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## **Structural Anatomy of the Ligurian Accretionary Wedge (Monferrato, NW-Italy), and Evolution of Superposed Mélanges**

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35 **Abstract**

36 We document in this study the internal structure of the Late Cretaceous–late Oligocene  
37 Ligurian accretionary wedge in northwestern Italy, and the occurrence in this exhumed wedge  
38 of broken formation and three different types of mélanges that formed sequentially through  
39 time. The *Broken Formation* is the oldest unit in the accretionary wedge and shows bedding-  
40 parallel boudinage structures, which developed as a result of layer-parallel extension at the  
41 toe of the internal part of the Alpine wedge front during the Late Cretaceous–middle Eocene.  
42 This *Broken Formation* experienced an overprint of tectonic, diapiric and sedimentary  
43 processes as a result of continental collision in the late Oligocene. The NE-vergent thrusting  
44 and associated shortening produced a structurally ordered block-in-matrix fabric through  
45 mixing of both native and exotic blocks, forming the *Tectonic Mélange*. The concentration of  
46 overpressurized fluids along the thrust fault planes triggered the upward rise of shaly material,  
47 producing the *Diapiric Mélange*, which in turn provided the source material for the downslope  
48 emplacement of the youngest, late Oligocene *Sedimentary Mélange*. The Sedimentary  
49 Mélange units unconformably cover the collisional thrust faults, constraining the timing of the  
50 youngest episode of contractional deformation in the accretionary wedge. Our multi-scale  
51 structural analysis of the Ligurian accretionary wedge shows that tectonic, diapiric and  
52 sedimentary processes played a significant role in its evolution, and that the interplay  
53 between and the superposition of these different processes strongly controlled the dynamic  
54 equilibrium of the accretionary wedge in the NW Apennines–W Alps. This kind of polygenetic  
55 mélange development may be common in many modern and ancient accretionary complexes,  
56 and the processes involved in their formation are likely to be responsible for major tsunamic  
57 events in convergent margins.

58

59 **Key words:** accretionary wedge; polygenetic mélange; tectonic, diapiric and sedimentary  
60 processes; Northern Apennines; Tertiary Piedmont Basin.

61

## 62 1. Introduction

63

64 The shape and growth of the frontal wedge of the modern accretionary complexes repeatedly  
65 change to maintain the dynamic equilibrium in the wedge through alternating tectonic and  
66 sedimentary (i.e., gravitational) activities (e.g., Davis et al., 1983; Scholl et al., 1977; von  
67 Huene and Lallemand, 1990; Gutscher et al., 1998; Cliff and Vannucchi, 2004; Wang and Hu,  
68 2006; Buitter, 2012; Gravelau et al., 2012; Haq, 2012). Highly sheared, disrupted and  
69 fragmented rock units and tectonic mélanges are the products of tectonics occurring along the  
70 basal décollements in accretionary wedges and out-of-sequence thrust-faults, and within the  
71 subduction channels (e.g., Karig and Sharman, 1975; Cloos, 1982; Moore and Byrne, 1987;  
72 Taira et al., 1992; Dileonardo et al., 2002; Collot et al., 2011). Mass-transport deposits and  
73 sedimentary mélanges result from slope instability in the trench-inner slope and in the upper  
74 parts of frontal wedges (e.g., Lallemand et al., 1990; Duperret et al., 1995; Goldfinger et al.,  
75 2000; von Huene et al., 2000; Collot et al., 2001; McAdoo et al., 2004; Sage et al., 2006;  
76 Mosher et al., 2008; Ogawa et al., 2011; Strasser et al., 2009, 2011). Shale and mud  
77 diapirism represent the upward rise of overpressured fluids migrating along the basal  
78 décollement or channeled along megasplay faults (e.g., Brown and Westbrook, 1988; Moore  
79 and Vrolijk, 1992; Kopf, 2002; Chamot-Rooke et al., 2006; Camerlenghi and Pini, 2009).

80

81 Mélanges commonly occur in ancient examples of exhumed accretionary wedges on-land,  
82 showing a complex internal block-in-matrix fabric that may vary both laterally and vertically  
83 (e.g., Maxwell, 1974; Cloos, 1984; Raymond, 1984; Cowan, 1985; Byrne and Fisher, 1990;  
84 Barnes and Korsch, 1991; Onishi and Kimura, 1995; Ogawa, 1998; Dilek et al., 1999, 2005;  
85 Pini, 1999; Dilek and Robinson, 2003; Codegone et al., 2012a, 2012b; Dilek et al., 2012;

86 Festa et al., 2010a; Ukar, 2012; Wakabayashi, 2012; Singlenton and Cloos, 2013). The  
87 primary internal structures of mélanges and mélange-forming processes are commonly  
88 obscured by subsequent deformational events, resulting in superposed and mixed mélanges  
89 types, such tectonic, sedimentary and diapirc mélanges. Much effort has been made to  
90 establish a set of useful criteria by which to distinguish mélange types in ancient accretionary  
91 complexes (e.g., Aalto, 1981; Naylor, 1982; Raymond, 1984; Cowan, 1985; Barber et al.,  
92 1986; Bettelli and Panini, 1989; Harris et al., 1998; Orange, 1990; Pini, 1999; Cowan and Pini,  
93 2001; Dela Pierre et al., 2007; Yamamoto et al., 2009, 2012; Festa et al., 2010, 2012;  
94 Vannucchi and Bettelli, 2010; Festa, 2011; Osozawa et al., 2009, 2011; Wakabayashi, 2011,  
95 2012; Codegone et al., 2012a, 2012b). These criteria are mainly based on meso-scale  
96 structural observations and analyses (e.g., Hsü, 1968; Cowan, 1985; Barber et al., 1986;  
97 Lash, 1987; Orange, 1990, Pini, 1999; Bettelli and Vannucchi, 2003) and are more rarely on  
98 map-scale or micro-scale studies (e.g., Aalto, 1981; Bettelli and Panini, 1989; Ogawa, 1998;  
99 Pini, 1999; Alonso et al., 2006; Dela Pierre et al., 2007; Festa, 2011; Saleeby, 1979, 2011;  
100 Wakabayashi, 2011, 2012; Hitz and Wakabayashi, 2012; Codegone et al., 2012a, Wakita,  
101 2012; Vannucchi and Maltman, 2000; Kawamura et al., 2007; Michiguchi and Ogawa, 2011).  
102 However, a multi-scale approach to differentiate different chaotic rock units that were formed  
103 by different processes in accretionary wedge development has been rather limited in the  
104 literature (see, e.g., Pini, 1999; Codegone et al., 2012a, 2012b).

105

106 In this paper, we document the internal structure, tectonostratigraphic units, and geological  
107 evolution of the Ligurian accretionary wedge in Monferrato of the NW Apennines in Italy (Fig.  
108 1) through multi-scale, field- and laboratory-based structural studies (from geological map-to  
109 meso-scale and scanning electron microscope-scale) of a composite chaotic rock unit,

110 previously designated as an “undifferentiated chaotic complex” (e.g., Elter et al., 1966;  
111 Bonsignore et al., 1969; Dela Pierre et al., 2003a). We differentiate the occurrence of  
112 “polygenetic mélanges” that were formed by the contemporaneous to sequential operation of  
113 tectonic, diapiric and sedimentary processes that took place to maintain the dynamic  
114 equilibrium during the evolution of this accretionary wedge. This study presents, therefore, a  
115 detailed structural anatomy of an exhumed accretionary wedge, whose evolution included  
116 both subduction-accretion and collisional tectonic events during the Late Cretaceous through  
117 late Oligocene.

118

## 119 **2. Regional geology**

120

121 The Ligurian Units in the Northern Apennines (Fig. 1) consist of the Mesozoic to early  
122 Cenozoic sedimentary successions and the Jurassic ophiolites that collectively represent the  
123 remnants of the Ligurian Ocean (Fig. 2A; see, e.g., Marroni et al., 2001; Bortolotti et al.,  
124 2005), which evolved between European plate and the Adria microplate (i.e., Africa  
125 promontory) (e.g., Coward and Dietrich, 1989; Cavazza et al., 2004, and references therein;  
126 see also Molli et al., 2010). The Internal, External and Sub-Ligurian Units (Fig. 1; e.g., Marroni  
127 et al. 2010, and references therein) contain those tectonosedimentary assemblages that were  
128 originally deposited in an oceanic basin, in an ocean-continent transition zone (OCT), and in a  
129 rifted continental margin of Adria, respectively (Fig. 2). During the Late Cretaceous through  
130 middle Eocene and prior to the continental collision, these Units were deformed and  
131 incorporated into the Alpine accretionary wedge (i.e., Principi and Treves, 1984; Marroni et  
132 al., 2001, 2010; Bortolotti et al., 2005; Vezzani et al., 2010). Here, the Ligurian Units (i.e., part  
133 of the modern Northern Apennine) and the Western Alpine Units (i.e., modern Western Alps)



134 were tectonically imbricated along oppositely verging (Fig. 2B), the internal (i.e. eastern) and  
135 external (i.e. western) parts of the Alpine wedge, respectively (e.g., Roure et al., 1996;  
136 Cavazza et al., 2004; Marroni et al., 2010 and reference therein).

137

138 In the middle Eocene (Figs. 2C and 2D), the east-dipping “alpine” subduction was halted due  
139 to the partial subduction of the European continental crust (e.g., Carminati et al., 2004,  
140 Marroni et al., 2010). The establishment of a West-dipping “Apennine” subduction formed an  
141 ENE-facing accretionary wedge (i.e., the proto-Apennines involving the External Ligurian  
142 Units) and involved the subduction of the thinned Adria continental margin (Figs. 2C and 2D;  
143 e.g., Marroni et al., 2010; see also Castellarin, 1994; Carminati et al., 2004; Cavazza et al.,  
144 2004; Vignaroli et al., 2008; Molli et al., 2010; Vezzani et al., 2010). As a result, the External  
145 Ligurian Units were underthrust below the Internal Ligurian Units (Figs. 2C and 2D).

146

147 Several episutural basins (Figs. 1 and 3) that developed in the proto-Northern Apennines (i.e.,  
148 Epi-ligurian Units; see, e.g., Mutti et al., 1995; Ricci Lucchi, 1986) and in the internal part of  
149 the Western Alps (i.e., *Tertiary Piedmont Basin*; see Piana and Polino, 1995; Biella et al.,  
150 1997) in the middle-late Eocene cover all the accretionary wedge assemblages and related  
151 structures.

152

153 The Monferrato and Torino Hill correspond to the northern part of the late Eocene–late  
154 Miocene *Tertiary Piedmont Basin*, representing the northernmost segment of the Northern  
155 Apennines where the External Ligurian Units (i.e., the remnants of the outer part of the  
156 Ligurian accretionary wedge) crop out (e.g., Elter et al., 1966; Dela Pierre et al., 2003a; Festa  
157 et al., 2009a). Monferrato is separated from the Torino Hill by the Rio Freddo Deformation

158 Zone (*sensu* Piana and Polino, 1995) (Fig. 1). Its tectono-stratigraphic evolution occurred in  
159 four main stages during the Rupelian, late Oligocene–pre late Burdigalian, late Serravallian,  
160 and Messinian (see Piana, 2000; Dela Pierre et al., 2003b, 2007; Festa et al., 2005, 2009b).  
161 During the Rupelian stage, NW-striking left-lateral transtensional faults associated with rifting  
162 of the Balearic Sea controlled the drowning of the early Oligocene shelf along a series of NW-  
163 striking pull-apart basins (Castellarin, 1994; Mutti et al., 1995). The subsequent late  
164 Oligocene–pre late Burdigalian stage was marked by the northwestward migration of the  
165 frontal thrust system of the Northern Apennines in Monferrato. Due to the E-W regional  
166 shortening, the previously formed transtensional faults were inverted into left-lateral  
167 transpressional faults, facilitating the transportation of the shelf sediments onto the slope  
168 deposits. The late Burdigalian unconformity, which overlapped these transpressional faults, was  
169 crosscut by the NE-SW-striking reverse faults, developed during the third tectonic stage in the  
170 Serravallian. Since the late Messinian, regional N-S shortening has caused the overthrusting  
171 of Monferrato and Torino Hill onto the Po Plain foredeep along the Northern Apennines frontal  
172 thrust (i.e., Padane Thrust Front in Fig. 1).

173

### 174 **3. Chaotic rock units in Monferrato**

175

176 In Monferrato, the exhumed Ligurian accretionary wedge consists mainly of an Upper  
177 Cretaceous–middle Eocene undifferentiated chaotic complex (i.e., “Undifferentiated complex”  
178 *sensu* Bonsignore et al., 1969; “La Pietra chaotic complex” *sensu* Dela Pierre et al., 2003a,  
179 2003b; Festa et al., 2009a, 2009b). Sacco (1935) and then Beets (1940) made the first  
180 lithostratigraphic distinction in this chaotic complex on their geological maps. Elter et al.  
181 (1966) and Bonsignore et al. (1969) correlated part of this undifferentiated chaotic complex

182 (i.e., the “Lauriano complex” of Albian–Cenomanian age and the “Monteu da Po Flysch” of  
183 Maastrichtian age) with the “basal complex” (i.e., *Argille varicolori* Auct. and Ostia  
184 sandstones) and the Monte Cassio Flysch (Cassio Unit Auct.) of the External Ligurian Units of  
185 the Northern Apennines, respectively. However, these authors did not distinguished this  
186 succession on their geological maps.

