric dominated by high-angle discontinuities. Those are interpretable as two opposite dipping normal faults

341   bordering the basin, well matching their positions mapped at surface (cfr. Pierantoni et al., 2013).

342   The main fault is here represented by the W-dipping Vf fault, reactivated during the 2016 earthquake (Villani et al., 2018a).

343   It can be traced, from its surface expression downward to hypocentre location along its deep seismic signature, made by

344   several high-angle seismic discontinuities cross-cutting the gently W-dipping reflectors (Figs. 4d and 7e). At depth, the Vf

345   seems also to displace the Top Basement (H) and the thrust (T) at about 3.2 s.

346   Analogous considerations can be extended to the E-dipping set of steep events at the westward side of CNb. These may

347   represent evidence of an antithetic fault (aVf), made by several minor fault strands (Villani et al., 2018b). Such a fault

348   appears connected at about 2-3 s to the W-dipping master Vf, producing a geometry of a conjugate system similar to Nb

349   (Figs. 4d and 7e).

350   For both Nb and CNb, the interpreted data suggest two slightly asymmetric fault systems, due to conjugate sets of

351   seismogenic master faults (Ramsay & Huber, 1987) producing a "basin-and-range" morphology (Serva at al., 2002). Those

352   control the evolution of the continental basins, and are associated with several complex sets of secondary strands, able to

353   produce surface ruptures as occurred in the 2016-2017seismic swarm.

354   The attribute images produced in this work suggest that such synthetic and antithetic tectonic structures at the Nb and CNb

355   cannot be actually simplified as a unique fault plane, but as complex and fractured fault zones (Fz, in Fig. 7d), like also

356   conceived also by Ferrario & Livio (2018) as "distributed faulting and rupture zones".

Conclusions

358   Taking into account the important role that seismic attributes play in the O&G industry their usage might be similar interest

359   for seismotectonic studies. And have a high potential impact on earthquakes hazard assessment.

360   This contribution presents one of the first case studies where the seismic attribute analysis is used for seismotectonic purposes.

361   The analysis is applied to seismic reflection data collected more than 30 years ago in Central Italy. Such industrial data,

362 nowadays irreproducible in regions where the seismic exploration is forbidden, represent, despite the limited quality, a unique

363 high-resolution source of information.

364 This contribution reveals that the use of seismic attributes can ~~greatly~~ improve the interpretation for the subsurface assessment

365 and structural characterization. Certainly, the overall low quality of the data sets did neither allow to extract rock petrophysical

366 parameters, nor more quantitative information. However, the attributes aid the seismic interpretation to better display the

367 reflection patterns of interest and provided new and original details on complex tectonic region in Central Italy. We

368 considerably improved the overall interpretability of the vintage seismic lines crossing the epicentral area of the 2016-2017

369 Norcia-Amatrice seismic sequence. In particular, we detected peculiar seismic signatures of a deep horizon of regional

370 importance, corresponding, most probably, to the base of the seismogenic layer, and to the location and geometry of the

371 complex active fault zones. Those consists of several secondary synthetic and antithetic splays in both the Quaternary basins,

372 generally consistent with its surface location, but also reinforcing the existence of faults with no clear surface outcrop, issue

373 currently much debated in the literature.

374 The analysis and integration of the seismic attributes has allowed the determination of the deep continuation of the (known

375 and supposed) faults and, the recently mapped co-seismic ruptures at surface, providing a pseudo-3D picture of the buried

376 structural setting of the area. The seismic attributes may help to reduce the gap between the surface geology and deep

377 seismological data, also revealing, a high structural complexity at different scales, that cannot generally be detected by using

378 only traditional interpretation techniques.This approach has shown the potential of the attributes analysis , that even when

379 applied on 2D vintage seismic lines, may significantly extend the data value. For all these reasons, we strongly encourage its

380 application for seismotectonic research to provide new information and additional constraints across other seismically active

381 regions around the world.

