



37 **Abstract:**

38 The Ofanto basin is a Pliocene-Pleistocene thrust-top basin that formed with an  
39 unusual E-W orientation along the frontal part of the Southern Apennine  
40 Allochthonous (SAA) during the latest stages of tectonic transport. Its tectonic and  
41 sedimentary evolution was studied integrating field surveys, biostratigraphic  
42 analyses and the interpretation of a large seismic grid. Well data and seismic  
43 interpretation indicate that a large E-W trending normal fault underlies the  
44 northern margin of the basin, displacing the Apulian carbonates that form the  
45 foreland and the footwall of the SAA. In our reconstruction the Ofanto basin  
46 formed at the rear of the bulge caused by buttressing of the SAA against this  
47 normal fault. In a second stage of contraction, the footwall of the SAA was  
48 involved in deformation with a different trend from normal faulting and buttressing.  
49 This caused eastward tilting of the basin and broad folding around its eastern  
50 termination. Good stratigraphic constrains permit defining as Early Pliocene the  
51 age of buttressing, and as Early Pleistocene the shortening in the Apulian  
52 carbonates. This work highlights the importance of early-orogenic normal faults in  
53 conditioning the evolution of the frontal parts of orogenic wedges.

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57 **Supplementary material:** A 3D reconstruction of the base of the Pliocene  
58 deposits of the Ofanto basin, based on seismic interpretation, is available at  
59 [www.geolsoc.org.uk/SUP-----](http://www.geolsoc.org.uk/SUP-----).

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61 The Southern Apennines of Italy are a relatively young orogenic belt that formed  
62 during the Neogene-Quaternary subduction of oceanic domains of the Neo-Tethys  
63 along the southern margin of the Alpine suture (Golonka 2004; Edwards &  
64 Grasmann 2009; Schettino & Turco 2010). During subduction, the original  
65 paleogeographic domains of the Neo-Thetys - Adria region were piled up, forming  
66 the Southern Apennine Allochthonous (i.e. Calabrian p.p., Sicilides, Apennine  
67 carbonate platform and Lagonegro basinal units), and eastwards thrust over the  
68 Apulia carbonate platform that forms the easternmost domain of Adria (Fig. 1)  
69 (Mostardini & Merlini 1986; Casero et al. 1988; Finetti et al. 2005; Vezzani et al  
70 2010). In the last 7 Ma, the leading edge of the Southern Apennines  
71 Allochthonous (SAA) migrated hundreds of kilometres toward the east (Scrocca et  
72 al. 2005; Edwards & Grasmann 2009) and was accompanied by the opening of  
73 the Tyrrhenian back-arc basin on its hinterland side. Both processes are thought  
74 to be driven by the roll-back of the subducting Neo-Thetyan (Ionian) oceanic  
75 lithosphere (Malinverno & Ryan 1986; Kastens et al. 1988; Doglioni 1995).  
76 Coeval to the migration of the SAA, Pliocene marine sediments deposited over the  
77 translating thrust sheets and recorded in their sedimentary evolution the  
78 deformation of the underlying thrust sheets as they emplaced over the Apulian  
79 foreland (Bonardi et al 2009; Vezzani et al. 2010). Pliocene thrust-top deposits are  
80 distributed over wide areas of the north-eastern part of the Southern Apennines,  
81 with the Ofanto synclinorium forming one of the largest outcrops (Fig 1). The study  
82 of these basins provides information on the interactions between the advancing  
83 frontal thrust sheets and the flexured Apulian foreland (Fig. 2), which is known to  
84 be affected by different processes such as bending, buckling and normal faulting

85 (Sella et al. 1990; Doglioni 1994; Mariotti & Doglioni 2000; Bertotti et al. 2001; Billi  
86 & Salvini 2003; Butler 2009).

87 The E-W trend of the Ofanto synclinorium represents an anomaly in the regional  
88 NW-SE structural trend of the Southern Apennines (Vezzani et al. 2010). Different  
89 hypotheses have been proposed to explain this anomaly. According to Ortolani  
90 (1974) major blind strike-slip faults oriented SW-NE underlie the eastern and  
91 western ends of the Ofanto basin and distort with left-lateral movement the NW-  
92 SE oriented regional folds of this portion of the Apennines. Alternatively, Hyppolite  
93 et al. (1994) proposed that the Ofanto basin formed in its present orientation,  
94 following to the development of E-W oriented ramp-flat-ramp system in the units  
95 underlying the Southern Apennine Allochthonous, in Early-Mid Pliocene times. In  
96 addition, Hyppolite et al. (1994) point out that evidence for extensional tectonics is  
97 lacking in the basin fill deposits and the sparse extensional faults measured in the  
98 basin are related to sediment compaction. On the contrary Patacca and Scandone  
99 (2007), based on seismic interpretation propose the existence of large normal  
100 faults defining the northern margin of the Ofanto basin, which acted during the  
101 deposition of the younger part of the basin fill (post 2.5 Ma, Late Pliocene).

102 The present paper integrates geological and biostratigraphic studies of the  
103 synorogenic Ofanto basin with the interpretation of about 300 km of reflection  
104 seismic lines and well data to define: a) the tectonic geometry of the region  
105 underlying and surrounding the Ofanto basin; b) the age of basin formation and its  
106 syntectonic deformation, based on new biostratigraphic results; c) the interactions  
107 between frontal thrust sheets and the Apulia foreland region affected by the roll-  
108 back process, and d) the contribution of this study into the larger scale  
109 understanding the Southern Apennine compressive belt.

110

## 111 **GEOLOGICAL SETTING**

112 The present-day Ofanto basin is a wide E-W trending synclinorium, about 30 km  
113 in length, located in the axial zone of the chain immediately north of the Picentini  
114 Mts / Marzano Mt carbonate relieves (Fig. 1). The substratum of this Pliocene  
115 basin is formed mainly by Mesozoic to Miocene pelagic units of the SAA, with  
116 overlying Late Miocene siliciclastic deposits of the Castelvetero flysch (Fig. 3).  
117 The main structural elements exposed at surface, affecting both the Allochthonous  
118 thrust sheets and to a smaller extent the Pliocene deposits, are represented by  
119 folds and thrusts oriented E-W to WNW-ESE, becoming NW-SE around the  
120 easternmost portion of the Ofanto basin (Fig. 3). Large segments of the southern  
121 and northern margins of the basin are characterised by thrusts and backthrusts,  
122 respectively, which bring the pre-Pliocene substratum over the basin-fill deposits.  
123 In some cases, these faults are sutured by younger deposits of the basin.

124 At the eastern end of the basin is the Mid-Late Pleistocene Vulture Volcano (0.67-  
125 0.13 Ma, Bonadonna et al. 1998). The products of this volcano, which are  
126 considered of 'orogenic' magmatism (i.e. subduction-related, Lustrino et al. 2011),  
127 cover the Pliocene deposits of the Ofanto basin and record WNW-ESE, left-lateral  
128 strike slip deformation, which constitute the latest contractional tectonic events of  
129 the Apennines (Schiattarella et al. 2005). The carbonate reliefs to the south and  
130 south-west of the Ofanto basin (Fig. 3) are part of the Triassic to Miocene  
131 Apennine carbonate platform (Casciello et al. 2006a), which was incorporated into  
132 the SAA in Early-Mid Miocene times (Vezzani et al. 2010). The age of thrusting of  
133 the SAA over the Apulian Carbonate Platform underlying at depth the Ofanto  
134 basin (Fig.2) is constrained by well data indicating a post Early Pliocene age for

135 the regional-scale superposition (Fig. 4). The direction of tectonic transport of the  
136 SAA is not known directly in the study area, however structural data from tectonic  
137 windows in the Picentini Mts. indicate an approximately northwards direction of  
138 shortening (Pappone & Ferranti 1995; Casciello et al. 2006b; Pappone et al.  
139 2009). During the Pliocene-Quaternary, the Apulian carbonate platform itself was  
140 deformed and reverse faults breached the basal thrust of the SAA (Boccaletti &  
141 Guazzone 1974; Cello & Mazzoli 1999). Tectonic underplating of Apulian  
142 carbonates gave rise to a largely buried thrust belt (Apulian belt, in Cello et al.  
143 1989) that developed in an inner position with respect to the leading edge of SAA,  
144 originating an orogen-scale duplex geometry (Fig. 2) (Mostardini & Merlini 1986;  
145 Cello & Mazzoli 1999). Remarkably, the buried Apulian belt in map view is shaped  
146 as a sequence of minor arcs of 100 km scale order, aligned in a NW-SE direction  
147 (Casero et al. 1988; Nicolai & Gambini 2007; Esetime 2009; Vezzani et al. 2010),  
148 which represent the main target in oil exploration. The deposits of the Ofanto  
149 thrust-top basin are coeval to the final stages of migration of the SAA and to the  
150 later deformation of the Apulian carbonates.