187

188 We have mapped in detail the Western Monferrato area, differentiating a lithostratigraphic  
189 succession that is comparable to the upper part of the Cassio Unit of the External Ligurian  
190 Units in the Northern Apennines (Figs. 3 and 4). This succession consists of the late  
191 Campanian(?)–Maastrichtian Monte Cassio Flysch (Fig. 3) that overlies a composite chaotic  
192 rock unit (i.e., part of the “undifferentiated complex” of Bonsignore et al., 1969). On the basis  
193 of its block-in-matrix fabric, macro- and micro-structural features (observed at various scales),  
194 and the nature, age and origin of its blocks (i.e., native or exotic), we have subdivided this  
195 composite chaotic rock unit into a broken formation and three different types of polygenetic  
196 mélanges. Each of the polygenetic mélanges represents the superposition of tectonic, diapiric  
197 and sedimentary processes that reworked the block-in-matrix fabric of the broken formation  
198 and the previously formed mélange/s. The broken formation corresponds to the Upper  
199 Cretaceous (Santonian – Campanian) *Argille varicolori* (i.e., upper part of the “basal  
200 complex”; see Figs. 3 and 4). It represents a lithostratigraphic unit resulting from the tectonic  
201 dismemberment of alternating shale, sandstone and manganiferous siltstone layers.

202

203 In the following, we refer to broken formation (*sensu* Hsü, 1968) a stratally disrupted unit  
204 preserving its lithological and chronological identity (see Fig. 4) and containing only “native”  
205 components (i.e., intraformational origin; see also Raymond, 1984; Cowan, 1985; Pini, 1999;

206 Festa et al., 2012 and reference therein, for a complete discussion on the terms “native” and  
207 “exotic”). On the contrary, we refer to “mélange” a body of mixed rocks, containing both  
208 “exotic” (i.e., extraformational origin) and “native” components, in a pervasively deformed  
209 matrix (see, e.g., Raymond, 1975, 1984; Silver and Beutner, 1980; Festa et al., 2012).  
210 Mélanges may be formed by tectonic, sedimentary, and intrusive processes or through the  
211 combination and superposition (i.e., polygenetic mélanges) of these processes (e.g.,  
212 Raymond, 1984; Festa et al., 2010a and reference therein).

### 213 214 **3.1 Broken Formation (i.e., Upper Cretaceous *Argille varicolori*)**

215  
216 The *Broken Formation* in Monferrato corresponds to the areally largest unit in the composite  
217 chaotic rock unit (see *Argille varicolori* in Fig. 4). At the mesoscale, its deformation is  
218 characterized by layer-parallel extension (Fig. 5A), which produced a progressive bedding-  
219 parallel boudinage of cm- to m-long blocks, which are exclusively of native origin (i.e., “intra-  
220 formational”). The preferred alignment and the boudinage structures of these blocks produced  
221 a strong fabric, defining pseudo-bedding in the *Argille varicolori*. The more competent  
222 sandstone, limestone, manganiferous siltstone, calcarenite, and marly limestone rocks show  
223 a progressive stratal disruption from continuous layering to isolated, phacoidal or tabular  
224 blocks in a shaly matrix. Elongated blocks (mean long-axis: 33 cm) display a high aspect ratio  
225 (long axis/short axis) with a mean value ranging from 3.5 to 4 (Figs. 6A and 6B), and an  
226 irregular, flat- to ellipsoidal shape corresponding to different degrees of extensional shearing  
227 of the bedding plane in two orthogonal directions. Pinch-and-swell and boudinage structures  
228 are mainly asymmetric, and define a planar alignment that is consistent with extensional  
229 shearing in the ESE-WNW direction (Figs. 5A and 6C). R and R' Riedel shears crosscut the

230 asymmetric, elongated blocks (Fig. 5A). The boudins, on the other hand, appear symmetrical  
231 in the NNE-direction (Fig. 5A).

232

233 Decimeter-wide noncylindrical, and asymmetrical intra-layer folds occur extensively  
234 throughout the *Broken Formation* (Fig. 5B). These folds are commonly rootless and  
235 transposed, and have curvilinear axial surfaces. Their fold axes display a broad girdle with  
236 two NNE- and WNW oriented maxima (Figs. 5B and 6C). The folds are sheath-like and  
237 symmetric along NNE–SSW cross-sections (Fig. 5B), whereas their limbs are asymmetrically  
238 boudinaged by R and C' shears along ESE–WNW cross-sections.

239

240 At a hand sample scale, we observe alternating layers (mm- to cm-thick) of stretched and  
241 disrupted varicolored shale, siltstone, limestone and sandstone as a result of layer-parallel  
242 extension (Figs. 5C, 5D and 5E). The more competent sandstone and limestone layers are  
243 asymmetrically boudinaged along ENE–WNW-oriented sections (Figs. 5C and 5D). The  
244 boudins are connected to each other by elongated wisps and tails, whose alignment defines a  
245 tectonically induced, pseudo-layering that is nearly parallel to the original depositional  
246 bedding (Fig. 5D). Numerous low- to high-angle normal faults and R–R' shears crosscut the  
247 more competent rocks (Fig. 5D), and continue into the weak shaly matrix as C'-type shears  
248 (*sensu* Passchier and Trouw, 2005) with only mm-scale displacements (Fig. 5E).

249

250 At the scanning electron microscope scale, the fabric of the shaly matrix is defined by the  
251 preferred alignment of the platelets of clay minerals, defining anastomosing cleavage  
252 domains with spacing of 3 to 18  $\mu\text{m}$  (Fig. 5F). This fabric in the matrix is parallel to the  
253 bedding in the rocks, suggesting that sediments underwent burial-related flattening (uniaxial

254 layer-normal compression) during the early stages of their lithification. Disjunctive shear  
255 surfaces (C'-type shear *sensu* Passchier and Trouw, 2005, and R shear) crosscut this  
256 bedding-parallel fabric at low-angles (Fig. 5F). These structures affected both the pseudo-  
257 bedding planes and the fold limbs, indicating that intralayer folding and boudinage  
258 development on the fold limbs were spatially and temporally related (see also Vannucchi et  
259 al., 2003). Extensional-shear surfaces mimic the geometry of those observed at the hand  
260 sample scale (Figs. 5E and 5F).

261

### 262 **3.2 Tectonic Mélange**

263

264 It is characterized by a highly sheared block-in-matrix fabric (Fig. 7A) with mixed blocks of  
265 both native (e.g., limestone, sandstone and manganiferous siltstone of the *Argille varicolori*)  
266 and exotic origin. The exotic rock blocks were wrenched from the lowest stratigraphic  
267 horizons of the “basal complex” (e.g., early Cretaceous Palombini shale, Cenomanian(?)–  
268 early Campanian Scabiazza sandstone), the older buried succession (Upper Jurassic-to lower  
269 Cretaceous Maiolica limestone), the late Campanian(?)–Maastrichtian Monte Cassio Flysch,  
270 and the Upper Eocene – Oligocene *Tertiary Piedmont Basin* succession.

271

272 At the map scale (Fig. 4), the *Tectonic Mélange* defines a narrow zone (up to 50 meters wide)  
273 in the hangingwall of the NE-vergent thrust faults, emplacing the *Argille varicolori* over the  
274 Monte Cassio Flysch and the Upper Eocene–Oligocene succession of the *Tertiary Piedmont*  
275 *Basin*. Here, the pre-existing fabric of the *Broken Formation* is strongly overprinted and  
276 reworked by shearing associated with thrusting, forming a scale independent, “structurally  
277 ordered” block-in-matrix fabric (*sensu* Festa, 2011; see Figs. 7A and 7B). Away from the

278 thrust faults, the rocks gradually acquire the original, layer-parallel extensional fabric of the  
279 *Broken Formation* (Fig. 4).

280

281 At the mesoscale, the structurally ordered block-in-matrix fabric gives way to the NE-vergent  
282 (Figs. 7A and 7B) shear zones (with secondary left-lateral strike slip component of movement)  
283 caused by E-W directed regional shortening (see Figs. 6C; see also Piana, 2000; Festa et al.,  
284 2005, 2009b). The blocks in the *Tectonic Mélange* show a prevalent phacoidal shape (more  
285 rarely tabular), with mean values of their aspect ratio (long axis/short axis) ranging from 2.5 to  
286 2.8 (Figs. 6A and 6B). Elongated blocks are imbricated in the direction of shortening and are  
287 bounded or disrupted by the anastomosing S-C shears (Figs. 7A and 7B). The exotic blocks  
288 are mixed with the native blocks derived from the *Broken Formation* along these shear zones.  
289 The long-axes of the SW-dipping native blocks (Fig. 6C) range in size from 5 cm to 90 cm  
290 with a mean length of ~20 cm (Fig. 6A). Exotic blocks are commonly larger in size (long-axis  
291 up to 125 cm, and mean length of 35 cm). The difference in size between the smaller native  
292 blocks and the larger exotic ones may be related to the nature of different processes of stratal  
293 disruption and to the thickness of the beds in the original stratigraphic succession. The mean  
294 size of the native blocks is smaller in the *Tectonic Mélange* (mean long-axis ~20 cm) than in  
295 the *Broken Formation* (mean long-axis 33 cm), indicating that the *Tectonic Mélange*  
296 developed by imposing significant tectonic strain on the earlier formed *Broken Formation*. In  
297 general, however, we observe a progressive decrease in the block size and in the intensity of  
298 tectonic mixing away from the thrust faults (Fig. 6B). This progressive decrease in the size of  
299 blocks away from the thrust faults appears to be related to the progressive decrease of mixing  
300 of native and exotic blocks.

301

302 The shaly matrix of the *Tectonic Mélange* shows a pervasive NE-vergent scaly fabric (Figs.  
303 7B and 7C) defined by anastomosing P and R shears, which are compatible with the overall  
304 reverse sense of shearing (Fig. 6C). Interlacing of disjunctive shear surfaces and the S-C  
305 fabric elements subdivides the shaly matrix into mm- to cm-long, lozenge-shaped lenses  
306 (Figs. 7B and 7C), whose surfaces are generally well polished and smooth.

307

308 Our scanning electron microscope observations also show the evidence of a pervasive S-C  
309 fabric in the shaly matrix that defines submillimetric to millimetric, sigmoidal-shaped lenses  
310 with polished and striated surfaces. These surfaces are finely spaced (few  $\mu\text{m}$ -to tens of  $\mu\text{m}$ )  
311 and envelope tabular, phacoidal (or rarely equidimensional), small clasts (5-20  $\mu\text{m}$  in size)  
312 that are strongly aligned with the main fabric in the rocks (Fig. 7D). This fabric is defined by  
313 the reorientation of clay particles and elongated clasts during shear deformation.

314

### 315 **3.3 Diapiric Mélange**

316

317 Diapiric processes reworked the block-in-matrix fabric elements of both the *Broken Formation*  
318 and the *Tectonic Mélange* of the *Argille varicolori*, forming tens to hundreds of meters-wide  
319 diapiric bodies and dm- to m-wide shaly dike injections in the hanging wall units of the main  
320 thrust faults (Figs. 4 and 8A). In the field, the subvertical block-in-matrix fabric of the diapiric  
321 intrusions makes a sharp contact against the low-angle, NW-striking and “structurally ordered”  
322 fabric of the older *Broken Formation* and the *Tectonic Mélange* (Fig. 8A). In map view, the  
323 wider diapiric bodies display a roughly rounded or an elliptical shape (Figs. 4 and 8A),  
324 characterized by the concentric juxtaposition of disrupted stratigraphic horizons wrenched  
325 from both the *Argille varicolori*, the buried “basal complex”, and the older stratigraphic



326 succession (i.e., Scabiazza sandstone, Maiolica limestone, Palombini shale, etc.; see Fig.  
327 8B). Irregularly shaped blocks of the Monte Cassio Flysch and some rare blocks of the Upper  
328 Eocene – Oligocene *Tertiary Piedmont Basin* succession also occur within the diapiric  
329 mélange.

330

331 At the mesoscale and in its type locality (located in the northern sector; see Fig. 8A), the  
332 diapiric bodies show internal structural zoning (*sensu* Orange, 1990; Dela Pierre et al., 2007;  
333 Festa, 2011). Their margins are characterized by a sub-vertical block-in-matrix fabric with  
334 mainly phacoidal (rarely tabular) blocks (Fig. 8B). The long axes of the blocks range from 20  
335 cm to 40 cm, with a mean aspect ratio (long axis/short axis) of 2.5 to 2.6 (Figs. 6A and 6B).  
336 These blocks are enveloped by a varicolored shaly matrix displaying a pervasive, vertical  
337 scaly fabric (Fig. 6C) and flame-shaped injections wrapping around the blocks (Fig. 8C). The  
338 center of the diapiric bodies shows non-cylindrical folds (isoclinal-to disharmonic) with  
339 irregular axial surfaces and subvertical fold axes (Figs. 6C and 8A). The limbs of these folds  
340 have changed progressively into boudinage and pinch-and-swell features. The shaly matrix  
341 includes meter-size and larger folds traced by the sub-vertical alignment of the fragments of  
342 disrupted beds. The blocks are commonly larger in the center of the diapiric bodies than those  
343 along the margins ranging in length from 35 cm to 90 cm, and showing a mean aspect ratio  
344 (long axis/short axis) of 2.1 to 2.3 (Figs. 6A and 6B).