Acknowledgments

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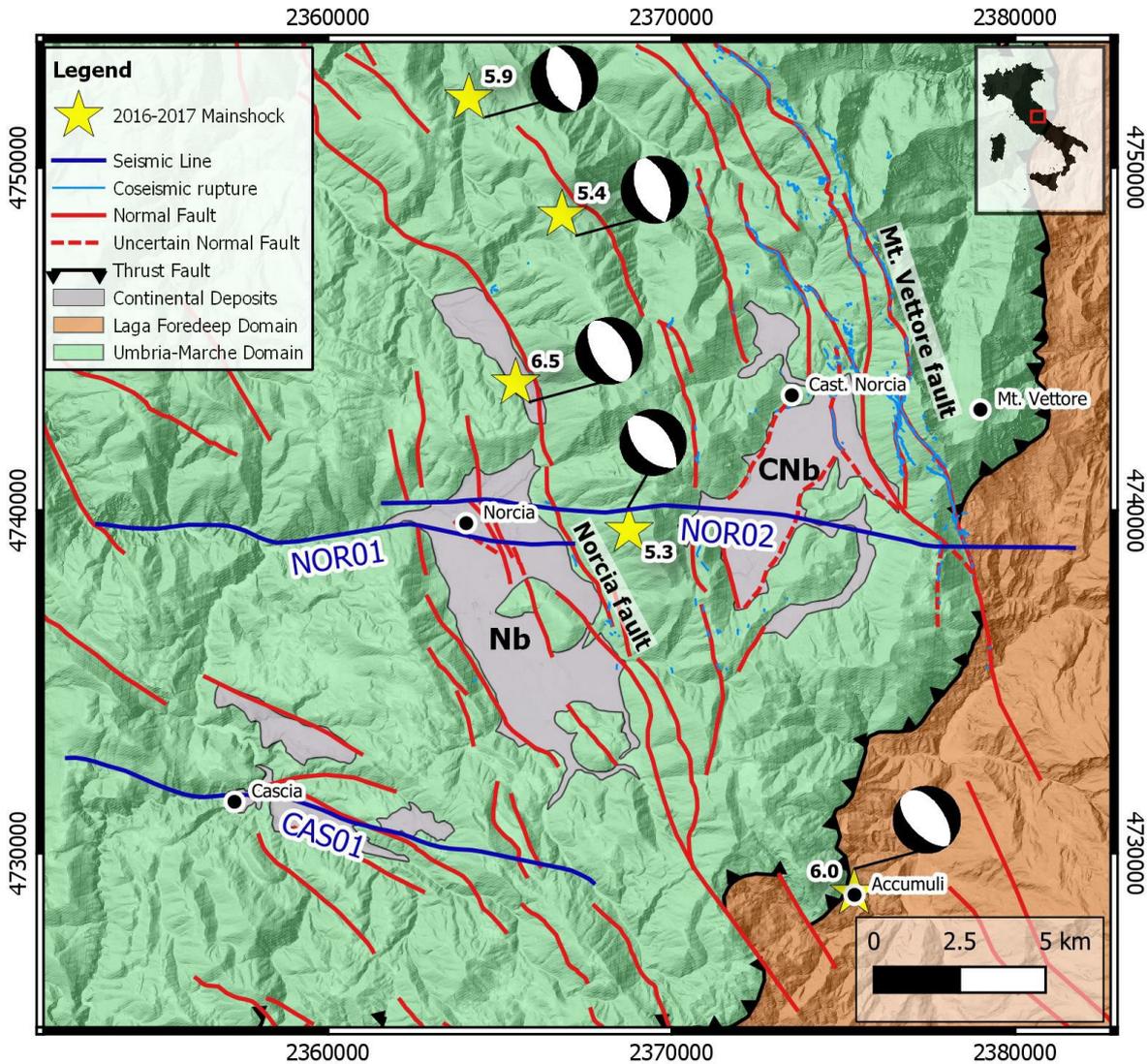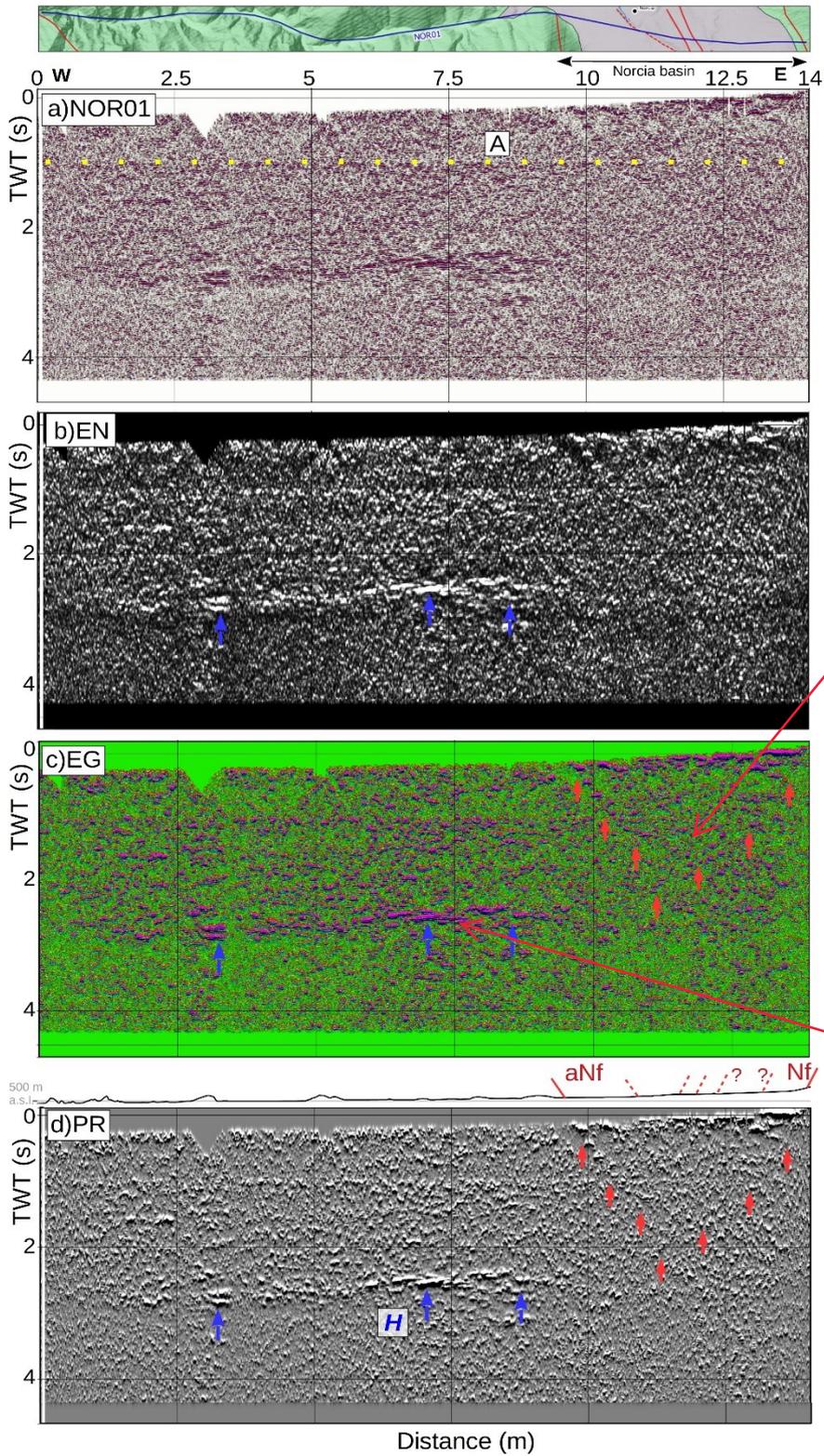
660 ---