151

## 152 **THE OFANTO BASIN INFILL**

153 The filling of the Ofanto syncline is composed by regressive Pliocene deposits of  
154 the Ariano Unit resting unconformably on the pre-Pliocene substratum (Ippolito et  
155 al. 1973; D'Argenio et al. 1975). Marine marly clays in the lower part of this unit  
156 are followed by coastal and alluvial sands and conglomerates towards the top.  
157 Remarkably, conglomerate bodies that were thought to represent the closure term  
158 of the basin fill (D'Argenio et al. 1975) are only present along the northern and  
159 eastern margins of the basin, further away from the topographically-elevated axial

160 part of the chain. Biostratigraphic data on calcareous nannoplankton indicate that  
161 the western and central parts of the Ofanto syncline are filled by Early Pliocene  
162 deposits (NN15, NN16 Zones) while the eastern part of the basin is younger,  
163 exposing Late Pliocene deposits (NN18 Zone; Gelasian) (Hyppolite et al., 1994;  
164 Bonardi et al. 2009; Giannandrea et al. 2009; Ascione et al. 2011). A modern  
165 stratigraphic analysis of the basin fill is available only for the eastern half of the  
166 basin (Giannandrea et al. 2009) where six unconformity-bounded units were  
167 defined, comprising marine to continental deposits of Pliocene to Early  
168 Pleistocene age.

169 In order to integrate and homogenize stratigraphic information for the entire  
170 basin 10 stratigraphic sections were sampled for analyses on planktonic  
171 foraminifera and field surveys were made throughout the basin. Biostratigraphic  
172 dating was aimed primarily at defining the age of conglomerate bodies along the  
173 basin's northern margin that can be used as markers for relative sea-level  
174 changes (Palladino et al. 2011). Sites of sampling and results of biostratigraphic  
175 analyses are shown in figure 3. The main outcome of this study is the recognition  
176 of three generations of conglomerates, spanning in age from Early Pliocene to  
177 Early Pleistocene and characterised by an approximately centrifugal distribution  
178 with respect to the E-W trend of the Ofanto syncline (Fig. 5).

179 The oldest conglomerates are fan-delta deposits exposed in the area of the  
180 Andretta village (Fig. 3). These conglomerates rest directly over the pre-Pliocene  
181 substratum and are stratigraphically overlain by transgressive marly-silty clays  
182 containing *G. puncticulata* (MPL4a - Early Pliocene). The Andretta basal  
183 conglomerate displays a clear southwards dip evidenced by a 15° tilted lacustrine  
184 interval comprised between coarse conglomerate beds (Casciello & Cesarano,

185 2000). Retrogradational fan-delta conglomerates that correlate to the Andretta  
186 deposits are distributed over large areas of the Southern Apennines (Ciarcia et al.  
187 2003; Palladino et al. 2011; Fig. 1) documenting a generalized subsidence during  
188 the late Early Pliocene (Ascione et al. 2011).

189 The second generation of conglomerates in the basin infill is found in the central  
190 part of the Ofanto syncline, creating high topographic relief around the Cairano  
191 and Calitri villages (Fig. 3). This younger generation of deltaic conglomerate  
192 bodies rest above the *G. puncticulata* marly clays and displays erosional basal  
193 contact marked by a slight angular unconformity. The observed exposures of  
194 basal strata around the Cairano village are characterised by decimetre-scale clay  
195 clasts composed by the same *G. puncticulata* mudstones that form the  
196 conglomerate substratum, indicating strong erosion of the source area.

197 Paleocurrent observations from imbricate clasts and sole marks at the base of  
198 arenaceous beds indicate a sediment supply mostly from the north.

199 The third and youngest generation of conglomerate is found around the eastern  
200 and western extremes of the Ofanto syncline. Planktonic associations containing  
201 *G. inflata* (MPL6 - latest Pliocene) were found in samples extracted from  
202 mudstones immediately underlying these conglomerates (Fig. 3) suggesting a  
203 Late Pliocene-Early Pleistocene age for the overlying rudite. While for the eastern  
204 conglomerates (i.e. Toppo Pescione) these results confirm calcareous  
205 nannoplankton datings provided by Hyppolite et al. (1994), and confirmed by  
206 Ascione et al. (2011) the western conglomerate exposures around the Guardia  
207 Lombardi village result younger than previously dated.

208

209 *UNCONFORMITY BOUNDED UNITS OF THE EASTERN PART OF THE BASIN*

210 In the eastern half of the basin a detailed stratigraphic analysis was performed by  
211 Giannandrea et al. (2009), resulting in the definition of six unconformity-bounded  
212 units encompassing the entire basin fill. This interpretation is used here to  
213 complement the stratigraphic framework of the Ofanto basin, with a special  
214 emphasis on the Late Pliocene deposits.

215 Comparison between the unconformity-bounded units of Giannandrea et al.  
216 (2009) and the subdivision adopted in the present study (Fig. 5) indicates overall  
217 correspondence, except for the youngest deposits, where a more detailed  
218 subdivision is proposed by Giannandrea et al. (2009). Within the third generation  
219 of conglomerates overlying the *G. inflata* mudstones, these authors differentiate  
220 two conglomerate bodies separated by an erosional angular unconformity. The  
221 lowermost body, composing the Difesa Synthem (Fig. 5), is a marine fan delta fed  
222 from NW that comprises grain-supported conglomerates in its proximal part and  
223 finer deposits with marine fossils in its distal south-eastern portion. The overlying  
224 Monte Sirico Synthem is composed by conglomerates and finer continental  
225 sediments that deposited with a slight angular unconformity over an erosional  
226 surface. Paleocurrent measures within these deposits show a radial, depocenter-  
227 directed pattern clearly testifying for an endorheic basin (Giannandrea et al 2003).  
228 The two described synthems (Difesa, Monte Sirico), which make up the third  
229 generation of conglomerate recognised in the basin (Fig. 5), document clearly the  
230 transition from marine to continental conditions which occurred in the Ofanto basin  
231 around the Pliocene-Pleistocene boundary (~ 1.8 Ma). Above these deposits only  
232 the Mid Pleistocene volcanic products of Mt. Vulture are present.

233

234 **SEISMIC INTERPRETATION**

235 The subsurface structural setting of the Ofanto basin was investigated using  
236 borehole data and the interpretation of a 2D seismic grid with a total length of  
237 approximately 300 km (Fig. 4). The primary objective of this analysis is to define  
238 the geometry of two key surfaces: 1) the base of the Pliocene infill of the Ofanto  
239 basin, and 2) the top of the Apulian Carbonate Platform.

240 The reconstruction of the base of the Ofanto basin was carried out transferring the  
241 exposed boundaries of the base of the Pliocene, reported by 1:100.000 scale  
242 geological maps, along the seismic sections. Seismic interpretation of the base of  
243 the Pliocene succession was facilitated by its well-layered seismic facies  
244 contrasting with the noisy signal containing interspersed anonymous horizons,  
245 which characterises the underlying Southern Apennine Allochthonous units. The  
246 complexity of these latter thrust units is due to their composite nature, comprising  
247 deepwater successions of the Lagonegro basin and Miocene siliciclastics of older  
248 foreland and thrust top settings (Pescatore, 1988; Vezzani et al. 2010), and to  
249 their poly-deformed history with remarkable shortening (e.g. Pappone & Ferranti,  
250 1995; Mazzoli et al., 2001). Seismic interpretation in this structural level was  
251 aimed essentially at the identification of structures that affect the overlying  
252 Pliocene deposits.

253 For the reconstruction of the top Apulian surface the Monte Forcuso1-2 and the  
254 Ciccone1 wells were used to calibrate the top of the carbonate platform (Fig. 4).  
255 Picking of top Apulian horizons started from calibrated lines, extending  
256 progressively across intersecting-points of the grids, guided also by the  
257 recognition of the high amplitude low frequency double event that characterises  
258 the seismic signal of the top Apulian surface (Shiner et al. 2004; Nicolai &

259 Gambini 2007). The poor quality of seismic signals at the top of the Apulian  
260 Platform does not permit a univocal interpretation of individual fault planes.  
261 Therefore, in this structural level the picking of horizons and the mapping were  
262 focused preferentially on the reconstruction of the structural relief of the top  
263 Apulian horizon.

264 The results of this analysis of seismic data are illustrated by 5 line drawings of  
265 seismic sections traversing the Ofanto syncline in a SW-NE direction (Figs. 6, 7)  
266 and by a 3D model constructed in CAD environment using all the available data  
267 (Fig. 8).