345

346 Scanning electron microscope observations of the shaly matrix of the diapiric bodies reveal a  
347 sub-vertical flow fabric defined by the overall alignment of the platelets of clay minerals  
348 defining anastomosing and folded cleavage domains (Fig. 8E). Surfaces of the clay platelets  
349 do not show striations. Clay particles in the center of the diapiric bodies are commonly

350 deformed into isoclinal or irregular and convolute folds (fold hinges 10-20  $\mu\text{m}$  wide) with axial  
351 surfaces aligned parallel to the flow fabric (Fig. 8E). Cleavage domains drape around the  
352 rounded to irregularly shaped clasts. Only the long-axes of the clasts are aligned with the flow  
353 fabric (Fig. 8E). Similar convolute folds also occur near and along the margins of the diapiric  
354 bodies with less irregularly deformed and well aligned clay particles (Fig. 8F) forming  
355 sigmoidal domains that are crosscut and reoriented by the sub-vertical S-C fabric elements.

356

### 357 **3.4 Sedimentary *mélange* (i.e., Polygenetic argillaceous breccias)**

358

359 The *Sedimentary mélange*, here named “*Polygenetic argillaceous breccias*” (Figs. 3 and 4),  
360 has been distinguished from the *Argille varicolori*. It consists of a late Oligocene chaotic block-  
361 in-matrix unit. At the map scale (Fig. 4), the polygenetic argillaceous breccias consist of up to  
362 50-m-thick, irregularly shaped chaotic mass-transport deposits with irregular shape that  
363 unconformably overlie both the External Ligurian Units (i.e., Monte Cassio Flysch and *Argille*  
364 *varicolori*) and the upper Eocene-Oligocene sedimentary rocks of the *Tertiary Piedmont Basin*  
365 (i.e., Monte Piano marls and Cardona Formation).

366

367 At the mesoscale (Fig. 9A), the block-in-matrix fabric of the argillaceous breccias is  
368 characterized by a highly disordered polymictic assemblage of rock clasts and blocks (1 cm to  
369 15 cm in size) of different ages and origins. The clasts and blocks are mainly angular to  
370 rounded in shape (mean aspect ratio of the blocks: 1.5–1.7; Figs. 6A and 6B) and are  
371 randomly distributed in a brecciated shaly matrix. The blocks are of the same lithologies as  
372 those of the diapiric *mélange*, and include some material derived from the “basal complex”  
373 (i.e., *Argille varicolori*, Scabiazza sandstone, Palombini shale) and the older stratigraphic

374 succession (i.e., Maiolica limestone, reddish limestone) of the External Ligurian units, as well  
375 as from the Monte Cassio Flysch, and the Upper Eocene–Upper Oligocene succession of the  
376 *Tertiary Piedmont Basin* (Monte Piano marls and Cardona Formation). The shaly matrix (Fig.  
377 9B) is typically brecciated and envelops a polymictic assemblage of sub-millimeter to cm-long,  
378 sub-angular to rounded clasts. Elongated clasts commonly display micro-faults or fractures  
379 that accommodated extensional deformation related to mass-transport movements. In the  
380 outcrop or in the hand sample, the breccias show a structureless, isotropic fabric defined by  
381 the random distribution and orientation of the clasts, dispersed in the shaly matrix (Figs. 9A,  
382 9B and 9C).

383

384 Locally, alternating superposition of dm- to m-thick, brecciated lenticular bodies are bounded  
385 by irregular erosional surfaces and highly sheared varicolored shaly layers (Fig. 9C). This  
386 feature may have formed as a result of the repeated emplacement and superposition of minor  
387 mass-transport deposits, which demonstrate different degrees of liquefaction and variety of  
388 blocks in the shaly matrix. The extensional shearing-related features, which correspond to a  
389 narrow (up to 50 m thick) shear zone, related to the emplacement of the polygenetic  
390 argillaceous breccias, indicate direction of emplacement of the different mass-transport  
391 bodies radially away from main diapiric bodies (Fig. 10A).

392

393 In the basal part of the argillaceous breccias the fabric shows a planar anisotropy defined by  
394 the alignment of elongated blocks parallel to the extensionally sheared layers and to the  
395 erosive basal surface (Fig. 10B). This fabric is crosscut at low angles by disjunctive  
396 extensional shear surfaces (low angle Riedel shear; see Fig. 10B).

397

398 Scanning electron microscope observations show scale invariance with the mesoscopic fabric  
399 described above. The microscale fabric of the argillaceous breccias is characterized in part by  
400 rounded clasts (up to 250  $\mu\text{m}$ -long) randomly distributed in a brecciated matrix, which  
401 contains strongly aligned clay particles (Fig. 9D). This matrix shows discontinuous and  
402 anastomosing surfaces wrapping around the clasts (Fig. 9E) without any trace of shearing.  
403 Only the long-axes of the clasts exhibit a common planar orientation roughly parallel to the  
404 alignment of clay particles. Spacing between the clay particles varies based on the presence  
405 or absence of clasts, and may range from  $\sim 10$  to 15  $\mu\text{m}$  in domains with abundant clasts, or  
406 from 3 to 5  $\mu\text{m}$  where clasts are scarce or absent (Fig. 9E).

407

408 Close to the basal erosional contact, the microscale fabric of the argillaceous breccias  
409 consists of sheared extensional domains defined by the alignment of compacted clay particles  
410 (cleavage domains, 3 to 5  $\mu\text{m}$  spaced) that are crosscut by low-angle, C'-type shear surfaces  
411 (*sensu* Passchier and Trouw, 2005) (Fig. 10C). Clasts here are mainly elongated and aligned  
412 parallel to the basal surface.

413

414 Decimeter- to meter-wide and up to few meter-long shale dikes intrude (Figs. 4 and 8A) the  
415 polygenetic argillaceous breccias. These dikes are composed of subvertical and convoluted  
416 injections of fluidal, red and gray shale with irregular but sharp contacts (Figs. 11A, 11B and  
417 11C). Small, cusped and flame structures, up to dm-wide, and cm- to dm-long, commonly  
418 occur along the sharp contacts of the dikes, and intrude laterally into the country rocks (Fig.  
419 11B and 11D). The matrix shows a sub-vertical deformational fabric wrapping around the  
420 tabular and boudinaged blocks (cm in size), which are rotated and reoriented parallel to the

421 subvertical margins of these injections (Figs. 11C and 11D). Locally, the matrix displays  
422 irregular, isoclinal folds with boudinaged limbs.

423

424 The microscale fabric (SEM images) of the shale dikes shows the same characteristic,  
425 vertically oriented structures commonly seen along the margins of the diapiric bodies. A  
426 microscale fabric similar to that described from the core zone of the diapiric bodies occurs  
427 only in the wider dike injections (few dm-wide; see Figs. 11E and 11F).

428

#### 429 **4. Discussion**

430

431 The imprint of tectonic, sedimentary and diapiric processes is recorded at all scales (from  
432 map- to micro-scale) in the fabric of the diverse chaotic rock units recognized in the “basal  
433 complex” of the External Ligurian Units and in the *Tertiary Piedmont Basin* succession in  
434 Monferrato (Table 1). The structural relationships between these chaotic rock units provide us  
435 with an excellent opportunity to document the processes of mélangé formation, their ages,  
436 and the polygenetic, time-progressive tectonic evolution of the Ligurian accretionary wedge  
437 during the Late Cretaceous through late Oligocene. In contrast to the Circum-Pacific  
438 mélanges (e.g., the Franciscan Complex in the Western Cordillera, USA) or to those  
439 metamorphic mélangé units (e.g., Western Alps), in which an age-ordered stratigraphic  
440 columnar section does not convey the duality in different ages of the accretionary complex  
441 units (i.e., formational age versus accretionary age of the units; formational age of far-traveled  
442 oceanic units versus formational age of offscraped trench sediments), the mélanges we  
443 describe from Monferrato can be easily compared with other mélangé occurrences all along  
444 the Ligurian accretionary wedge whose stratigraphy (see Fig. 3) is readily correlated across

445 the major thrust faults. Thus, the mélanges documented in this paper provide new constraints  
446 on the lateral variations (i.e., along strike) in the structural evolution of the Ligurian  
447 accretionary wedge in NW Italy.

448

#### 449 **4.1. Late Cretaceous - middle Eocene tectonic stage**

450

451 The layer-parallel extensional block-in-matrix fabric of the *Broken Formation* (i.e., Upper  
452 Cretaceous *Argille varicolori*) is consistent with a large –magnitude lateral spreading that  
453 resulted in flattening (mean aspect ratio of the blocks: 3.5–4; [Fig. 6B](#) and [Table 1](#)) in two  
454 orthogonal directions in unconsolidated sediments. The mechanisms responsible for this type  
455 of deformation have been discussed extensively in the literature and are commonly  
456 interpreted as a product of tectonic flattening across the basal shear zone of accretionary  
457 wedges (e.g., Davis et al., 1983; Lash, 1987; Kimura and Mukai, 1991; Onishi and Kimura,  
458 1995; Hashimoto and Kimura, 1999; Kusky and Bradley, 1999; Yamamoto, 2006) or  
459 gravitational sliding on the inner trench slope (e.g., Cowan, 1985; Pini, 1999). In the Northern  
460 Apennines, this deformation has been related to a shortening event which occurred in the  
461 frontal and shallower levels of the Ligurian accretionary wedge (e.g., Pini, 1999; Vannucchi  
462 and Bettelli, 2002; Bettelli and Vannucchi, 2003) in the latest stages of accretion, and prior to  
463 the continental collision (e.g., Principi and Treves, 1984; Vai and Castellarin, 1993; Marroni  
464 and Pandolfi, 1996; Pini, 1999; Bettelli and Vannucchi, 2003; Codegone et al., 2012b).

465

466 Our data and observations suggest that during the early stages of deformation, the *Argille*  
467 *varicolori* underwent vertical compaction due to burial ([Fig. 12](#)), which resulted in the  
468 formation of boudinage structures, in the compaction and flattening of clay particles, and the

469 decrease of porosity (Fig. 12B). When sediments made their way to the toe of the wedge,  
470 compressional stress and tectonic loading produced asymmetrical boudinage and R and R'  
471 shears in the more lithified layers, and C'-type shears (*sensu* Passchier and Trouw, 2005) in  
472 the shaly matrix (Fig. 12C).

473

474 The coeval development of flattened, intralayer sheath-like folds, layer-parallel extensional  
475 fabric, and asymmetric boudinage (Fig. 12C) might have resulted from the heterogeneity of  
476 deformation at the toe of the accretionary wedge (e.g., Kimura and Mukai, 1991; Onishi and  
477 Kimura, 1995; Kusky and Bradley, 1999). The undulation of the decollement surface (see  
478 Onishi and Kimura, 1995) and/or the orientation of the layers with respect to  $\sigma_1$  might have  
479 also played a role in this heterogeneous deformation (see Kusky and Bradley, 1999). Layers  
480 dipping at high angles ( $30^\circ$ - $45^\circ$ ) to  $\sigma_1$  may have experienced both brittle extension (i.e.,  
481 boudinage, R-R', C' shears and low-angle extensional faulting) and ductile contraction (i.e.,  
482 folding) (Fig. 12C). Thus, at the toe of an accretionary wedge (Fig. 12A) different domains can  
483 exist where layer-parallel extension develops parallel to the fold axial surfaces, and the  
484 structures can be indistinguishable from the early extensional fabric related to vertical loading  
485 (see Kusky and Bradley, 1999).

486

487 The above-described observations indicate that deformation started just after the deposition  
488 of sediments, under unconsolidated conditions, and continued throughout progressive  
489 lithification. Therefore, the age of the earliest deformation episode must have been very close  
490 to the timing of deposition (i.e., Late Cretaceous-to middle Eocene). The structures related to  
491 this earliest deformation stage have been sealed by the unconformable deposition of the

492 upper Eocene Monte Piano marls, which represent the base of the *Tertiary Piedmont Basin*  
493 succession (Fig. 4).