Figure 1

Figure 2

665   Distance (m)   **Figure 3**

666

Figure 4

24

667

Figure 5

668

Figure 6

669

670
671

a)

these beachballs have not been projected onto the 3D perspective. it could be misleading... you can simply report them in sections as done for the Mw 6.5 event.

Mw 6.5
301017

Mw 5.9
261017

Mw 5.4
261017

Visso

Castelluccio
di Norcia

Mt.
Vettore

CNb

N

Mw 5.3
240817

NOR02

B'

B

A'

NOR01

Norcia

Nb

5 km

W   Nb   E
aNf   Nf
0   ?
(s)   ?
2,5   H ~7 km   d)

W   CNb
aVf   Vf
0
Fz   Fz
(s)   ?   ?
3.2   Mw 6.5   T
      H ~9 km   e)

0

3.2
s

b)   Nb

2,5 s   c)   CNb

1s
2 km

1s
2 km

A   A'   B   B'

672
673   Figure 7
674

26

675   **Table 1**
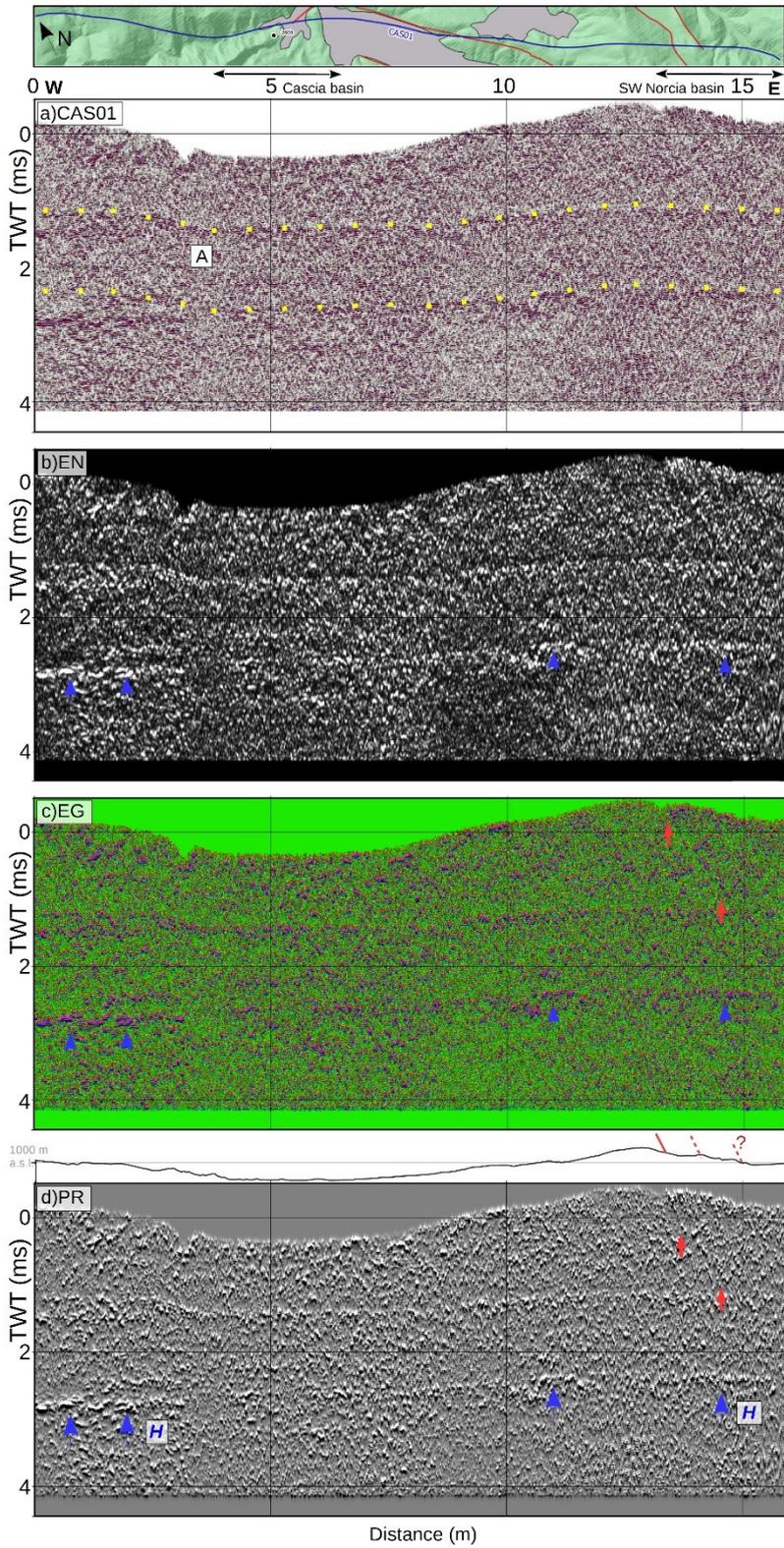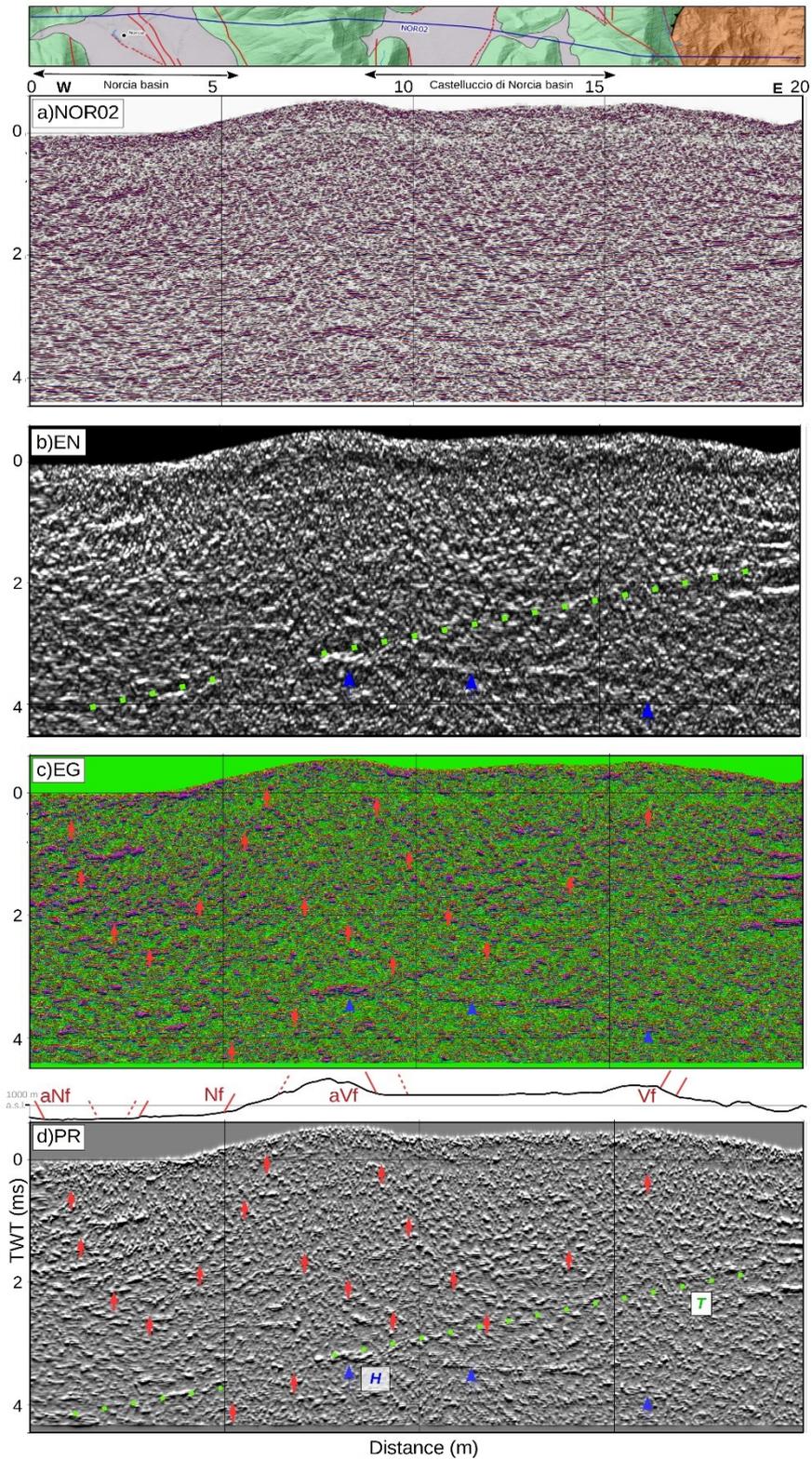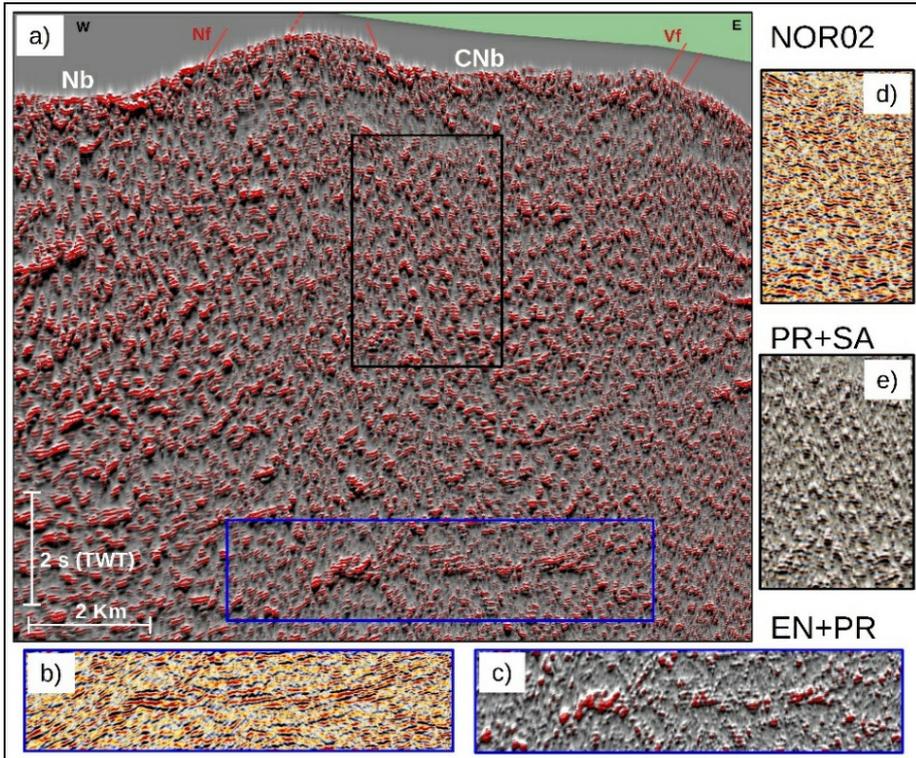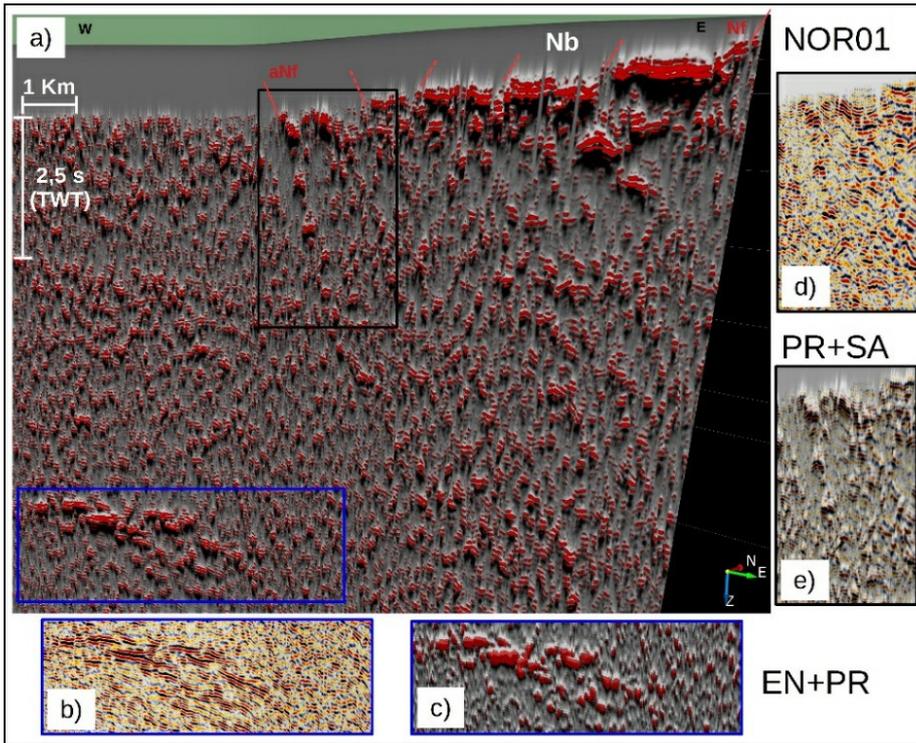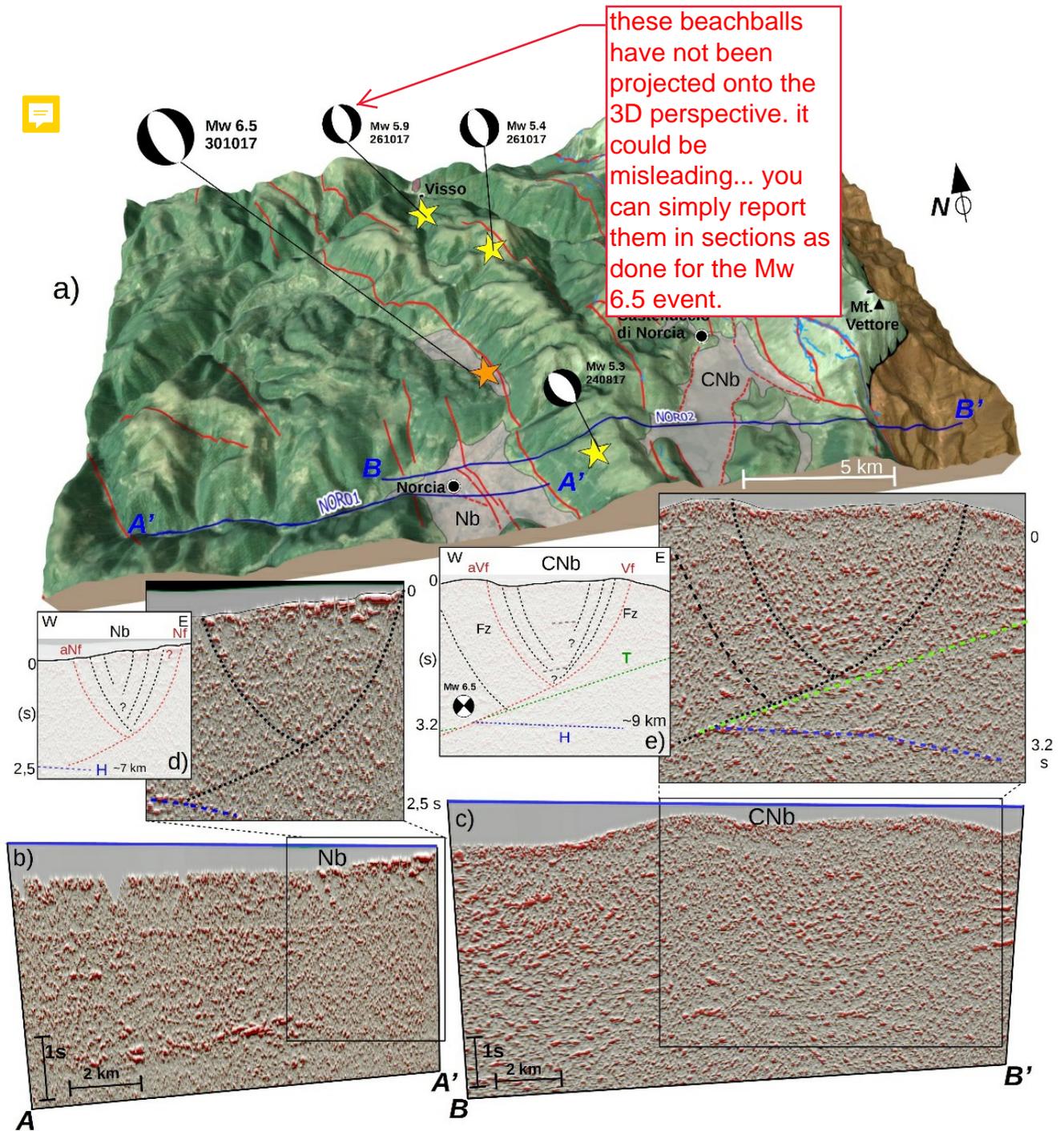
Parameters	NOR01	NOR02	CAS01
Source	Vibroseis	Vibroseis	Explosive
Length (km)	14	20	16
Number of traces	938	825	1069
Samples/trace	1600	1750	1600
Time window (ms)	6400	7000	6400
Sampling interval (ms)	4	4	4
Trace interval (m)	15	25	15
Mean Spectral amplitude (dB)			
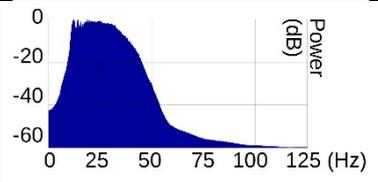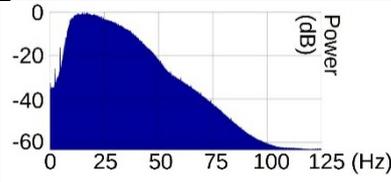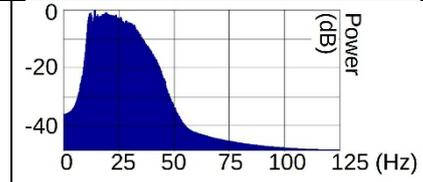
676