268

#### 269 *SHALLOW STRUCTURE OF THE OFANTO BASIN*

270 The Pliocene filling of the Ofanto basin is clearly imaged in the seismic sections,  
271 being characterized by strong and continuous reflectors. The five parallel line  
272 drawings of figure 6 illustrate a progressive deepening of the basin from west to  
273 east, which is in agreement with the eastwards younging of the deposits exposed  
274 at surface (Fig. 3). However, despite the eastward deepening the plan-width of the  
275 basin remains fairly constant along its axis (E-W direction), displaying an average  
276 N-S width of 7-10 km. All the studied seismic sections show an overall asymmetry  
277 of the basin's profile with the northern margin more steeply inclined than the  
278 southern one. Except for line A, which traverses the basin in its western  
279 termination and presents a lower quality, all studied sections show that the base  
280 of the Pliocene basin is involved in thrust deformation. The southern and northern  
281 margins are deformed by north-verging thrusts and by south-verging back-thrusts,  
282 respectively, that have also been recognised in field-based studies (Fig. 3)  
283 (Casciello & Cesarano, 2000; Giannandrea et al. 2009). Along the southern

284 margin, the activity of these thrusts produces shallow marginal depocentres  
285 connected to the main basin (Fig. 6B-C). On the opposite side, back-thrusts  
286 affecting the northern shoulder of the basin are more evident showing larger  
287 apparent displacements and contributing to the steeper conformation of the  
288 basin's northern margin.

289 Deformation during Pliocene deposition is documented also by angular  
290 unconformities in the basin fill and by the shifting of depocentres through time. In  
291 lines B, D of figure 6 depocentres are located in the northern side of the basin and  
292 appear to progressively migrate southwards, as noted by Hippolyte et al. (1994),  
293 in response to the uplift of the northern shoulder of the basin. Uplift of the northern  
294 margin also correlates well with evidence of strong erosion of the Early Pliocene  
295 *G. puncticulata* mudstones along the northern margin and its re-deposition as clay  
296 clasts in the second generation of conglomerates (Fig. 5), as observed in the area  
297 of Cairano village. Section D displays an approximately homogeneous southwards  
298 growth of the basin; on the contrary, the easternmost section (line E in Fig. 6)  
299 presents a more complex architecture, with packages of reflectors that diverge  
300 alternatively to the south and to the north and the younger part of the section, up  
301 to the Late Pliocene-?Pleistocene conglomerate, dipping homogeneously to the  
302 NE. This late-stage north-eastwards tilt of the basin fill was suggested to be  
303 related to the growth of an antiformal stack within the Lagonegro allochthonous  
304 units (S. Fele antiformal stack) causing also the thickening of the Southern  
305 Apennine Allochthonous in this area (Hippolyte et al., 1994; Patacca & Scandone,  
306 2007).

307

308 *DEEP STRUCTURE OF THE OFANTO BASIN*

309 The deep structural elements of the studied area are formed by the Apulian  
310 Platform Unit, which lies below the Southern Apennine Allochthonous and  
311 represents the lowermost tectonic unit of the Southern Apennines (Fig. 2). At a  
312 regional scale, well data indicate that the top of the Apulian carbonate platform is  
313 a diachronous level varying in age from Early Cretaceous (Acerno 1 well) to  
314 Miocene (Melfi1, Lavello 4-5; Fig. 4). This surface is locally covered by Messinian  
315 evaporites and by siliciclastic intervals spanning in age from Early Pliocene to  
316 Late Pliocene-Quaternary towards the foreland area (Fig. 2). The diachronous age  
317 of the top Apulian Platform suggests a structural and morphological relieve prior to  
318 burial by the migrating Allochthonous units. This is in agreement with seismic and  
319 field evidence of major normal faults, both pre-orogenic (Mesozoic) and syn-  
320 orogenic (Neogene), dissecting the Apulian Platform in the Central and Southern  
321 Apennines (Scisciani et al. 2001, Calamita et al. 2010).

322 Seismic sections indicate that a large normal fault in the Apulian carbonates is  
323 present below the northern margin of the Ofanto syncline (Fig. 7). The M. Forcuso  
324 1 and the Ciccone 1 wells (Fig. 4) are drilled in the footwall and hangingwall of this  
325 normal fault and intercept the top of the Apulian Platform at depths of 1100 m and  
326 2500 m respectively, indicating a vertical displacement exceeding 1 km. In  
327 addition, the Ciccone 1 well encounters a lower Pliocene breccia in the  
328 hangingwall of the normal fault that suggests a Late Miocene – Early Pliocene age  
329 for this normal fault. Conversely, the lack of Pliocene deposits and of the post-  
330 Cretaceous section in the wells M. Forcuso 1 and 2 suggest erosion of the uplifted  
331 footwall block.

332 The fault-throw of the normal fault is confirmed in all sections along the studied  
333 grid and allows the reconstruction of an E-W ESE-WNW fault-trend, dipping

334 towards the south (Fig. 7). The fault displacement does not propagate up-dip into  
335 the Allochthonous, presenting a fault-tip at the level of its basal thrust, indicating  
336 that normal fault activity occurred prior to its emplacement. The basal thrust  
337 surface of the Allochthonous units displays smooth trajectories across the step  
338 produced by the normal fault, manifested by inclined reflectors connecting points  
339 of the top Apulia platform in the hangingwall to the footwall cut-off (Fig. 6).

340 A different set of structures involving the Apulian carbonates is represented by  
341 reverse/thrust faults, and associated folds, which displace the basal thrust of the  
342 Allochthonous. These contractional structures are thus posterior to the  
343 emplacement of the SAA thrust sheets. The overall trend of these thrusts in the  
344 Apulian carbonate platform is NW-SE, with branches that display NNW-SSE  
345 orientation and local arched geometries (Fig. 7). Due to their different trends the  
346 contractional structures cross-cut and displace the normal fault (Fig. 8), so that its  
347 eastern part is uplifted in the thrust's hangingwall (Fig. 6A) while the western part  
348 of the normal fault remains in the footwall of the contractional structure (Fig. 6B,  
349 C, D, E.). Thrust imbricates within the Apulian carbonate platform and the  
350 associated ramp anticlines result in an overall structural uplift of the top Apulian  
351 surface by 1.2-1.8 seconds twt with respect to the footwall (Fig. 7).

352

## 353 **DISCUSSION**

354 The most evident structural elements exposed at surface are represented by folds  
355 and thrusts oriented E-W to WNW-ESE, becoming NW -SE around the  
356 easternmost portion of the Ofanto basin (Fig. 3). These orientations are in  
357 agreement with paleostress reconstructions provided by Hyppolite et al. (1994),  
358 which indicate three main directions of maximum compression: N 170° (i.e. N

359 350°) and N 25° during the Pliocene, and N70° in Early Pleistocene. However,  
360 when comparing the orientation of surficial structures (Fig. 3) to the trend of  
361 contractional faults in the buried Apulian carbonates (Fig. 7) a noticeable  
362 mismatch becomes apparent. Thrusts affecting the Apulian platform are in fact  
363 oriented predominantly NW-SE, agreeing in orientation only to the latest  
364 contractional event, Pleistocene in age, identified by Hyppolite et al. (1994).  
365 E-W trending surficial structures, however, correspond to the orientation of the  
366 normal fault in the Apulian carbonates (Fig. 7), which forms a structural step with 1  
367 km throw just below the northern margin of the Ofanto basin. Seismic  
368 interpretation indicates that this normal fault pre-dates the emplacement of the  
369 Southern Apennines Allochthonous (i.e. the fault does not propagate across the  
370 basal thrust of the SAA). Therefore it seems reasonable to suggest that the  
371 escarpment of this large normal fault played a significant role during the  
372 emplacement of the Allochthonous. In this scenario the approximately E-W  
373 trending thrusts and back-thrusts that bound the Ofanto syncline to the south and  
374 to the north can be interpreted as accommodation structures related to the  
375 buttressing of the Southern Apennines Allochthonous against this structural step  
376 during its translation towards the foreland (Fig. 9). The resulting structural setting,  
377 characterized by thrust systems with opposing senses of vergence resting on a  
378 common detachment surface (Fig. 6), may be assimilated to a large triangle zone  
379 (Erickson, 1995; Couzens-Shultz et al., 2003) with the Ofanto syncline located at  
380 the apex of the triangle. The timing of this main phase of Allochthonous translation  
381 and buttressing is comprised between the lowermost Pliocene age of the  
382 underthrust deposits containing *Sphaerodinellopsis* (Ciccione 1 well in Fig. 4;  
383 stage A in Fig. 9), and the uppermost Early Pliocene age of the *G. puncticulata*

384 mudstones involved in buttressing-related thrust deformation (stage C in Fig. 9). It  
385 is worth highlighting that the youngest generation of conglomerate (i.e. Toppo  
386 Pescione and Guardia Lombardi in Fig. 5) of Late Pliocene-?Early Pleistocene  
387 age, does not show E-W trending, buttressing-related structures.

388 In a later phase of shortening, the Apulian carbonates in the footwall of the SAA  
389 became involved in contractional deformation and regional NW-SE trending  
390 reverse faults (Fig. 7) developed, cutting through the basal thrust of the  
391 Allochthonous units (stage E in Fig. 9). These NW-SE trending Apulian thrusts,  
392 corresponding to the frontal structures of the Buried Apulian Belt (Casero et al.  
393 1988; Cello et al. 1989; Eserime, 2009), generate an eastward slope in the top  
394 Apulian carbonates that compose the hangingwall of the normal fault (Fig. 8). This  
395 eastward tilt of the top Apulian carbonates is mirrored at shallower depth by a  
396 corresponding eastward deepening of the base of the Ofanto basin (Fig. 3 and 3D  
397 model of the base of the Pliocene, in supplementary material). We therefore  
398 propose that the overall eastward axial plunge of the Ofanto syncline is related to  
399 the deep structuring of the Apulian carbonates.