494

#### 495 **4.2. Late Oligocene**

496

497 The layer-parallel extensional fabric of the *Broken Formation* (i.e., Upper Cretaceous *Argille*  
498 *varicolori*) was overprinted and reworked by NE–vergent thrusting (with secondary left-lateral  
499 strike slip component of movement) and associated shearing during the late Oligocene (Fig.  
500 4). Thrusting and shearing collectively led to the development of a polygenetic mélange of a  
501 tectonic origin (i.e., *Tectonic Mélange*; Figs. 13A and 13A'), characterized by a “structurally  
502 ordered” block-in-matrix fabric that is consistent with the direction of inferred regional  
503 shortening (see Fig. 6C). This shortening event emplaced the External Ligurian Units onto the  
504 Upper Eocene–Oligocene stratigraphic units of the *Tertiary Piedmont Basin* (e.g., Piana,  
505 2000; Dela Pierre et al., 2003b; Festa et al., 2005; 2009b; see also Fig. 6C), and resulted in  
506 the imbrication and mixing of native and exotic blocks, mainly derived from the buried Monte  
507 Cassio Flysch, the “basal complex” (i.e., Scabiazza sandstone, Palombini shale), the older  
508 lithostratigraphic units (i.e., Maiolica limestone), and minor slices of the Upper Eocene–  
509 Oligocene *Tertiary Piedmont Basin* succession. Exotic blocks offscraped from the footwall  
510 units were accreted within the thrust shear zone and mixed with native blocks derived from  
511 the earlier *Broken Formation*. The shaly varicolored matrix facilitated the concentration of  
512 shearing deformation (i.e., pervasive scaly fabric and S-C shears), and together with fluid  
513 focused along the fault surface helped the mobilization of hard blocks and mixing processes  
514 (Figs. 13A and 13A'). The smaller size of native blocks in the *Tectonic Mélange* (mean long-  
515 axis 20 cm) with respect to those in the *Broken Formation* (mean long-axis 33 cm) shows that



516 the magnitude of the tectonic strain during this thrusting event was significant. The gradual  
517 transition from the *Tectonic Mélange* to the *Broken Formation*, as evidenced by decreasing of  
518 both shear deformation and the occurrence of exotic blocks far from the thrust surface, shows  
519 that the fault zone was not bounded by a sharp tectonic contact on top. The shaly matrix  
520 accommodated thrust-related deformation along a series of several dm-thick shear zones and  
521 a pervasive scaly fabric, rather than concentrating the deformation in subparallel major thrust  
522 faults bounding the *Tectonic Mélange*.

523

524 The *Tectonic Mélange* differs from those ones occurring in typical subduction (e.g., Circum-  
525 Pacific region) or collisional (e.g., Western Alps) settings where exotic blocks commonly  
526 derived from a long-subducted footwall and/or by return flow (e.g., flow mélanges of Cloos,  
527 1982). Our *Tectonic Mélange*, that formed at shallow structural levels within the accretionary  
528 wedge, provides another example in supporting that mélanges formed directly by tectonic  
529 processes correspond to tectonic units structurally equivalent to mappable fault zones (see  
530 Cowan, 1974; Festa et al., 2010a). For example, in fact, the block-in-matrix fabric of the San  
531 Andreas fault (California) at depth, observed through drill cores, has been compared with  
532 those of tectonic mélanges (see Bradbury et al., 2011).

533

534 Because of the low permeability of the *Argille varicolori*, fluids concentrated along both thrust  
535 faults and micron- to mm-scale scaly cleavage surfaces reached the overpressure conditions,  
536 which are required to facilitate shale diapirism (e.g., Collison, 1994; Maltman, 1994; Festa,  
537 2011, Codegone et al., 2012b; see [Fig. 13B](#)). Then, overpressurized sediments exceeding the  
538 hydrostatic pressure started rising upward and formed the diapiric injections. The difference in  
539 the velocity gradient of the upward rising shaly material (acting as a viscous fluid), increasing

540 from the margins toward the core of the shale diapirs, produced an internal zoning within the  
541 diapiric bodies (Fig. 8A) (e.g., Komar, 1972; Bishop, 1978; Orange, 1990; Dela Pierre et al.,  
542 2007; Festa, 2011). This process resulted in: (i) the distribution of small phacoidal blocks  
543 (long-axis length: 20 to 40 cm; mean aspect ratio: 2.5-2.6; Figs. 6A, 6B and Table 1) along  
544 the margins of the diapiric bodies, and in their preferred alignment with the intrusive contacts;  
545 and (ii) the irregular distribution of larger, irregularly shaped blocks (long-axis length: 35 to 90  
546 cm; mean aspect ratio: 2.1-2.3; Figs. 6A, 6B and Table 1) and the formation of irregular folds  
547 with steeply plunging axes in the cores of these diapirs. The flow fabric, as observed on the  
548 scanning electron microscope images of the samples from the cores of the diapirs (Fig. 8E),  
549 is consistent with the occurrence of overpressurized fluids without shearing. On the contrary,  
550 shearing-induced structural fabric characterizes the internal architecture of the marginal  
551 zones of the diapiric bodies (Fig. 8F).

552

553 Extrusion of the diapiric bodies on the seafloor formed topographic highs (Fig. 13B), causing  
554 the downslope mobilization of unconsolidated sediments and promoting local mass-transport  
555 movements (Fig. 13C and 13C'). These mass-transport deposits were locally augmented by  
556 the extruded diapiric material (Figs. 13C and 13C'), as evidenced by the occurrence of the  
557 same exotic and native blocks in both the diapiric and sedimentary *mélanges* (*Polygenetic  
558 argillaceous breccias*). Both the radial direction of extensional shearing at the base of the  
559 polygenetic argillaceous breccias and the distribution of mass-transport bodies with respect to  
560 the main diapiric bodies (Fig. 10A) are consistent with the role of diapirism in providing the  
561 source material for the emplacement of mass-transport chaotic deposits (see also Barber et  
562 al., 1986; Barber and Brown, 1988; Barber, 2013). Although, this role is well documented in  
563 modern accretionary prisms (see, e.g., Camerlenghi and Pini, 2009 and reference therein);

564 rarely has it been documented from ancient examples (see Barber, 2013 and reference  
565 therein). The *Sedimentary mélanges* in Monferrato unconformably overlie and cover the thrust  
566 fault, which was responsible for the emplacement of the External Ligurian Units on the upper  
567 Eocene–Oligocene *Tertiary Piedmont Basin* succession. These spatial and temporal  
568 relationships constrain the timing of the emplacement of the mass-transport chaotic deposits  
569 as the late Oligocene (Fig. 4).

570

571 The occurrence, at all scales, of the sheared extensional fabric at the base of these mass-  
572 transport chaotic deposits (Fig. 10B) and its passing upward to a random distribution of  
573 rounded and irregular blocks in a brecciated matrix (Figs. 9A and 9B) is consistent with the  
574 mode of debris flow and mud flow processes (e.g., Pini et al., 2012). These processes were  
575 able to disaggregate, mix and reorient the fabric of the source material in the *Diapiric Mélange*  
576 as also supported by the smaller size of hard blocks of the *Sedimentary Mélange* with respect  
577 to that of the *Diapiric Mélange*.

578

579 The occurrence of small-scale shale dike injections piercing through the Upper Oligocene  
580 *Polygenetic argillaceous breccias* suggests that the upward rise of overpressured fluids  
581 locally continued during and/or after the formation of these breccias (Figs. 13C' and 13C'').  
582 These shale dikes have also been documented in the Northern Apennines (Codegone et al.,  
583 2012b) where, however, different causative links have been documented between tectonic,  
584 sedimentary and diapiric processes, supporting that the structural and morphological  
585 reconstruction of the Ligurian accretionary wedge was highly dynamic and varied along strike.  
586 The combined effect of sedimentary loading provided by the early post-emplacement of the  
587 *polygenetic argillaceous breccias* (i.e., dissipation of internal fluid overpressure) and the

588 discharge of fluids after the faulting stage was responsible for the emplacement of these small  
589 dike injections. It is difficult to make these observations at the same scale (meters to tens of  
590 meters) in mass-transport deposits in modern accretionary wedges because these types of  
591 overpressured fluid features (i.e., shale dike injections) are below the standard resolution of  
592 geophysical investigations. However, the documentation of a new, overpressurized fluid  
593 supply following the emplacement of a *Sedimentary Mélange* may provide important  
594 information on the preconditioning factors that may induce downslope remobilization of the  
595 previously formed mass-transport deposits or sedimentary mélanges in modern accretionary  
596 wedges. Such remobilization may trigger major tsunami events, and hence they are  
597 potentially highly dangerous (see Kawamura et al., 2012).

598

## 599 **5. Conclusions**

600

601 The Late Cretaceous–late Oligocene Ligurian chaotic deposits exposed in Monferrato (NW  
602 Italy) represent an ancient analogue of a modern convergent margin accretionary wedge. This  
603 exhumed accretionary wedge includes a composite chaotic unit, known as the Upper  
604 Cretaceous *Argille varicolori*, and *Tectonic*, *Diapiric* and *Sedimentary Mélanges*. The  
605 youngest, *Sedimentary Mélange* is a result of the late Oligocene gravitational reworking of the  
606 previously formed mélanges. All these chaotic deposits and mélanges display a record of the  
607 mutual causative links among tectonic, diapiric and sedimentary processes that controlled the  
608 dynamic equilibrium of the wedge through time.

609

610 A gradual transition from homogeneous to heterogeneous deformation occurred at the toe of  
611 the accretionary wedge in the Late Cretaceous through middle Eocene, following the

612 deposition of the Upper Cretaceous *Argille varicolori*. The stratal disruption of this unit  
613 produced the *Broken Formation* with increased shearing. The frontal part of the wedge was  
614 subject to high instability during and after the continental collision in the late Oligocene. Out-  
615 of-sequence thrusting (with a secondary strike-slip component of movement) in the inner  
616 wedge formed the polygenetic *Tectonic Mélange*, and facilitated the mixing of exotic blocks  
617 with the *Broken Formation*. The increase of fluid pressure along the thrust faults created over-  
618 pressurized hydraulic conditions triggering diapiric processes, which caused the reworking of  
619 the previously formed *Broken Formation* and *Tectonic Mélange*. This event developed the  
620 *Diapiric Mélange*. The downslope mobilization of unconsolidated, diapiric material produced  
621 the late Oligocene *Sedimentary Mélange*. These chaotic deposits of the *Sedimentary*  
622 *Mélange* sealed the out-of-sequence thrust faults and marked the end of *mélange* formation  
623 within the Ligurian accretionary wedge.

624

625 Our findings from the Late Cretaceous–late Oligocene chaotic deposits in Monferrato show  
626 that the frontal wedge of an accretionary complex may evolve through a combination of  
627 tectonic, diapiric and sedimentary processes that commonly overlap in time and space.  
628 Studying and documenting the mode and time of these processes in both modern and ancient  
629 examples of accretionary wedges is highly important and relevant in order for us to better  
630 understand how the gravitational instability and tectonic processes in these convergent  
631 margin products may lead to tsunamic events.

632

633

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641

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643

## 644 **References**

645

646 Aalto, K.R., 1981, Multistage melange formation in the Franciscan Complex, northernmost California:  
 647 *Geology*, v. 9, p. 602–607.

648

649 Alonso, J.L., Marcos, A., and Suárez, A., 2006, Structure and organization of the Porma mélange:  
 650 progressive denudation of a submarine nappe toe by gravitational collapse, *American Journal of*  
 651 *Science*, v. 306, p. 32–65.

652

653 Barber, T., 2013, Mud diapirism: The origin of mélanges: cautionary tales from Indonesia: *Journal of*  
 654 *Asian Earth Sciences*, early on line, <http://dx.doi.org/10.1016/j.jseaes.2012.12.021>.

655

656 Barber, T., and Brown, K., 1988, Mud diapirism: The origin of melanges in accretionary complexes?:  
 657 *Geology Today*, v. 4, p. 89–94.

658

659 Barber, A.J., Tjokrosapoetro, S., and Charlton, T.R., 1986, Mud volcanoes, shale diapirs, wrench  
 660 faults, and melanges in accretionary complexes, Eastern Indonesia: *American Association of*  
 661 *Petroleum Geologists Bulletin*, v. 70, no. 11, p. 1729-1741.

662

663 Barnes, P.M., and Korsch, R.J., 1991, Mélange and related structures in Torlesse accretionary wedge,  
 664 Wairarapa, New Zealand: *New Zealand Journal of Geology and Geophysics*, v. 34, p.517–532.

665

666 Beets, C., 1940, Die Geologie des Westlichen Teiles der Berge von Monferrato zwischen Turin und  
 667 Murinsengo. Ein Beitrag Zur Geologie des Nortapennis: *Leidsche Geologische Mededeelingen*,  
 668 v. 12, p. 195-250.

669

670 Bello, M., and Fantoni, R., 2002, Deep oil play in Po Valley: Deformation and hydrocarbon generation  
 671 in a deformed foreland,. In: *Deformation history, fluid flow reconstruction and reservoir appraisal*  
 672 *in foreland fold and thrust belts: American Association of Petroleum Geologists, Hedberg*  
 673 *Conference*, 1–4.

674

675 Bettelli, G., and Panini, F., 1989, I mélanges dell'Appennino settentrionale tra il T. Tresinaro ed il T.  
 676 Sillaro: *Memorie della Società Geologica Italiana*, v. 39, p. 187–214.

677

678 Bettelli, G., and Vannucchi, P., 2003, Structural style of the offscraped Ligurian oceanic sequences of  
 679 the Northern Apennines: new hypothesis concerning the development of mélange block-in-matrix  
 680 fabric: *Journal of Structural Geology*, v. 25, p. 371-388.

681

682 Biella, G., Polino, R., de Franco, R., Rossi, P.M., Clari, P., Corsi, A., and Gelati, R., 1997, The crustal  
 683 structure of the Western Po Plain: reconstruction from integrated geological and seismic data:  
 684 *Terra Nova*, v. 9, p. 28-31.

685

686 Bigi, G., Cosentino, D., Parotto, M., Sartori, R., and Scandone, P., 1983, Structural Model of Italy:  
 687 Geodynamic project, C.N.R., S.El.Ca. Firenze, scale 1:500,000, 9 sheets.