677   **Figures and Tables captions:**

678   Figure 1: Simplified geological map of the study area (modified after Porreca et al., 2018), showing the 2D seismic data tracks, the
679   2016-2017 mainshock locations, beachballs and magnitudes, the surface ruptures and the known master faults. Nb Norcia basin,
680   CNb Castelluccio di Norcia basin.

681   Figure 2: Stack version of NOR01; a) reflection amplitude, yellow dots underline a processing artefact (A); b) Energy attribute
682   enhancing a strong reflectivity contrasts (H, blue arrows); c) Energy Gradient, improving the detection of dipping alignments and
683   continuity of reflectors; d) Pseudo-Relief enhancing the reflection patterns cross-cut by steep discontinuities (red arrows). Nf Norcia
684   fault, aNf antithetic Norcia fault.

685   Figure 3: Stack version of CAS01, with same attributes computation: a) reflection amplitude (yellow dots display processing
686   artefacts); b) Energy attribute c) Energy Gradient attribute; d) Pseudo-Relief, showing the strong regional reflector H (blue arrows).
687   A high-angle discontinuity on the western margin is interpretable as a normal fault, showing an attribute signature analogous to
688   aNf.

689   Figure 4: Time migrated version of NOR02; a) reflection amplitude; b) Energy attribute displaying the reflector H (blue arrows)
690   and a possible low angle discontinuity (T, green dots); c) Energy Gradient attribute, showing the master faults bounding the basins
691   (red arrows); d) Pseudo-Relief, improving the reflectors continuity/discontinuity and the master faults display (red arrows). Nf
692   Norcia fault, aNf antithetic Norcia fault; Vf Mt. Vettore fault, aVf antithetic Mt. Vettore fault.

693   Figure 5: Multi-attribute display of NOR02; a) EN+PR attributes, the seismic facie in the blue box is compared with the original
694   seismic line (b) and EN+PR (c) for comparison; the same plot for the black box is reported in figures d) and e) (original line and
695   PR+SA, respectively).

696 **Figure 6: Multi-attribute display of NOR01; a) EN+PR attributes, the seismic facie in the blue box showing a strong set of deep**
697 **reflectors is compared with the original seismic line in b) and EN+PR c). An analogous plot of the black box reports in figures d)**
698 **and e) the original line and the combination PR+SA.**

699 **Figure 7: Integration of surface and subsurface data (DTM by Tarquini et al., 2012); a) 3D-view of a W-E section crossing Nb and**
700 **CNb, and the mainshock locations (ISIDe working group, 2016). Surface and deep data allow to correlate the master faults and**
701 **coseismic ruptures at the surface. The multi-attribute display of NOR01 (b) and NOR02 (c), is obtained overlapping the reflection**
702 **amplitude in transparency with the Pseudo-Relief and Energy attributes (red palette). A significative improvement of the subsurface**
703 **images provides unprecedent details on the seismogenic fault zones: the two conjugate basins show master faults along the borders**
704 **and some minor synthetic and antithetic splays (see d) and e) sketches).**

705 **Table 1: List of some parameters extracted from SEG-Y headers and three mean frequency spectra of the three seismic lines. An**
706 **approximate vertical resolution equal to 80 m was derived (v=6 km/s).**