400 The age of north-eastwards thrusting in the Apulian platform, and consequently of  
401 the eastwards tilt of the Ofanto syncline, is certainly posterior to the main phase of  
402 Allochthonous translation and buttressing (Early Pliocene), and may correspond to  
403 the age of formation of the large open syncline oriented NW-SE, found in the  
404 eastern termination of the Ofanto basin (Fig. 3). This syncline deforms the third  
405 and youngest generation of conglomerates (Toppo Pescione), which overlie the  
406 *G. inflata* mudstones (Fig. 5) and is therefore almost certainly of Pleistocene age.

407 The youngest contractional structures in the studied area are represented by  
408 WNW-ESE left-lateral strike slip faults that deform volcanic deposits of Mt. Vulture

409 and are sealed by younger volcanic products ( $484 \pm 8$  ka; Schiattarella et al.  
410 2005). Based on kinematic compatibility with north-eastwards shortening in the  
411 Apulian carbonates, we consider this youngest contractional deformation (up to  
412 mid-Pleistocene in age) as a late-stage expression of NE directed tectonic  
413 shortening.

414

#### 415 *COMPARISON WITH OTHER PLIO-PLEISTOCENE BASINS OF THE* 416 *SOUTHERN APENNINES*

417 Immediately to the north and to the east of the study area, other thrust-top  
418 deposits are present that are time equivalent to those analysed in the Ofanto  
419 basin (Fig. 1). Correlation with the deposits exposed around the Ariano Irpino area  
420 (Ciarcia et al. 2003; Di Nocera et al. 2006) and in the Acerenza area (Palladino et  
421 al. 2011) permits integrating the tectono-sedimentary evolution of the Ofanto basin  
422 into a more regional perspective. Conglomerate bodies in particular, can be  
423 correlated throughout these thrust-top basins (Fig. 5), reflecting the regional scale  
424 of the processes that control the formation or destruction of accommodation space  
425 along the front of the southern Apennines (Palladino et al. 2011). In all thrust-top  
426 basins a basal alluvial fan-delta conglomerate is followed by a generalised  
427 drowning documented by Early Pliocene (MPL4a) clays containing *G. puncticulata*  
428 (stage B in figure 9), reflecting relative sea-level rise and narrowing of the  
429 emerged areas (Ciarcia et al. 2003; Palladino 2011).

430 Around the end of biozone MPL4a, coeval to buttressing in the Ofanto basin  
431 (stages B and C, in figure 9), syn-sedimentary contractional deformation is also  
432 recorded in the Acerenza and Ariano Irpino areas. Relative sea-level drop and  
433 emersion of approximately NW-SE trending ridges of pre-Pliocene substratum is

434 accompanied by deposition of a younger generation of fan-delta conglomerate  
435 equivalent to the II generation of conglomerate (Cairano-Calitri, Figs. 3, 5) of the  
436 present study. A new transgression above this latter conglomerate is recorded at  
437 a regional scale by the deposition of *G. crassaformis* mudstones (Fig. 5)  
438 accompanied by renewed compression along the frontal thrusts of the chain  
439 (Palladino 2011). This interval corresponds to the transition between stages C-D  
440 of the Ofanto basin evolution (Fig. 9), occurring before a period of quiescence in  
441 the late Pliocene (Ciarcia et al. 2003). The last part of the Ofanto basin infill,  
442 formed by *G. inflata* mudstones and the overlying conglomerate (Fig. 5) is not  
443 represented in the Ariano Irpino or Acerenza sectors. In the Ofanto basin these  
444 Late Pliocene-?Pleistocene deposits record large wavelength NE directed folding  
445 related to the contractional deformation of the Apulian carbonates (Fig. 8). This  
446 latter tectonic event may not be recorded in the Ariano and Acerenza areas,  
447 because of the lack of deposits of suitable age (Ariano) or because the front of the  
448 Apulian thrusts is several tens of kilometres to the west (hinterlandwards) of the  
449 front of the Apennine chain (Acerenza) (Fig. 2).

450 Approximately 100 km south of the Ofanto basin, the S. Arcangelo basin (Fig. 1)  
451 constitutes an analogous but younger thrust-top basin of the southern Apennines  
452 (Hyppolite et al. 1994; Benvenuti et al. 2006; Ascione et al. 2011). According to  
453 Calabrò et al. (2002) this Late Pliocene-Pleistocene basin evolved in a similar way  
454 as the Ofanto basin, during buttressing of the Southern Apennines Allochthonous  
455 against pre-existing NW-SE normal faults in the Apulian foreland. The main phase  
456 of buttressing and back-thrusting in this basin is Early Pleistocene (Calabrò et al.  
457 2002; Benvenuti et al. 2006), in agreement with a southwards younging of tectonic  
458 deformation along the southern Apennine orogen (Vezzani et al. 2010). Although

459 for the S. Arcangelo basin the age of the normal faults is not constrained, the  
460 similarity in the mechanisms of formation highlights the role of early-formed  
461 structures in the foreland unit in conditioning the geometry of the frontal parts of  
462 orogenic wedges.

463

#### 464 *OROGENIC NORMAL FAULTS*

465 The existence of large syn-orogenic normal faults (or early-orogenic, in De Paola  
466 et al. 2006), which form foreland-wards of the advancing thrust fronts, is well  
467 documented in the Italian Apennines (Mazzoli, 1994; Tavarnelli & Peacock 1999;  
468 Calamita et al. 1998, 2009; Scisciani et al. 2001, 2002; Billi & Salvini 2003; Butler  
469 et al. 2006; De Paola et al. 2006) and in other orogenic belts (Martínez et al. 1989;  
470 Berástegui et al. 1998; Hayman & Kidd 2002; Séjournée & Malo 2007; Sieniawska  
471 et al. 2010; Casini et al. 2011). Their origin is generally attributed to: a) flexure of  
472 the foreland plate due to the load of the advancing thrust system or due to the pull  
473 of the down-going slab (Royden 1993), or b) to outer-arc extension in the hinge of  
474 the subducting plate (Doglioni 1995). These two mechanisms are not mutually  
475 exclusive; instead, they can complement and reinforce each other producing  
476 higher amounts of extensional strain. We believe that a specific analysis of the  
477 factors that determine the formation of these normal faults, their orientation, the  
478 size and location with respect to the subducting lithosphere hinge could offer a  
479 significant contribution to the comprehension of lithospheric subduction and its  
480 roll-back process.

481

#### 482 **CONCLUSIONS**

483

484

485 Two principal and consecutive stages, marked by different tectonic processes,  
486 characterise the evolution of the Ofanto basin. The first stage, lasting throughout  
487 the Early Pliocene (post 5.33 - 3.57 Ma) and possibly extending into the  
488 lowermost part of the Late Pliocene, is the main translation of the SAA over the  
489 Apulian carbonate platform, which behaved as the inactive footwall, passively  
490 influencing the emplacement of the Southern Apennine Allochthonous with its pre-  
491 existing structures (Fig. 9 A-C). The main tectonic process resulting from this  
492 interaction is the buttressing and thickening of the Allochthonous against the  
493 escarpment of the normal fault in the Apulian carbonates and the development of  
494 the Ofanto syncline. In a later stage, almost certainly Early Pleistocene in age, the  
495 footwall of the SAA, which is formed by Apulian carbonates, became actively  
496 involved in the shortening and developed NW-SE trending reverse faults that cut  
497 through the basal thrust of the SAA (Figs. 7, 8, 9E). Although thrust displacement  
498 is modest within the Apulian carbonates, the overall structural relief caused by  
499 thrusting and the associated folding is significant (Fig. 6). The net result of this  
500 stage of tectonic activity is the eastwards tilting of the Ofanto syncline and broad  
501 NW-SE folding of the Late Pliocene-?Early Pleistocene conglomerate in the  
502 western termination of the basin (Fig. 3).

503 Our interpretation implies a significantly lower amount of shortening of the  
504 Apulian Carbonates than in previous interpretations (e.g. Hyppolite et al. 1994),  
505 favouring a thick-skinned mode of deformation (Shiner et al. 2004; Scrocca et al.  
506 2005) for the last evolutionary stage of the Southern Apennines. More generally,  
507 our study remarks the importance of early-orogenic extensional faults, which form

508 ahead of the leading edge of accretionary wedges, in controlling the tectonic  
509 geometry at the front of the orogen.

510

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## 770 FIGURE CAPTIONS

771

772 Figure 1. Geological map of the Southern Apennines showing the main  
773 lithotectonic assemblages composing the belt and the location of the Ofanto  
774 basin.

775

776 Figure 2. Schematic regional cross section of the Southern Apennines. Trace in  
777 Figure 1 (redrawn from Mostardini & Merlini 1988).