688

- 689 Bishop, R.S., 1978, Mechanism for emplacement of piercement diapirs: American Association of  
690 Petroleum Geologists Bulletin, v. 62, p. 1561–1583.  
691
- 692 Bonsignore, G., Bortolami, G., Elter, G., Montrasio, A., Petrucci, F., Ragni, U., Sacchi, R., Sturani, C.,  
693 and Zanella, E., 1969, Note Illustrative dei Fogli 56-57, Torino-Vercelli della Carta Geologica  
694 d'Italia alla scala 1:100,000: Servizio Geologico d'Italia, Roma, 96 p.  
695
- 696 Bortolotti, V., Marroni, M., Pandolfi, L., and Principi, G., 2005, Mesozoic to Tertiary tectonic history of  
697 the Mirdita ophiolites, northern Albania: Island Arc, v. 14, p. 471–493.  
698
- 699 Bradbury, K.M., Evans, J.P., Chester, J.S., Chester, F.M., and Kirschner, D.L., 2012, Lithology and  
700 internal structure of the San Andreas fault at depth based on characterization of Phase 3 whole-  
701 rock core in the San Andreas Fault Observatory at Depth (SAFOD) borehole: Earth and  
702 Planetary Science Letters, v. 310, p. 131–144.  
703
- 704 Brown, K.M., 1990, The nature and hydrogeologic significance of mud diapirs and diatremes for  
705 accretionary systems: Journal of Geophysical Research, v. 95, p. 8969–8982.  
706
- 707 Brown, K.M., and Westbrook, G.K., 1988, Mud diapirism and subcretion in the Barbados ridge  
708 accretionary complex: The role of fluids in the accretionary processes: Tectonics, v. 7, p. 613–  
709 640.  
710
- 711 Buiter, S.J.H., 2012, A review of brittle compressional wedge models: Tectonophysics, v. 530-531, p.  
712 1-17.  
713
- 714 Byrne, T., and Fisher, D., 1990, Evidence for a weak overpressured décollement beneath sediment-  
715 dominated accretionary prisms: Journal of Geophysical Research, v. 95, B6, p. 9081-9097.  
716
- 717 Camerlenghi, A., and Pini, G.A., 2009, Mud volcanoes, olistostromes and Argille scagliose in the  
718 Mediterranean region: Sedimentology, v. 56, p. 319-365.  
719
- 720 Carminati, E., Doglioni, C., and Scrocca, D., 2004, Alps vs Apennine, *in* Crescenti, U., D'offizi, S.,  
721 Merlino, S., and Sacchi, L., eds., Geology of Italy: Special volume of the Italian Geological  
722 Society for the IGC 32 Florence-2004, p. 141–152.  
723
- 724 Castellarin, A., 1994, Strutturazione eo-mesoalpina dell'Appennino Settentrionale attorno al “nodo  
725 ligure”, *in* Capozzi, R., and Castellarin, A., eds., Studi preliminari all'acquisizione dati del profilo  
726 CROP 1–1A La Spezia–Alpi orientali: Studi Geologici Camerti, Volume Speciale 1992/2,  
727 Camerino, Università degli Studi di Camerino, p. 99-108.  
728
- 729 Cavazza, W., Roure, F., and Ziegler, P.A., 2004, The Mediterranean area and the surrounding  
730 regions: active processes, remnants of former Tethyan oceans and related thrust belts, *in*  
731 Cavazza, W., Roure, F., Spakman, W., Stampfli, G.M., and Ziegler, P.A., eds., The TRANSMED  
732 Atlas: The Mediterranean Region from crust to mantle: Springer, p. 1–29.  
733
- 734 Chamot-Rooke, N., Rabaute, A., and Kreemer, C., 2006, Western Mediterranean Ridge mud belt  
735 correlates with active shear strain at the prism-backstop geological contact: Geology, 33, p. 861–  
736 864.  
737
- 738 Clift, P., and Vannucchi, P., 2004, Controls on tectonic accretion versus erosion in subduction zones:  
739 Implications for the origin and recycling of the continental crust: Reviews of Geophysics, v. 42,  
740 RG2001, doi:10.1029/2003RG000127.

- 741  
742 Cloos, M., 1982, Flow melanges: Numerical modeling and geologic constraints on their origin in the  
743 Franciscan subduction complex, California: Geological Society of America Bulletin, v. 93, p. 330–  
744 345.
- 745  
746 Cloos, M., 1984, Flow mélanges and structural evolution of accretionary wedges, *in* Raymond L.A.,  
747 ed., Mélanges: their nature, origin and significance: Geological Society of America Special Paper  
748 198, p. 71-79.
- 749  
750 Codegone, G., Festa, A., and Dilek, Y., 2012a, Formation of Taconic mélanges and Broken formations  
751 in the Hamburg Klippe, Central Appalachian orogenic belt, Eastern Pennsylvania:  
752 Tectonophysics, v. 568-569, p. 215-229. doi:10.1016/j.tecto.2012.03.017
- 753  
754 Codegone, G., Festa, A., Dilek, Y., and Pini, G.A., 2012b, Small-scale Polygenetic mélanges in the  
755 Ligurian accretionary complex, Northern Apennines, Italy, and the role of shale diapirism in  
756 superposed mélange evolution in orogenic belts: Tectonophysics, v. 568-569, p. 170-184.  
757 doi:10.1016/j.tecto.2012.02.003
- 758  
759 Collison, J., 1994, Sedimentary deformational structures, *in* Maltman, A., ed., The geological  
760 deformation of sediments: Chapman & Hall, London, p. 96–125.
- 761  
762 Collot, J-Y., Lewis, K., Lamrche, G., and Lallemand, S. 2001, The giant Ruatoria debris avalanche on  
763 the northern Hikurangi margin, New Zealand: Result of oblique seamount subduction: Journal of  
764 Geophysical Research, v. 106, B9, p. 19271-19297.
- 765  
766 Collot, J.-Y., Ribodetti, A., Agudelo, W., and Sage, F., 2011, The South Ecuador subduction channel:  
767 Evidence for a dynamic mega-shear zone from 2D fine-scale seismic reflection imaging and  
768 implications for material transfer: Journal of Geophysical Research, v. 116, B11102,  
769 doi:10.1029/2011JB008429.
- 770  
771 Cowan, D.S., 1974, Deformation and metamorphism of the Franciscan Subduction Zone Complex  
772 northwest of Pacheco Pass, California. Geological Society of America Bulletin: v. 85, p. 1623–  
773 1634.
- 774  
775 Cowan, D.S., 1985, Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of  
776 North America: Geological Society of America Bulletin, v. 96, p. 451-462.
- 777  
778 Cowan, D.S., and Pini, G.A., 2001, Disrupted and chaotic rock units in the Apennines, *in* Vai, G.B.,  
779 and Martini, I.P., eds., Anatomy of a Mountain Belt: The Apennines and Adjacent Mediterranean  
780 Basins: Kluwer Academic Publishers, Dordrecht, p. 165-176.
- 781  
782 Coward, M.P., and Dietrich, D., 1989, Alpine tectonics - an overview, *in* Coward, M.P., Dietrich, D.,  
783 and Park, R.G., eds., Alpine tectonics: Geological Society London Special Publications 45, p.  
784 1–29.
- 785  
786 Davis, D., Suppe, J., and Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary  
787 wedges: Journal of Geophysical Research, v. 88, p. 1153-1172.
- 788  
789 Dela Pierre, F., Festa, A., and Irace, A., 2007, Interaction of tectonic, sedimentary and diapiric  
790 processes in the origin of chaotic sediments: an example from the Messinian of the Torino Hill  
791 (Tertiary Piedmont Basin, NW Italy): Geological Society of America Bulletin, v. 119, 1107-1119.
- 792



- 793 Dela Pierre, F., Piana, F., Boano, P., Fioraso, G., and Forno, M.G., 2003a, Carta Geologica d'Italia  
794 alla scala 1:50,000 – Foglio 157 “Trino”: ISPRA, Istituto Superiore per la Protezione e Ricerca  
795 Ambientale. Ed. Litografia Geda, Nichelino, 1 Sheet.  
796
- 797 Dela Pierre, F., Piana, F., Fioraso, G., Boano, P., Bicchi, E., Forno, M.G., Violanti, D., Clari, P., and  
798 Polino, R., 2003b, Note Illustrative della Carta Geologica d'Italia alla scala 1:50,000. Foglio 157  
799 “Trino”: APAT, Dipartimento Difesa del Suolo, 147 p.  
800
- 801 Dilek, Y., Thy, P., Hacker, B., and Grundvig, S., 1999, Structure and petrology of Tauride ophiolites  
802 and mafic dike intrusions (Turkey): implications for the Neotethyan ocean: *Geological Society of  
803 America Bulletin*, v. 111, p. 1192–1216.  
804
- 805 Dilek, Y. and Robinson, P.T., 2003. Ophiolites in Earth history: Introduction, *in* Dilek, Y. and Robinson,  
806 P.T. (Eds.), *Ophiolites in Earth History: Geological Society of London Special Publications*, vol.  
807 218, p. 1-8.  
808
- 809 Dilek, Y., Shallo, M., and Furnes, H., 2005. Rift-drift, seafloor spreading, and subduction zone  
810 tectonics of Albanian ophiolites: *International Geology Review*, v. 47, p. 147–176.  
811
- 812 Dilek, Y., Festa, A., Ogawa, Y., and Pini, G.A., 2012, Chaos and geodynamics: Mélanges, Mélange-  
813 forming processes and their significance in the geological record: *Tectonophysics*, v. 568-569, p.  
814 1-6.  
815
- 816 Dileonardo, C.G., Moore, J.C., Nissen, S., and Bangs, N., 2002, Control of internal structure and fluid-  
817 migration pathways within the Barbados Ridge décollement zone by strike-slip faulting: Evidence  
818 from coherence and three-dimensional seismic amplitude imaging: *Geological Society of  
819 America Bulletin*, v. 114, p. 51–63.  
820
- 821 Duperret, A., Bourgois, J., Lagabrielle, Y., and Suess, E., 1995, Slope instabilities at an active  
822 continental margin: Large-scale polyphase submarine slides along the northern Peruvian  
823 margin, between 5°S and 6°S: *Marine Geology*, v. 122, p. 303–328, doi:10.1016/0025-  
824 3227(94)00125-5.  
825
- 826 Elter, G., Elter, P., Sturani, C., and Weidmann, M., 1966, Sur la prolongation du domaine ligure de  
827 l'Apennin dans le Monferrat et les Alpes et sur l'origine de la Nappe de la Simme s.l. des  
828 Préalpes romandes et chablaisannes: *Archives des Sciences de Genève*, v. 19, p. 279-377.  
829
- 830 Festa, A., 2011, Tectonic, sedimentary, and diapiric formation of the Messinian mélange: Tertiary  
831 Piedmont Basin (northwestern Italy), *in* Wakabayashi, J., and Dilek, Y., eds., *Mélanges:  
832 Processes of formation and societal significance: Geological Society of America Special Paper  
833 480*, p. 215-232. doi: 10.1130/2011.2480(10).  
834
- 835 Festa, A., Boano, P., Irace, A., Lucchesi, S., Forno, M.G., Dela Pierre, F., Fioraso, G., and Piana, F.,  
836 2009a, Carta Geologica d'Italia alla scala 1:50,000. Foglio 156 “Torino Est”. ISPRA, Istituto  
837 Superiore per la Protezione e Ricerca Ambientale. Ed. Litografia Geda, Nichelino, 1 Sheet.  
838
- 839 Festa, A., Dela Pierre, F., Irace A., Piana F., Fioraso G., Lucchesi S., Boano P., and Forno M.G.,  
840 2009b, Note Illustrative della Carta Geologica d'Italia alla scala 1:50,000. Foglio 156 “Torino  
841 Est”: ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale, Litografia Geda,  
842 Nichelino, p. 143.  
843

- 844 Festa, A., Dilek, Y., Pini, G.A., Codegone, G., and Ogata, K., 2012, Mechanisms and processes of  
845 stratal disruption and mixing in the development of mélanges and broken formations: Redefining  
846 and classifying mélanges: *Tectonophysics*, v. 568-569, p. 7-24. doi:10.1016/j.tecto.2012.05.021  
847
- 848 Festa, A., Piana, F., Dela Pierre, F., Malusà, M.G., Mosca, P., and Polino, R., 2005, Oligocene-  
849 Neogene kinematic constraints in the retroforeland basin of the Northwestern Alps: *Rendiconti  
850 della Società Geologica Italiana (nuova serie)*, v. 1, p. 107-108.  
851
- 852 Festa, A., Pini, G.A., Dilek, Y., and Codegone, G., 2010a, Mélanges and mélange-forming processes:  
853 a historical overview and new concepts: *in* Dilek, Y., ed., *Alpine Concept in Geology:  
854 International Geology Review*, v. 52, nos. 10-12, p. 1040-1105. doi:  
855 10.1080/00206810903557704.  
856
- 857 Festa, A., Pini, G.A., Dilek, Y., Codegone, G., Vezzani, L., Ghisetti, F., Lucente, C.C., and Ogata, K.,  
858 2010b, Peri-Adriatic mélanges and their evolution in the Tethyan realm, *in* Dilek, Y., ed.,  
859 Eastern Mediterranean geodynamics (Part II): *International Geology Review*, v. 52, nos. 4-6),  
860 p. 369-406. doi: 10.1080/00206810902949886.  
861
- 862 Goldfinger, C., Kulm, L.D., McNeill, L.C., and Watts, P., 2000, Super-scale failure of the southern  
863 Oregon Cascadia margin: *Pure and Applied Geophysics*, v. 157, p. 1189–1226, doi:  
864 10.1007/s000240050023.  
865
- 866 Gravelau, F., Malavieille, J., and Dominguez, S., 2012, Experimental modeling of orogenic wedges: a  
867 review: *Tectonophysics*, v. 538-540, p. 1-66.  
868
- 869 Gutscher, M.A., Kukowski, N., Malavieille, J., and Lallemand, S., 1998, Episodic imbricate thrusting  
870 and underthrusting: Analog experiments and mechanical analysis applied to the Alaskan  
871 accretionary wedge: *Journal of Geophysical Research*, v. 103, B5, 10, p.161–10,176,  
872 doi:10.1029/97JB03541.  
873
- 874 Haq, S.S.B., 2012, Out-of-sequence thrusting in experimental Coulomb wedges: implications for the  
875 structural development of mega-spaly and forearc basins: *Geophysical Research Letters*, v. 39,  
876 L20306, doi: 10.1029/2012GL053176  
877
- 878 Harris, R.A., Sawyer, R.K., and Audley-Charles, M.G., 1998, Collisional melange development:  
879 geologic associations of active melange-forming processes with exhumed melange facies in the  
880 western Banda orogen, Indonesia: *Tectonics*, v. 17, n. 3, p. 458-479.  
881
- 882 Hashimoto, Y., and Kimura, G., 1999, Underplating process from mélange formation to duplexing:  
883 Example from the Cretaceous Shimanto Belt, Kii Peninsula, southwest Japan: *Tectonics*, v. 18,  
884 p. 92–107.  
885
- 886 Hitz, B., and Wakabayashi, J., 2012, Unmetamorphosed sedimentary mélange with high-pressure  
887 metamorphic blocks in a nascent forearc basin setting: *Tectonophysics*, v. 568-569, p. 124-134.  
888
- 889 Hsü, K.J., 1968, Principles of mélanges and their bearing on the Franciscan-Knoxville Paradox:  
890 *Geological Society of America Bulletin*, v. 79, p. 1063–1074.  
891
- 892 Karig, D.E., and Sharman, G., 1975, Accretion and subduction in Pacific trenches: *Geological Society  
893 of America Bulletin*, v. 86, p. 377-389.  
894

- 895 Kawamura, K., Ogawa, Y., Oyagi, N., Kitahara, T., and Anma, R., 2007, Structural and fabric analyses  
896 of basal slip zone of the Jin'nosuke-dani landslide, northern central Japan: its application to the  
897 slip mechanism of decollement: *Landslides*, v. 4, p. 371-380.  
898
- 899 Kawamura, K., Sasaki, T., Kanamatsu, Y., Sakaguchi, A., Ogawa, Y., 2012, Large submarine  
900 landslides in the Japan Trench: A new scenario for additional tsunami generation: *Geophysical*  
901 *Research Letters*, v. 39, doi: 10.1029/2011GL050661.  
902
- 903 Kimura, G., and Mukai, A., 1991, Underplated units in an accretionary complex: melange of the  
904 Shimanto belt of eastern Shikoku, southwest Japan: *Tectonics*, v. 10, n. 1, p. 31-50.  
905
- 906 Komar, P.D., 1972, Flow differentiation in igneous dikes and sills: Profiles of velocity and phenocryst  
907 concentration: *Geological Society of America Bulletin*, v. 83, p. 3443–3448.  
908
- 909 Kopf, A., 2002, Significance of mud volcanism: *Reviews of Geophysics*, v. 40, p. 1–51.  
910
- 911 Kusky, T.M., and Bradley, D.C., 1999, Kinematic analysis of melange fabrics: examples and  
912 applications from the McHugh Complex, Kenai Peninsula, Alaska: *Journal of Structural Geology*,  
913 v. 21, p. 1773-1796.  
914
- 915 Lallemand, S., Collot, J.Y., Pelletier, B., Rangin, C., and Cadet, J.P., 1990, Impact of oceanic  
916 asperities on the tectonogenesis of modern convergent margins: *Oceanologica Acta*, v. 10, p.  
917 17–30.  
918
- 919 Lash, G.G., 1987, Diverse melanges of an ancient subduction complex: *Geology*, v. 15, p. 652-655.  
920
- 921 Maltman, A., 1994, Introduction and overview, *in* Maltman, A., ed.: *The geological deformation of*  
922 *sediments*. Chapman & Hall, London, p. 1–35.  
923
- 924 Marroni, M., and Pandolfi, L., 1996, The deformation history of an accreted ophiolite sequence: The  
925 internal Liguride units (northern Apennines, Italy): *Geodinamica Acta*, v. 9, p. 13–29.  
926
- 927 Marroni, M., and Pandolfi, L., 2007, The architecture of an incipient oceanic basin: a tentative  
928 reconstruction of the Jurassic Liguria-Piemonte basin along the Northern Apennines–Alpine  
929 Corsica transect: *International Journal of Earth Sciences*, v. 96, p. 1059–1078.  
930
- 931 Marroni, M., Meneghini, F., and Pandolfi, L., 2010, Anatomy of the Ligure-Piemontese subduction  
932 system: evidence from Late Cretaceous–middle Eocene convergent margin deposits in the  
933 Northern Apennines, Italy: *International Geology Review*, v. 52, p. 1160-1192.  
934
- 935 Marroni, M., Molli, G., Ottria, G., and Pandolfi, L., 2001, Tectono-sedimentary evolution of the External  
936 Liguride units (Northern Apennines, Italy): insight in the pre-collisional history of a fossil ocean-  
937 continent transition zone: *Geodinamica Acta*, v. 14, p. 307-320.  
938
- 939 Maxwell, J.C., 1974, Anatomy of an orogeny: *Geological Society of America Bulletin*, v. 85, p. 1195–  
940 1204.  
941
- 942 McAdoo, B.G., Capone, M.K., and Minder, K., 2004, Seafloor geomorphology of convergent margins:  
943 Implications for Cascadia seismic hazard: *Tectonics*, v. 23, TC6008,  
944 doi:10.1029/2003TC001570.  
945

- 946 Michiguchi, Y., and Ogawa, Y., 2011, Implication of dark bands in Miocene–Pliocene accretionary  
947 prism, Boso Peninsula, central Japan, *in* Wakabayashi, J., and Dilek, Y., eds., *Melanges:*  
948 *Processes of formation and societal significance: Geological Society of America Special Papers*  
949 *480*, p. 247-260.
- 950  
951 Moore, J.C., and Byrne, T., 1987, Thickening of fault zones: A mechanism of melange formation in  
952 accreting sediments: *Geology*, v. 15, p. 1040–1043.
- 953  
954 Moore, J.C., and Vrolijk, P., 1992, Fluids in accretionary prisms: *Reviews of Geophysics*, v. 30, no. 2),  
955 p. 113-135.
- 956  
957 Molli, G., Crispini, L., Malusà, G.M., Mosca, P., Piana, F., and Federico, L., 2010, Geology of the  
958 Western Alps – Northern Apennines junction area: a regional review: *Journal of Virtual Explorer*,  
959 v. 36, no. 10, doi: 10.3809/jvirtex.2010.00215
- 960  
961 Mosca, P., Polino, R., Rogledi, S., and Rossi, M., 2010, New data for the kinematic interpretation of  
962 the Alps-Apennines junction (Northwestern Italy): *International Journal of Earth Science*, v. 99,  
963 no. 4, p. 833-849.
- 964  
965 Mosher, D.C., Austin, J.A., Jr., Fisher, D., and Gulick, S.P., 2008, Deformation of the northern  
966 Sumatra accretionary prism from high-resolution seismic reflection profiles and ROV  
967 observations: *Marine Geology*, v. 252, p. 89–99, doi:10.1016/j.margeo.2008.03.014.
- 968  
969 Mutti, E., Papani, L., di Biase, D., Davoli, G., Mora, S., Degadelli, S., and Tinterri, R., 1995, Il bacino  
970 terziario epimesoalpino e le sue implicazioni sui rapporti tra Alpi e Appennino: *Memorie della*  
971 *Società Geologica*, v. 47, p. 217–244.
- 972  
973 Naylor, M.A., 1982, The Casanova Complex of the Northern Apennines: A *mélange* formed on a distal  
974 passive continental margin: *Journal of Structural Geology*, v. 4, p. 1–18.
- 975  
976 Ogawa, Y., 1998, Tectonostratigraphy of the Glen App area, Southern Uplands, Scotland: anatomy of  
977 Ordovician accretionary complex: *Journal of the Geological Society of London*, v. 155, p. 651-  
978 662.
- 979  
980 Ogawa, Y., Anma, R., and Dilek, Y., 2011, Accretionary prism and convergent margin tectonics in the  
981 Northwest Pacific Basin. *Book Series in Modern Approaches in Solid Earth Sciences*, Springer  
982 Science+Business Media B.V. 2011Springer Science, Dordrecht, The Netherlands. ISBN 978-  
983 90-481-884-0.
- 984  
985 Onishi, C.T., and Kimura, G., 1995, Change in fabric of *mélange* in the Shimanto Belt, Japan: Change  
986 in relative convergence?: *Tectonics*, v. 14, p. 1273–1289.
- 987  
988 Orange, D.L., 1990, Criteria helpful in recognizing shear-zone and diapiric *mélanges*: examples from  
989 the Hoh accretionary complex, Olympic Peninsula, Washington: *Geological Society of America*  
990 *Bulletin*, v. 102, p. 935-951.
- 991  
992 Osozawa S., Morimoto J., and Flower F.J., 2009, “Block-in-matrix” fabrics that lack shearing but  
993 possess composite cleavage planes: A sedimentary *mélange* origin for the Yuwan accretionary  
994 complex in the Ryukyu island arc, Japan: *Geological Society of America Bulletin*, v. 121, p.  
995 1190–1203.
- 996

- 997 Osozawa S., Pavlis T., and Flowers M.F.J., 2011, Sedimentary block-in-matrix fabric affected by  
998 tectonic shear, Miocene Nabae complex, Japan, *in* Wakabayashi, J., and Dilek, Y., eds.,  
999 *Mélanges: Processes of Formation and Societal Significance: Geological Society of America*  
1000 *Special Paper 480*, p. 189-206. doi: 10.1130/2011.2480(08)
- 1001
- 1002 Passchier, C.W., and Trouw, R.A., 2005, *Microtectonics: Springer, Berlin - Heidelberg - New York*, 365  
1003 p.
- 1004
- 1005 Piana, F., 2000., Structural features of Western Monferrato (Alps-Appennines junction zone, NW Italy):  
1006 *Tectonics*, v. 19, p. 943-960.
- 1007
- 1008 Piana, F., and Polino, R., 1995, Tertiary structural relationships between Alps and Apennines: The  
1009 critical Torino Hill and Monferrato area: *Northwestern Italy: Terra Nova*, v. 7, p. 138–143.
- 1010
- 1011 Pini, G.A., 1999, Tectonosomes and olistostromes in the Argille Scagliose of the Northern Apennines,  
1012 Italy: *Geological Society of America Special Paper 335*, 73 p.
- 1013
- 1014 Pini, G.A., Ogata, K., Camerlenghi, A., Festa, A., Lucente, C.C., and Codegone, G., 2012,  
1015 Sedimentary mélanges and fossil mass-transport complexes: a key for better understanding  
1016 submarine mass movements?, *in* Yamada, Y., et al., eds., *Submarine mass movements and*  
1017 *their consequences: Advances in natural and technological hazards research*, 31: Springer  
1018 Science+Business Media B.V., p. 585–594.
- 1019
- 1020 Principi, G., and Treves, B., 1984, Il sistema Corso-Appenninico come prisma di accrezione. Riflessi  
1021 sul problema generale del limite Alpi-Appennini: *Memorie della Società Geologica Italiana*, v. 28,  
1022 p. 549-576.
- 1023
- 1024 Raymond, L.A., 1975, Tectonite and mélange - a distinction: *Geology*, v. 3, p. 7–9.
- 1025
- 1026 Raymond, L.A., 1984, Classification of mélanges, *in* Raymond L.A., ed., *Mélanges: their nature, origin*  
1027 *and significance: Geological Society of America Special Paper 198*, p. 7-20.
- 1028
- 1029 Remitti, F., Vannucchi, P., Bettelli, G., Fantoni, L., Panini, F., and Vescovi, P., 2011, Tectonic and  
1030 sedimentary evolution of the frontal part of an ancient subduction complex at the transition from  
1031 accretion to erosion: the case of the Ligurian wedge of the northern Apennines, Italy: *Geological*  
1032 *Society of America Bulletin*, v. 123, n. 1-2, p. 51-70.
- 1033
- 1034 Ricci Lucchi, F., 1986, The Oligocene to recent foreland basin of the Northern Apennines, *in* Allen,  
1035 P.A., and Homewood, P., eds., *Foreland basins: International Association of Sedimentologists,*  
1036 *Special Publication*, v. 8, p. 105–139.
- 1037
- 1038 Roure, F., Bergerat, F., Damotte, B., Mugnier, J.L., and Polino, R., 1996, The Ecors-Crop Alpine  
1039 seismic traverse: *Bulletin de la Société Géologique de France*, v. 170, p. 1–113.
- 1040
- 1041 Sacco, F., 1935, Note Illustrative della Carta Geologica d'Italia alla scala 1:100,000. Fogli di Torino,  
1042 Vercelli, Mortara, Carmagnola, Asti, Alessandria, Cuneo, Ceva, Genova N. e Voghera O.  
1043 costituenti il bacino terziario del Piemonte. Ministero delle Corporazioni, Regio Ufficio Geologico  
1044 di Roma, 85 p.
- 1045
- 1046 Sage, F., Collot, J.-Y., and Ranero, C.R., 2006, Interplate patchiness and subduction-erosion  
1047 mechanisms: evidence from depth-migrated seismic images at the central Ecuador convergent  
1048 margin: *Geology*, v. 34, n. 12, p. 997-1000.