778

779 Figure 3. Geological map of the Ofanto basin showing the main structural  
780 features, results of biostratigraphic analyses and traces of seismic lines of figure

781 6. Biostratigraphic data on calcareous nannoplankton (square symbols) is  
782 according to Hippolyte et al. 1994.

783

784 Figure 4. Schematic logs of exploration wells in the studied area. Location of  
785 wells, of the studied seismic grid (dashed lines) and of the line drawings in figure 6  
786 (solid lines), is shown in A.

787

788 Figure 5. Lithostratigraphic chart of the units exposed along the northern margin of  
789 the Ofanto syncline, based on field data and original biostratigraphic analyses  
790 (Figure 3). The columns on the right show the unconformity-bounded units  
791 recognised in the eastern half of the Ofanto basin, and the unconformity-bounded  
792 units recognised in the contiguous basins of Acerenza (1 - Palladino et al. 2011)  
793 and Ariano Irpino (2 - Ciarcia et al. 2003); square patterns indicate the main  
794 conglomerate bodies.

795

796 Figure 6. Line drawings of selected seismic profiles crossing the Ofanto basin.  
797 Location is shown in figure 3.

798

799 Figure 7. Depth map in TWT of the top Apulian carbonates in the Ofanto basin  
800 area.

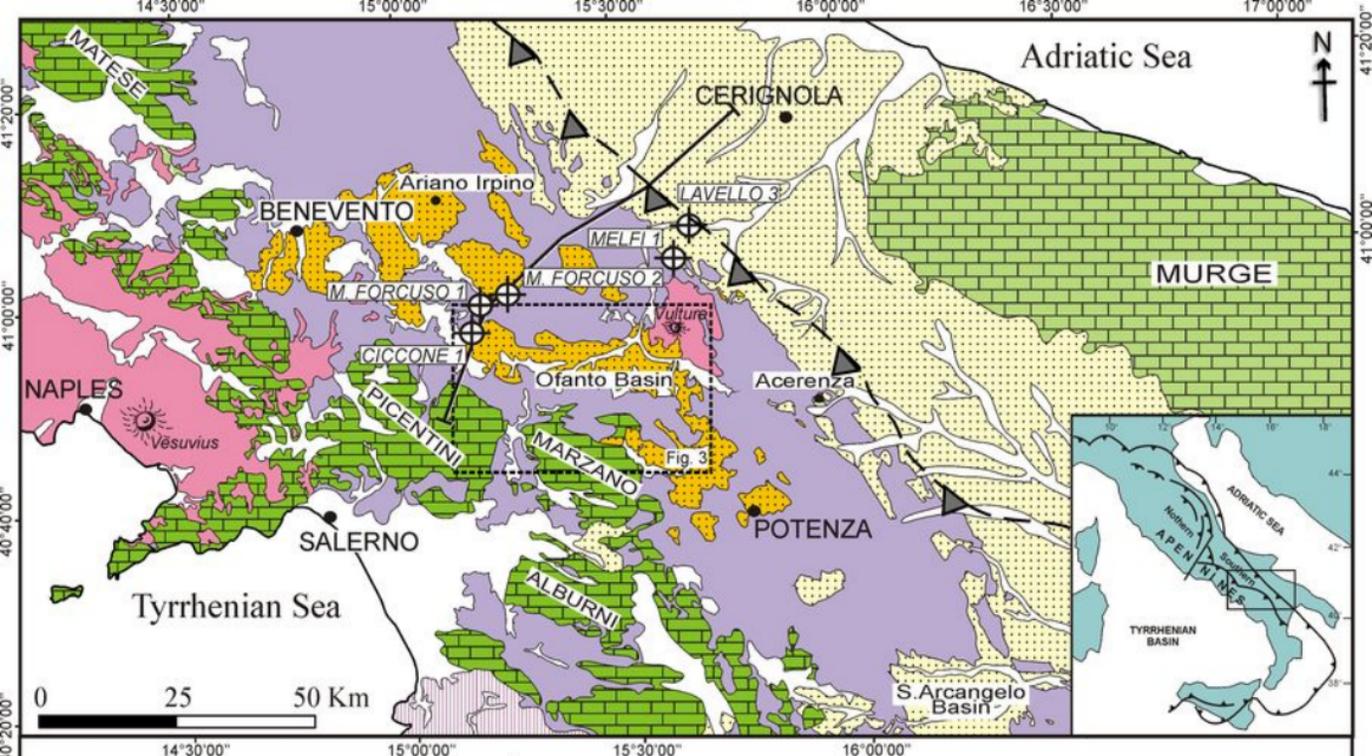
801

802 Figure 8. 3D model of the top Apulian surface underlying the Ofanto basin. The  
803 model was constructed in GoCad<sup>®</sup>, using the line drawings shown in figure 6, and  
804 is sliced in a direction parallel to the trend of the Ofanto syncline (E-W) in order to  
805 highlight the eastward slope of the top Apulian carbonates in the hangingwall  
806 block of the normal fault. Refer to figure 7 for a map view.

807

808 Figure 9. Cartoon illustrating the tectono-sedimentary evolution of the Ofanto  
809 thrust-top basin. Vertical distance is not to scale, horizontal scale is approximate.

810 In stage E the direction of tectonic transport is out of the section plane.



Continental and marine deposits  
[Quaternary]

Lavas and volcanoclastic deposits  
[Upper Pleistocene-Holocene]

Foreland-foredeep system and thrust top basins deposits; a) Ariano Unit  
[Pliocene-Quaternary]

Calabrian and Ligurian Units  
[Jurassic-Miocene]

Apenninic Carbonate Platform Units  
[Triassic-Miocene]

Undifferentiated Basinal Units  
(Sicilide, Sannio and Lagonegro)  
and siliciclastic deposits  
[Early Triassic-Miocene]

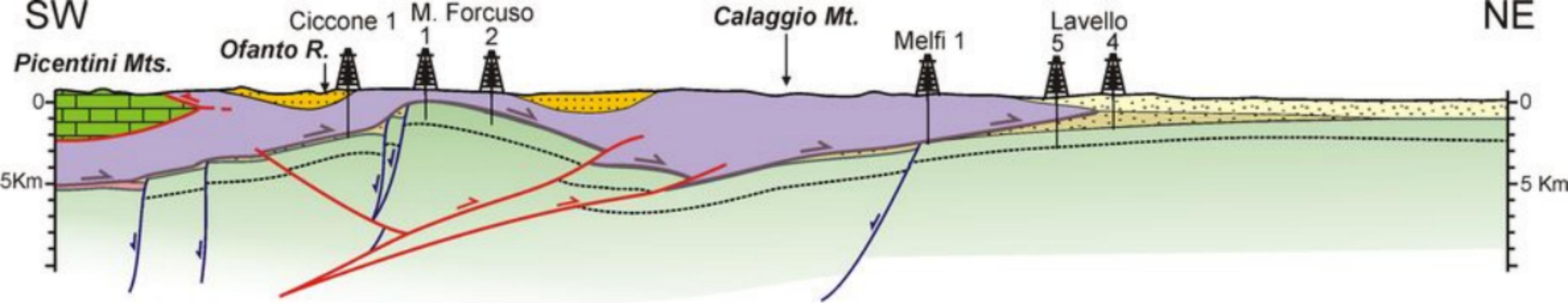
Apulian Carbonate Platform Units  
[Late Triassic-Miocene]

Allochthonous frontal thrust

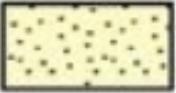
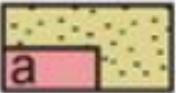
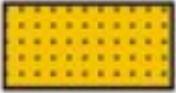
Trace of cross-section in Fig. 2