- 1049  
1050 Saleeby, J., 1979, Kaweah serpentinite mélange, southwest Sierra Nevada foothills, California:  
1051 Geological Society of America Bulletin, v. 90, p. 29-46.  
1052
- 1053 Saleeby, J., 2011, Geochemical mapping of the Kings-Kaweah ophiolite belt, California – Evidence for  
1054 progressive mélange formation in a large offset transform-subduction-inization environment, *in*  
1055 Wakabayashi, J., and Dilek, Y., eds., *Melanges: Processes of formation and societal*  
1056 *significance*. Geological Society of America Special Paper 480, p. 31-73.  
1057
- 1058 Scholl, D. W., Vallier, T.L., and Stevenson A.J., 1987, Geologic evolution and petroleum geology of  
1059 the Aleutian Ridge, *in* Scholl, D. W., Grantz, A., and Vedder, J. G., eds., *Geology and resource*  
1060 *potential of the continental margin of western North America and adjacent ocean basins -*  
1061 *Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources, Earth*  
1062 *Science Series*, v. 6, p. 124-155, Houston, Texas.  
1063
- 1064 Silver, E.A., and Beutner, E.C., 1980, *Melanges: Geology*: v. 8, p. 32–34.  
1065
- 1066 Singlenton, J.S., and Cloos, M., 2013, Kinematic analysis of mélange fabrics in the Franciscan  
1067 Complex near San Simeon, California: Evidence for sinistral slip on the Nacimiento fault zone?:  
1068 *Lithosphere*, v. 5, p. 179-188.  
1069
- 1070 Stampfi, G.M., and Borel, G.D., 2002, A plate tectonic model for the Paleozoic and Mesozoic  
1071 constrained by dynamic plate boundaries and restored synthetic oceanic isochrones: *Earth and*  
1072 *Planetary Science Letters*, v. 196, p. 17 - 33.  
1073
- 1074 Stampfi, G.M., Borel, G.D., Marchant, R., and Mosar, J., 2002, Western Alps geological constraints on  
1075 western Tethyan reconstructions, *in* Rosenbaum, G., and Lister, G.S., eds., *Reconstruction of*  
1076 *the evolution of the Alpine-Himalayan Orogen: Journal of the Virtual Explorer*, v. 7, p. 75 - 104.  
1077
- 1078 Strasser, M., Moore, G.F., Kimura, G., Kitamura, Y., Kopf, A.J., Lallemand, S., Park, J-O., Screamon,  
1079 E.J., Su, X., Underwood, M.B., and Zhao, X., 2009, Origin and evolution of a splay fault in the  
1080 Nankai accretionary check: *Nature Geosciences*, v. 2, p. 648–652, doi:10.1038/ngeo609.  
1081
- 1082 Strasser, M., Moore, G.F., Kimura, G., Kopf, A.J., Underwood, M.B., Guo, J., and Screamon, E.J.,  
1083 2011, Slumping and mass transport deposition in the Nankai fore arc: Evidence from IODP  
1084 drilling and 3-D reflection seismic data: *Geochemistry Geophysics Geosystems*, v.12, Q0AD13,  
1085 doi:10.1029/2010GC003431.  
1086
- 1087 Taira, A., Hill, I., Firth, J., Berner, U., Bruckmann, W., Byrne, T., Chabernaud, T., Fisher, A., Foucher,  
1088 J-P., Gamo, T., Gieskes, J., Hyndman, R., Karig, D., Kastner, M., Kato, Y., Lallemand, S., Lu, R.,  
1089 Maltman, A., Moore, G., Moran, K., Olafsson, G., Owens, W., Pickering, K., Siena, F., Taylor, E.,  
1090 Underwood, M., Wilkinson, C., Yamano, M., Zhang, J., 1992, Sediment deformation and  
1091 hydrogeology of the Nankai trough accretionary prism: synthesis of shipboard results of ODP  
1092 Leg 131: *Earth and Planetary Science Letters*, v. 109, p.431–450.  
1093
- 1094 Ukar, E., 2012, Tectonic significance of low-temperature blueschist blocks in the Franciscan mélange  
1095 at San Simeon, California: *Tectonophysics*, v. 568-569, p. 154–169.  
1096
- 1097 Vai, G.B., and Castellarin, A., 1993, Correlazione sinottica delle unità stratigrafiche nell'Appennino  
1098 Settentrionale, *in* Capozzi, R., and Castellarin, A., eds., *Studi preliminari all'acquisizione dati del*  
1099 *profilo CROP 1-1a La Spezia-Alpi orientali: Studi Geologici Camerti, Volume Speciale 2*, p. 171-  
1100 185.

- 1101  
1102 Vannucchi, P., and Bettelli, G., 2002, Mechanism of subduction accretion as implied from the broken  
1103 formations in the Apennines, Italy: *Geology*, v. 30, n. 9, p. 835-838.  
1104
- 1105 Vannucchi, P., and Bettelli, G., 2010, Myths and recent progress regarding the Argille Scagliose,  
1106 Northern Apennines, Italy, *in* Dilek, Y., ed., *Alpine Concept in Geology: International Geology*  
1107 *Review*, v. 52, nos. 10–12, p. 1106–1137.  
1108
- 1109 Vannucchi, P., and Maltman, A., 2000, Insight into shallow-level processes of mountain building from  
1110 the Northern Apennines, Italy: *Journal of Geological Society, London*, v. 157, p. 105–120.  
1111
- 1112 Vannucchi, P., Maltman, A., Bettelli, G., and Clennel, B., 2003, On the nature of scaly fabric and scaly  
1113 clay: *Journal of Structural Geology*, v. 25, p. 673-688.  
1114
- 1115 Vezzani L., Festa, A., and Ghisetti, F., 2010, Geology and Tectonic evolution of the Central-Southern  
1116 Apennines, Italy: *Geological Society of America Special Paper 469*, 58 p., accompanying by a  
1117 CD-ROM including the “Geological-Structural Map of the Central-Southern Apennines (Italy)” at  
1118 1:250,000 scale, Sheets 1 and 2. doi: 10.1130/2010.2469.  
1119
- 1120 Vignaroli, G.L., Faccenna, C., Jolivet, L., Piromallo, C., and Rossetti, F., 2008, Subduction polarity  
1121 reversal at the junction between the Western Alps and the Northern Apennines, Italy:  
1122 *Tectonophysics*, v. 450, p. 34-50.  
1123
- 1124 von Huene, R., and Lallemand, S., 1990, Tectonic erosion along the Japan and Peru convergent  
1125 margins: *Geological Society of America Bulletin*, v. 102, p. 704-720.  
1126
- 1127 von Huene, R., Ranero, C.R., Weinrebe, W., and Hinz, K., 2000, Quaternary convergent margin  
1128 tectonics of Costa Rica, segmentation of the Cocos Plate, and Central American volcanism:  
1129 *Tectonics*, v. 19, p. 314–334, doi:10.1029/1999TC001143.  
1130
- 1131 Wakabayashi, J., 2011, Mélanges of the Franciscan Complex, California: Diverse structural settings,  
1132 evidence for sedimentary mixing, and their connection to subduction processes. *Geological*  
1133 *Society of America Special Papers 480*, 117-141. doi: 10.1130/2011.2480(05).  
1134
- 1135 Wakabayashi, J., 2012, Subducted sedimentary serpentinite mélanges: Record of multiple burial–  
1136 exhumation cycles and subduction erosion: *Tectonophysics*. V. 568-569, p. 230-274.  
1137
- 1138 Wakita, K., 2012, Mappable features of mélanges derived from Ocean Plate Stratigraphy in the  
1139 Jurassic accretionary complexes of Mino and Chichibu terranes in Southwest Japan:  
1140 *Tectonophysics*, v. 568-569, p. 74-85.  
1141
- 1142 Wang, K., and Hu, Y., 2006, Accretionary prisms in subduction earthquake cycles: The theory of  
1143 dynamic Coulomb wedge: *Journal of Geophysical Research*, v. 111, B6, p. B06410, doi:  
1144 10.1029/2005JB004094.  
1145
- 1146 Yamamoto, Y., 2006, Systematic variation of shear-induced physical properties and fabrics in the  
1147 Miura-Boso accretionary prism: the earliest processes during off-scraping: *Earth and Planetary*  
1148 *Science Letters*, v. 244, p. 270-284.  
1149
- 1150 Yamamoto, Y., Nidaira, M., Ohta, Y., and Ogawa, Y., 2009, Formation of chaotic rock units during  
1151 primary accretion processes: examples from the Miura-Boso accretionary complex, central  
1152 Japan: *Island Arc*, v. 18, p. 496-512.

- 1153  
1154 Yamamoto, Y., Yamada, Y., Yamashita, Y., Chiyonobu, S., Shibata, T., Hojo, M., 2012, Systematic  
1155 development of submarine slope failures at subduction margins: fossil record of accretion-related  
1156 slope failure in the Miocene Hota Accretionary Complex, Central Japan, *in* Yamada, Y.,  
1157 Kawamura, K., Ikehara, K., Ogawa, Y., Urgeles, R., Mosher, D., Chaytor, J., and Strasser, M.,  
1158 eds., Submarine mass movements and their consequences. *Advances in Natural and*  
1159 *Technological Hazards Research* 31, p. 355-364.  
1160  
1161



1162 **Figure captions**

1163

1164 **Figure 1** – (A) Structural sketch map of the northwestern Italy (modified from Bigi et al., 1983; Marroni  
1165 et al., 2010; Mosca et al., 2010; Vezzani et al., 2010). (B) Location of Figure 1A. (C) Geological cross  
1166 section across the northern sector of the *Tertiary Piedmont Basin* and Po plain (modified from Bello  
1167 and Fantoni, 2002). The trace of the section is shown in Figure 1A. (D) Schematic crustal-scale cross  
1168 section across the Western Alps to the *Tertiary Piedmont Basin* (modified from Roure et al., 1996;  
1169 Stampfli et al., 2002). The section line is shown in Figure 1A.

1170

1171 **Figure 2** –Paleogeographic reconstruction (in map and in section) of the western Tethyan realm in (A,  
1172 B) the Late Cretaceous (modified after Stampfli and Borel, 2002 and Stampfli et al., 2002 for map view;  
1173 Vignaroli et al., 2008 and Marroni et al., 2010 for section view) and (C-D) middle-late Eocene times  
1174 (modified after Castellarin, 1994; Festa et al., 2010b; Mosca et al., 2010 for map view; Marroni et al.,  
1175 2010, for section view).

1176

1177 **Figure 3** – Stratigraphic columns of the External Ligurian Units in the Northern Apennines and  
1178 Monferrato, and of the overlying Epiligurian and *Tertiary Piedmont Basin* successions. Modified from  
1179 Marroni and Pandolfi (2007); Marroni et al. (2001, 2010); Codegone et al. (2012b).

1180

1181 **Figure 4** – (A) Simplified geological-structural map of the study area (location in Fig. 1A), showing the  
1182 structural relationships between different chaotic rock units. (B) Geological cross section.

1183

1184 **Figure 5** – *Broken Formation*: (A) Schematic 3D drawing of an outcrop exposure (North of Gerbole)  
1185 showing the different degrees of layer-parallel extension in two orthogonal directions. Asymmetrical  
1186 boudinage, pinch-and-swell features, and R and R' shears characterize the WNW-striking section;  
1187 symmetrical flattening and boudinage are present on the NNE-striking section. (B) Schematic 3D

1188 drawing of an outcrop exposure (North of Gerbole), showing (a) the geometry of intralayer folds that  
 1189 show a sheath-like geometry on the NNE-stringing section. Note the asymmetric boudinage of fold  
 1190 limbs on the WSW-striking section. (b) 3D model of the intralayer fold showing the curvilinear fold  
 1191 axis. (C) Line-drawing of a polished hand sample, showing the asymmetric boudinage associated with  
 1192 extensional shearing and *in situ* disruption of alternating layers of sandstone (black) and shale (white)  
 1193 (NW of Gerbole). Black lines indicate R-shears. (D) Photograph showing a close-up of Fig. 5C. Black  
 1194 lines indicate R-shears. (E) Photograph of a polished surface of hand sample showing C'-type shears  
 1195 (*sensu* Passchier and Trouw, 2002; see white lines) that transecting the varicolored shaly layers  
 1196 (North of Piazzo). (G) SEM image showing anastomosing domains of flattened clay particles,  
 1197 transected by C'-type shears (*sensu* Passchier and Trouw, 2002; see white lines).