SAA

Fig. 3



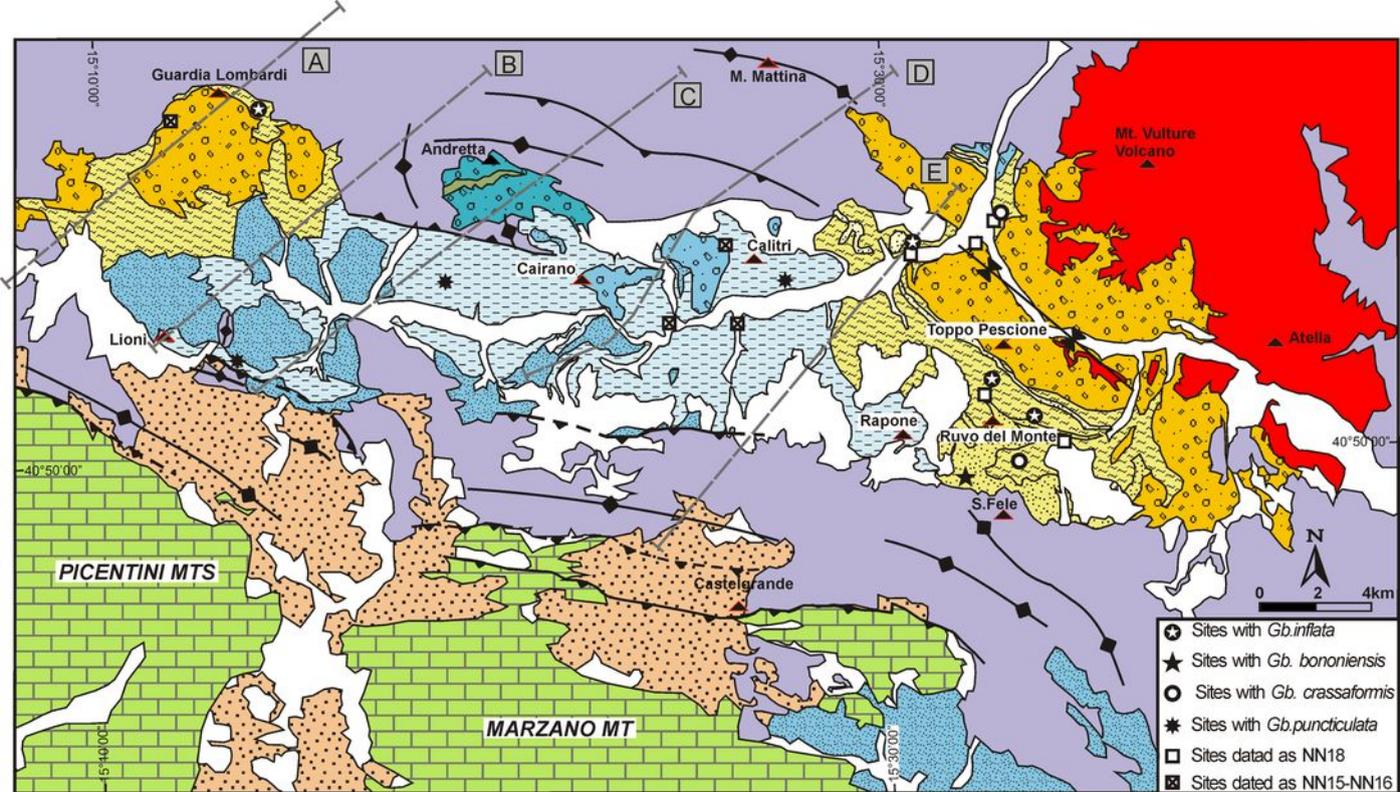
**Siliciclastic deposits**

-  Pleistocene
-  Pliocene,  
a) Messinian evaporites
-  Pliocene piggy-back deposits

**Allochthonous Units (SAA)**

-  Apennine Carbonate Platform  
Early Triassic-Miocene
-  Undifferentiated Basinal Units  
(Sicilide, Sannio and Lagonegro)  
and siliciclastic deposits  
Early Triassic-Miocene

-  Apulian Carbonate Platform  
Late Triassic-Miocene
-  Basal thrust of the Southern  
Apennine Allochthonous



Quaternary Alluvial deposits and landslide covers



Late Pliocene-Early Pleistocene  
a) day; b) sand; c) conglomerate



Upper Miocene Castelvetero Flysch

Quaternary Volcanic and volcanodastic products



Early-Late Pliocene  
a) day; b) sand; c) conglomerate

Jurassic-Miocene Undifferentiated Basinal Units and related siliclastic deposits



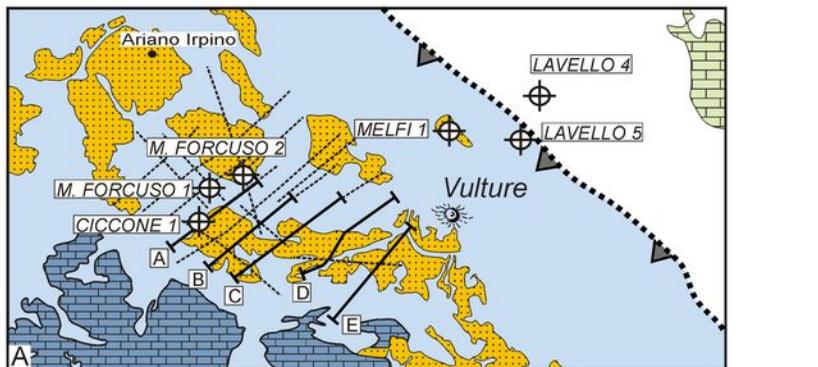
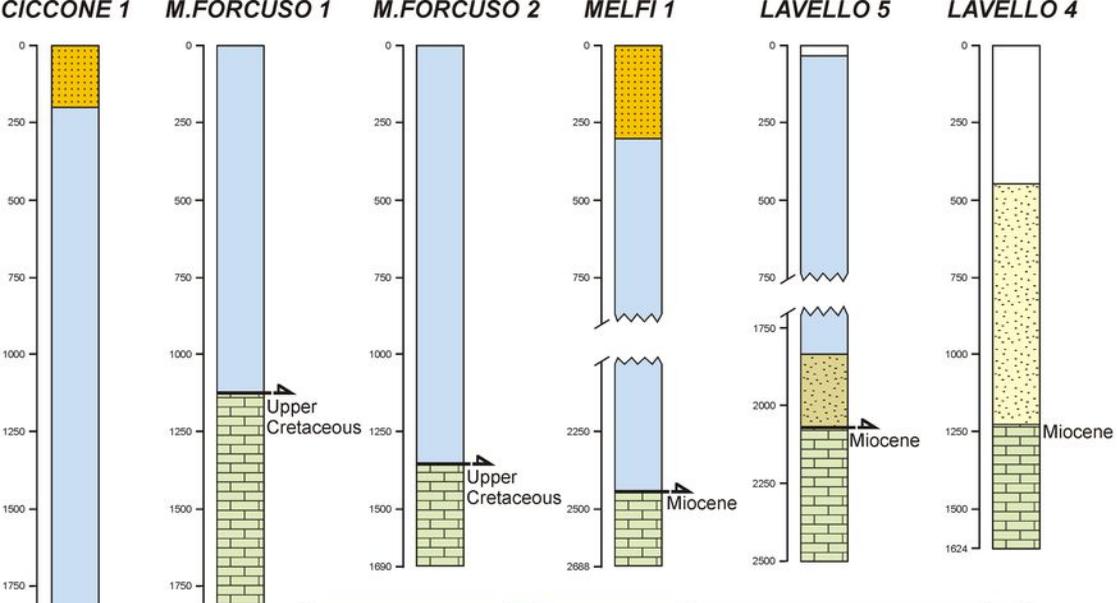
Early Pliocene Andretta basal conglomerate with lacustrine level



Mesozoic-Cenozoic Apenninic Carbonate Platform

- ⊙ Sites with *Gb. inflata*
- ★ Sites with *Gb. bononiensis*
- Sites with *Gb. crassaformis*
- ✱ Sites with *Gb. puncticulata*
- Sites dated as NN18
- ⊠ Sites dated as NN15-NN16

- ↖ Axial trace of anticline
- ↔ Axial trace of syncline
- ↘ Thrust fault dashed where inferred



Quaternary deposits

Pliocene thrust-top deposits

Late Pliocene siliciclastic deposits

Early Pliocene siliciclastic deposits

Early Pliocene calcareous breccias

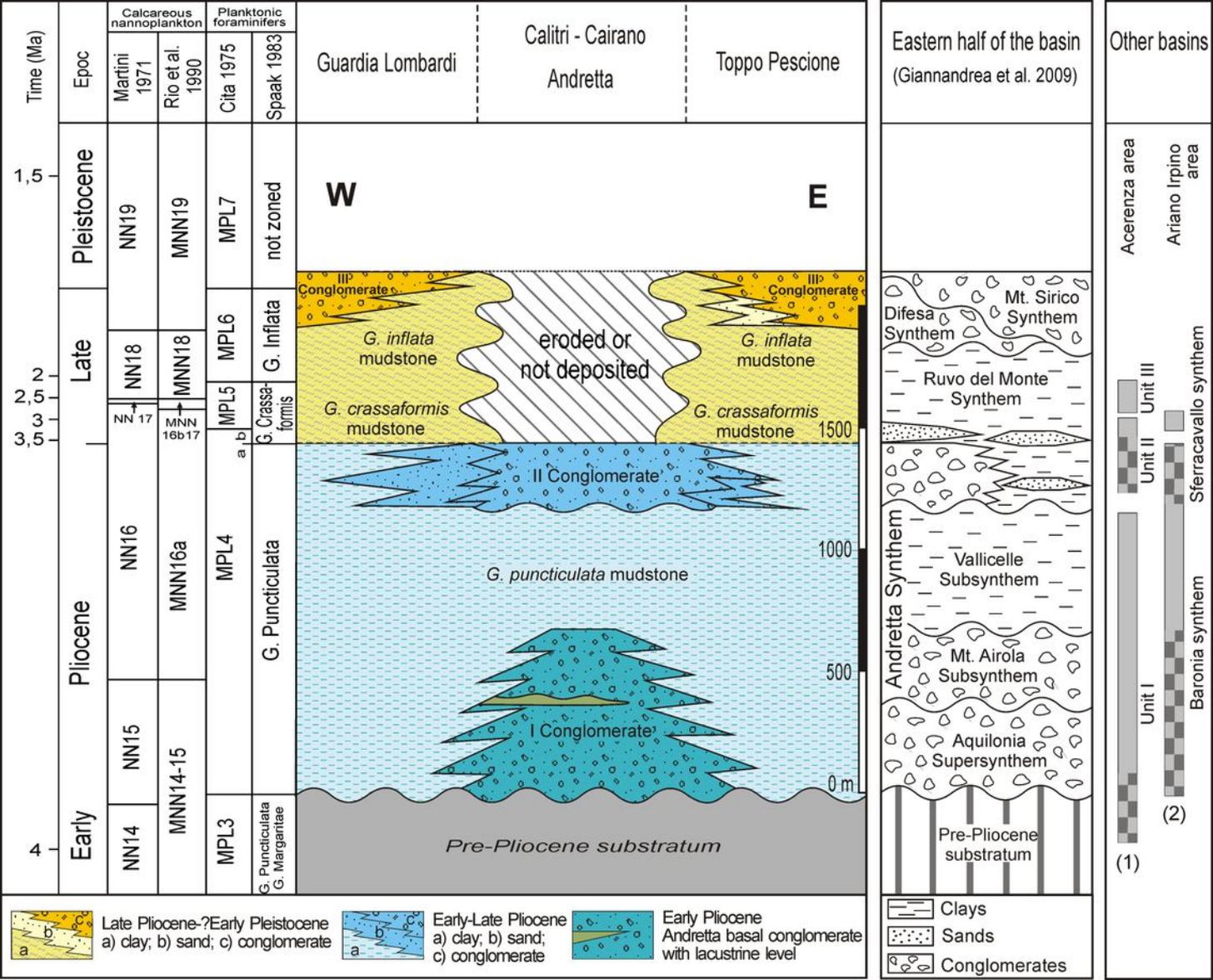
Lagonegro basinal units and related siliciclastic deposits

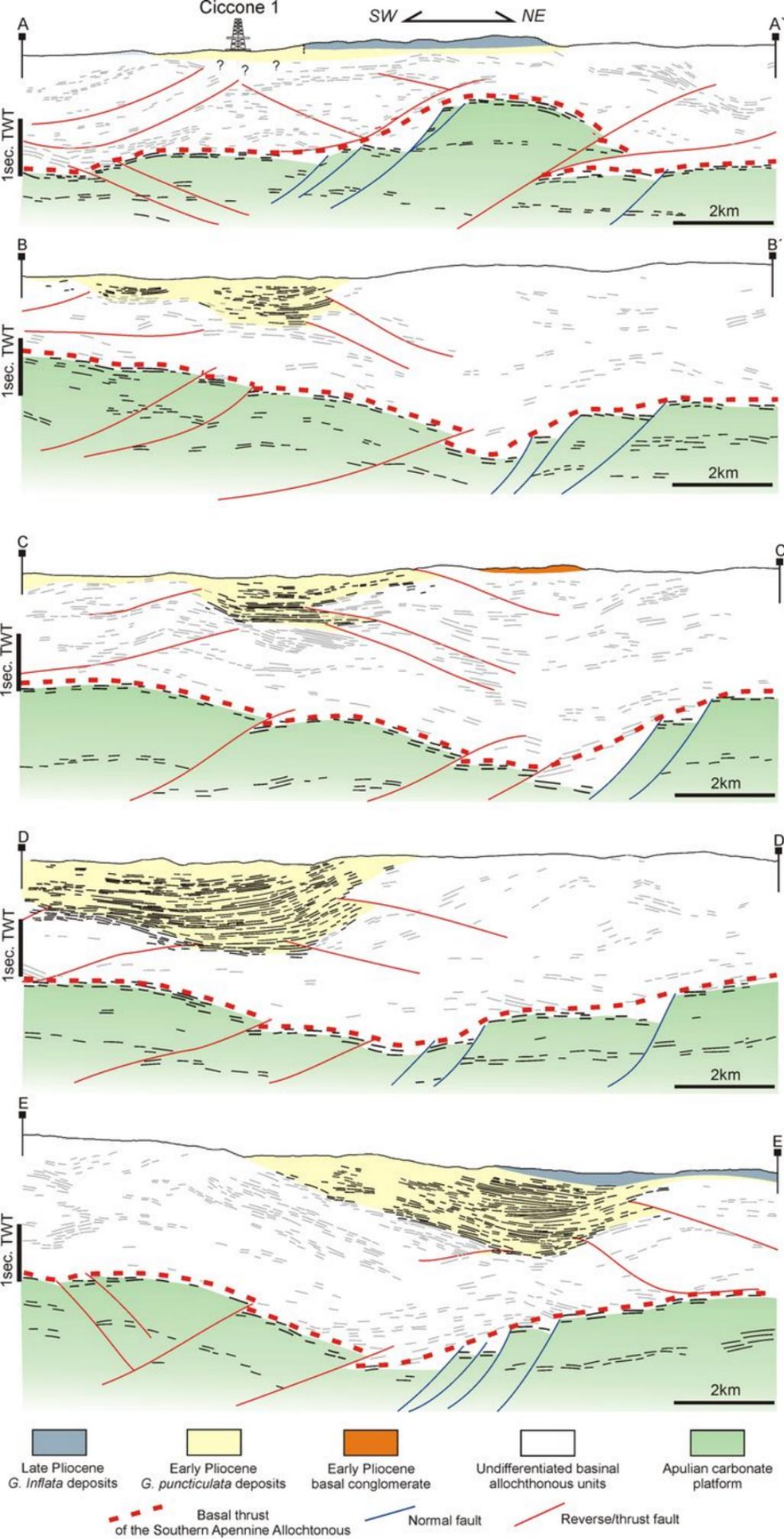
Apulian Carbonate Platform

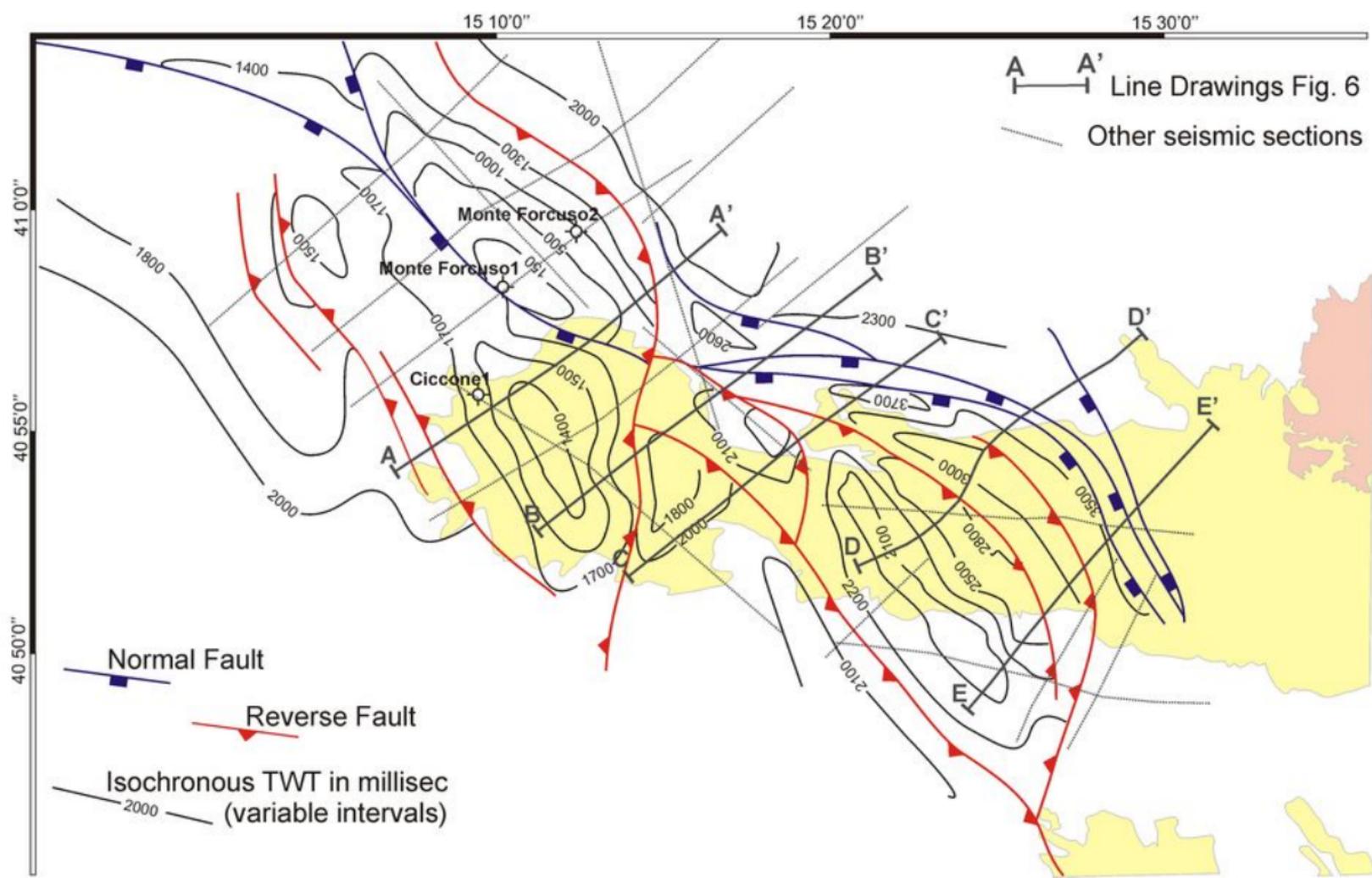
Basal thrust of the Southern Apennine Allochthon

Studied seismic grid

Line drawings of figure 6







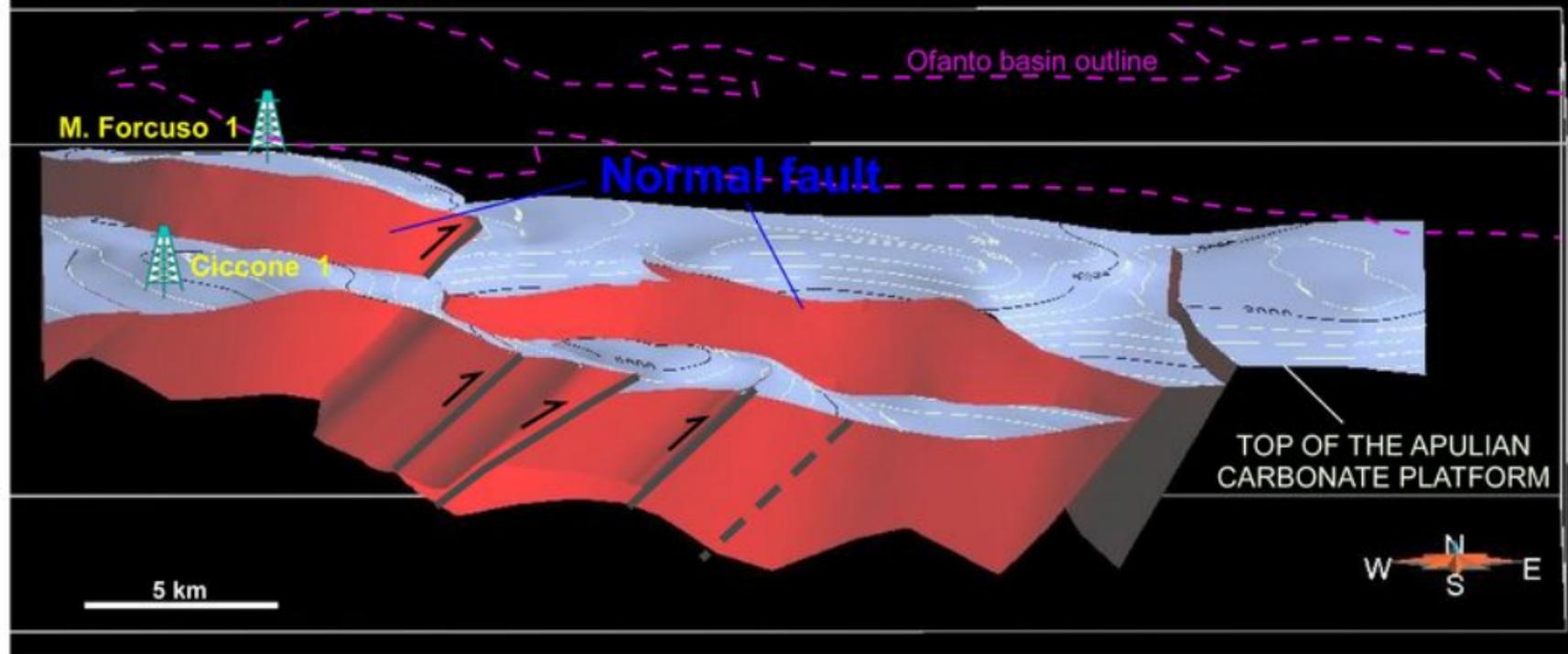
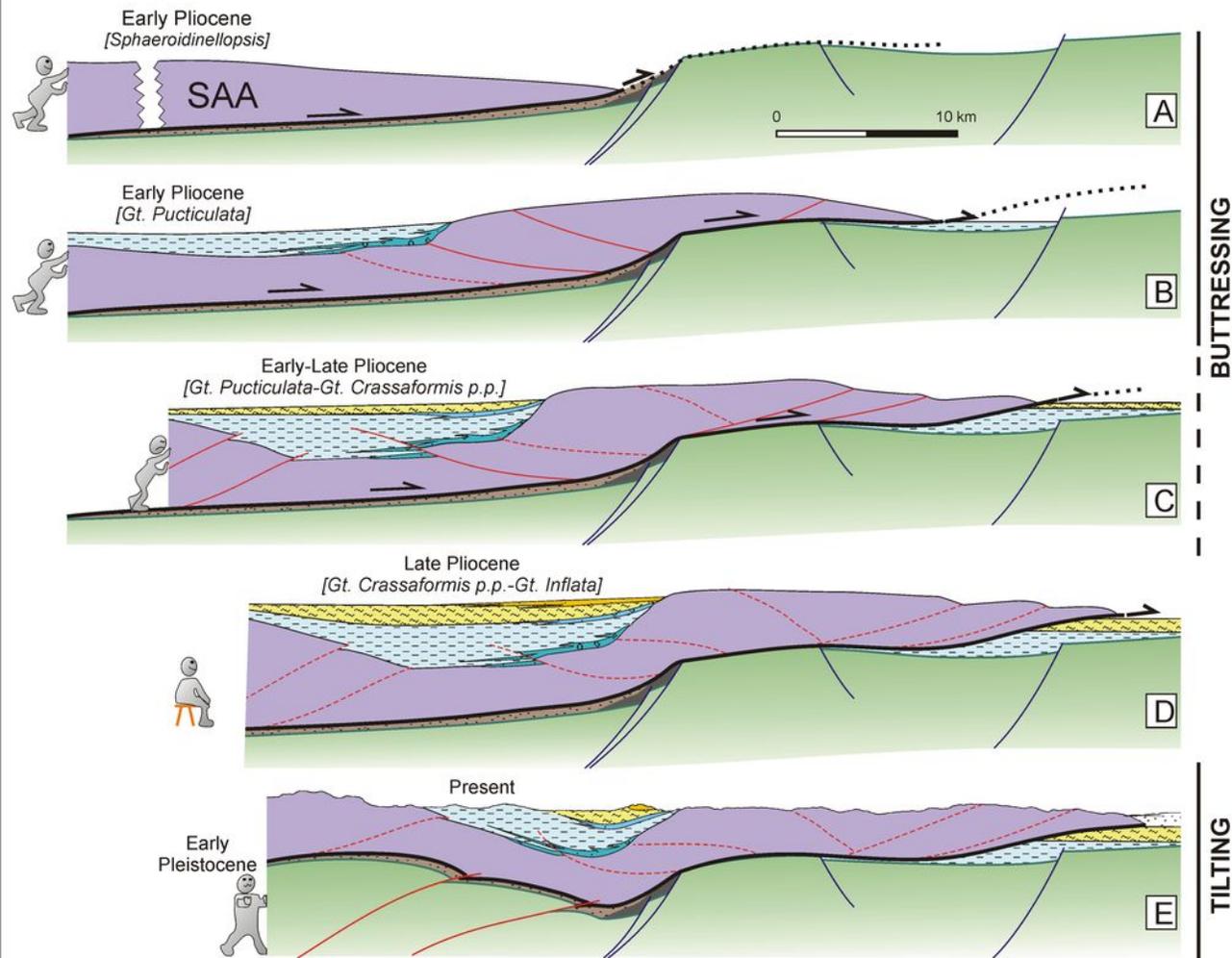


Figure 8. 3D model of the top Apulian surface underlying the Ofanto basin. The model was constructed in GoCad, using the line drawings shown in figure 6, and is sliced in a direction parallel to the trend of the Ofanto syncline (E-W) in order to highlight the eastward slope of the top Apulian carbonates in the hangingwall of the normal fault. Refer to figure 7 for a map view.



**Pleistocene**



**Late Pliocene-?Early Pleistocene (a)**  
deposits containing *Gt. crassaformis*,  
*Gt. inflata*. (a) III conglomerate  
"Toppo Pescione"



**Early Pliocene**  
deposits containing *Gt. pucticulata*.  
(a) II conglomerate  
"Cairano-Calitri"



**Early Pliocene**



Basal (I) conglomerates  
"Andretta conglomerate"

**Early Pliocene**



deposits containing  
*Sphaeroidinellopsis*

**Late Miocene-?Early Pliocene**



Calcareous Breccias