1198

1199 **Figure 6** –Diagrams showing different organizational types of the blocks and the rock fabric in diverse  
 1200 types of chaotic rock units: (A) Aspect ratio (blocks long axis/short axis) versus block long axis. (B)  
 1201 Aspect ratio (blocks long axis/short axis) versus location of chaotic units (i.e., distance from the thrust  
 1202 faults). Data are plotted as means with 95% error bars indicated. (C) Mesoscale data (Schmidt net,  
 1203 lower hemisphere) of scaly fabric, lineation of the long-axis of the blocks, and folds of *Broken*  
 1204 *Formation*, *Tectonic Mélange* and *Diapiric Mélange*.

1205

1206 **Figure 7** – *Tectonic Mélange*: (A) Line-drawing of an outcrop exposure (SW of la Pietra), showing the  
 1207 “structurally ordered” block-in-matrix fabric related to a NE-verging reverse shear (black lines). Dark-  
 1208 gray color indicates both native and exotic blocks (see text); white color indicates the shaly matrix. (B)  
 1209 Close-up of Fig. 7A. The photograph shows elongated to phacoidal blocks embedded in the scaly  
 1210 matrix that is pervasively affected by an S-C fabric. (C) Line-drawing of polished hand sample,  
 1211 showing the reorientation of elongated blocks (dark-gray color) to S-C fabric (black lines). White color  
 1212 indicates the shaly matrix (NW of Gerbole). (D) SEM image of the shaly matrix, showing the S-C fabric  
 1213 (white dashed lines). The arrow indicates an elongated clast aligned parallel to the C-shear surface.

1214

1215 **Figure 8** – *Diapiric Mélange*: (A) Detailed geological map of the diapiric body located to the NE of  
 1216 Piazzo (location in Fig. 4A). Note the irregular rounded shape and the two-fold zonation of  
 1217 deformation, which is characterized by marginal and core zones (see text for major details). The  
 1218 intrusive contact (white dashed line) crosscuts the NW-striking bedding of the Broken formation and  
 1219 the structural fabric of the *Tectonic Mélange*. (B) Core zone: tabular and phacoidal limestone and  
 1220 sandstone blocks aligned parallel to the sub-vertical fluidal fabric of the shaly matrix (NE of Piazzo).  
 1221 (C) Close-up of the marginal zone: elongated calcareous marly block aligned parallel to the sub-  
 1222 vertical flow fabric of the varicolored shaly matrix (NE of Piazzo). (D) Close-up of the transition zone  
 1223 between the *Diapiric* and *Sedimentary Mélanges*: the polished surface of a hand sample in top-view  
 1224 showing the inclusion of part of the *Diapiric Mélange* (central part of the photograph) in a brecciated  
 1225 matrix, which was developed during the emplacement of the *Sedimentary Mélange* (NE of Pareglio).  
 1226 (E) SEM image of the matrix in the core zone showing irregular and convolute folds (marked by  
 1227 dashed white lines) affecting the clay particle alignment. Clay surfaces gently wrap around elongated  
 1228 and lenticular clasts (white arrows). (F) SEM image of the matrix in the marginal zone, showing the  
 1229 finely-spaced alignment of clay particles that define sigmoid-shaped sub-vertical domains. White  
 1230 arrows indicate shear surfaces.

1231

1232 **Figure 9** – *Sedimentary Mélange* (i.e., Polygenetic argillaceous breccias): (A) Highly disordered block-  
 1233 in-matrix fabric. Variably-shaped blocks (equidimensional, tabular, phacoidal and irregular) of  
 1234 limestone, sandstone, marl and siltstone randomly float in the brecciated shaly matrix (NW of  
 1235 Gerbole). (B) Polished surface of hand sample showing the isotropic texture of the brecciated shaly  
 1236 matrix of Fig. 9A. (C) Polished surface of hand sample, showing the superposition along an erosive  
 1237 surface (white arrows) of a brecciated lenticular body onto extensionally sheared, varicolored shaly  
 1238 layers (North of Piazzo). (D) SEM image of the brecciated matrix of the hand sample of Fig. 9B.  
 1239 Rounded and irregular-shaped clasts (dashed white lines) randomly float in a clayey matrix (dashed

1240 black lines). (F) SEM image of the brecciated matrix of the hand sample of Fig. 9C. The arrow  
1241 indicates the gradual decrease of the spacing between clay particles from the clast-supported to clast-  
1242 poor part of the rocks.

1243

1244 **Figure 10** – *Sedimentary Mélange* (i.e., Polygenetic argillaceous breccias): (A) Simplified structural  
1245 map, showing the structural relationships between different chaotic rock units and the direction of  
1246 emplacement of *Sedimentary Mélange* bodies (i.e., Polygenetic argillaceous breccias). Rose diagrams  
1247 show the sub-radial distribution of the direction of extensional shearing measured at the base of the  
1248 Polygenetic argillaceous breccias. (B) Polished surface of hand sample of the basal part of the  
1249 *Sedimentary Mélange*. Extensionally sheared layers show a planar anisotropy crosscut by low-angle  
1250 extensional shear surface (R-shear) (North of Piazzo). (C) SEM image of the matrix in Fig. 10B,  
1251 showing the alignment of elongated clasts and compacted clay particles truncated by C'-type shears  
1252 (*sensu* Passchier and Trouw, 2002; see white arrows).

1253

1254 **Figure 11** – *Shale dike injections*: (A) Line-drawing of an outcrop exposure, showing shale dike  
1255 injections (grey color) intruding into the brecciated matrix of the Polygenetic argillaceous breccias  
1256 (white color). Elongated blocks (black color) are reoriented by the sub-vertical shale injections (NE of  
1257 Piazzo). (B) Close-up of Fig. 11A. Dashed white lines mark the margins of the blocks and of the shale  
1258 dike injections. (C) Close-up of Fig. 11A. Tabular block aligned parallel to the sub-vertical fluidal  
1259 features of the shale dike injection. (D) Polished surface of hand sample showing a subvertical flame-  
1260 shaped injection of red shale within the brecciated matrix of the Polygenetic argillaceous breccias.  
1261 Elongated limestone and sandstone clasts are rotated and aligned parallel to the intrusive contacts  
1262 (NE of Pareglio). (E) SEM image of the matrix of a shale dike injection showing irregular to isoclinal  
1263 folds (white lines) affecting the flow fabric of the finely spaced clay particles. White arrows indicate  
1264 rounded clasts. (F) SEM image showing a close-up of an irregular fold.

1265

1266 **Figure 12** – (A) Conceptual model for the evolution of the Ligurian accretionary wedge during the Late  
 1267 Cretaceous – middle Eocene (accretionary stage). Not-to-scale. (B) Block diagram showing the  
 1268 deformation of sediments prior to accretion. Vertical compaction of unconsolidated sediments occurs  
 1269 prior to accretion, forming a symmetrical boudinage. The increasing shear during the approach to the  
 1270 toe of the accretionary wedge promotes asymmetrical boudinage and development of R-shears in  
 1271 more competent layers. (C) Block diagram showing the deformation of sediments within the toe of the  
 1272 accretionary wedge. Heterogeneous deformation results in the contemporaneous production of  
 1273 flattened, intralayer, sheath like folds, layer-parallel extensional fabric, and asymmetric boudinage.  
 1274 This heterogeneous deformation is likely related to the inclination of sedimentary layers with respect to  
 1275 the  $\sigma_1$  (see Kusky and Bradley, 1999). See text for a detailed discussion.

1276

1277 **Figure 13** –Conceptual model for the evolution of the Ligurian accretionary wedge during late  
 1278 Oligocene intracollisional deformation. The superposition of tectonic, diapiric and sedimentary  
 1279 processes occurred in this short time span. (A) Thrusting related to NE-verging regional shearing  
 1280 formed the *Tectonic Mélange*. This is characterized by (A') a structurally ordered block-in-matrix fabric  
 1281 produced by mixing of the exotic and native blocks that are wrenched from the overlying units (see  
 1282 stratigraphic column in Fig. 13A). (B) *Diapiric Mélange* formed by the upward rise of unconsolidated  
 1283 sediments that are triggered by overpressurized fluids, which are concentrated along the shear  
 1284 surface of thrust faults. (C) *Sedimentary Mélange* (i.e., Polygenetic argillaceous breccias) formed by  
 1285 the collapse of the margins of the topographic high formed by the emergence of a diapiric body on the  
 1286 seafloor. (C') Downslope emplacement of *Sedimentary Mélanges* units sealed the thrust faults,  
 1287 superposing the External Ligurian Units on the late Eocene–Oligocene Tertiary Piedmont Basin  
 1288 sedimentary succession. Shale dike injection is triggered by the combined effect of sedimentary  
 1289 loading (provided by the emplacement of the *Sedimentary Mélange*) and discharge of fluids after the  
 1290 thrust faulting stage, intrudes into the *Sedimentary Mélange* (i.e., Polygenetic argillaceous breccias).  
 1291 (C'') Close-up of a shale dike injections into the block-in-matrix fabric of the *Sedimentary Mélange*.

1292

1293 **Table 1** – Diagnostic structural features observed at the map-to meso- and micro-scales in the *Broken*  
1294 *Formation* and in the *Tectonic, Diapiric* and *Sedimentary Mélanges*.

Figure 1  
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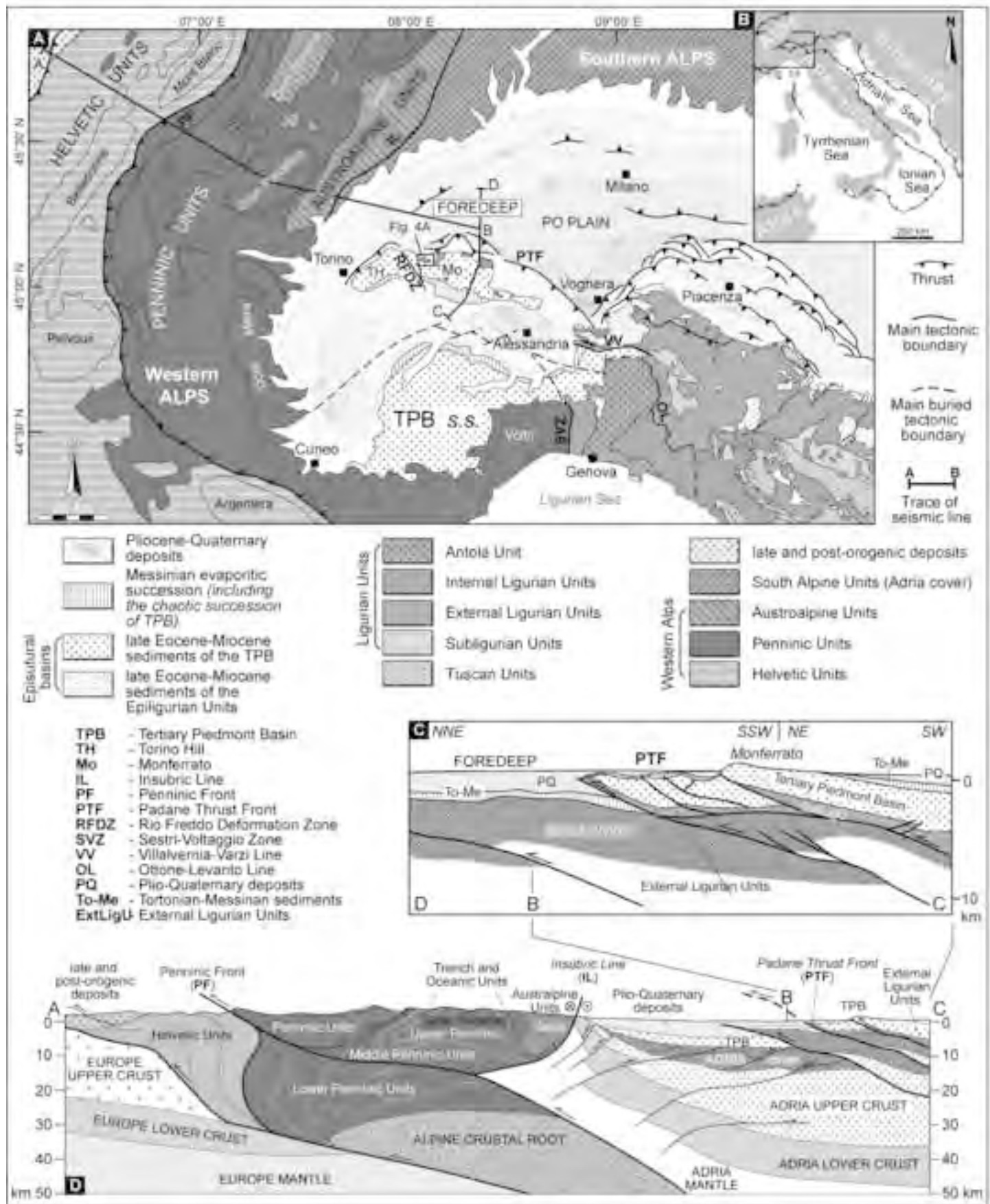


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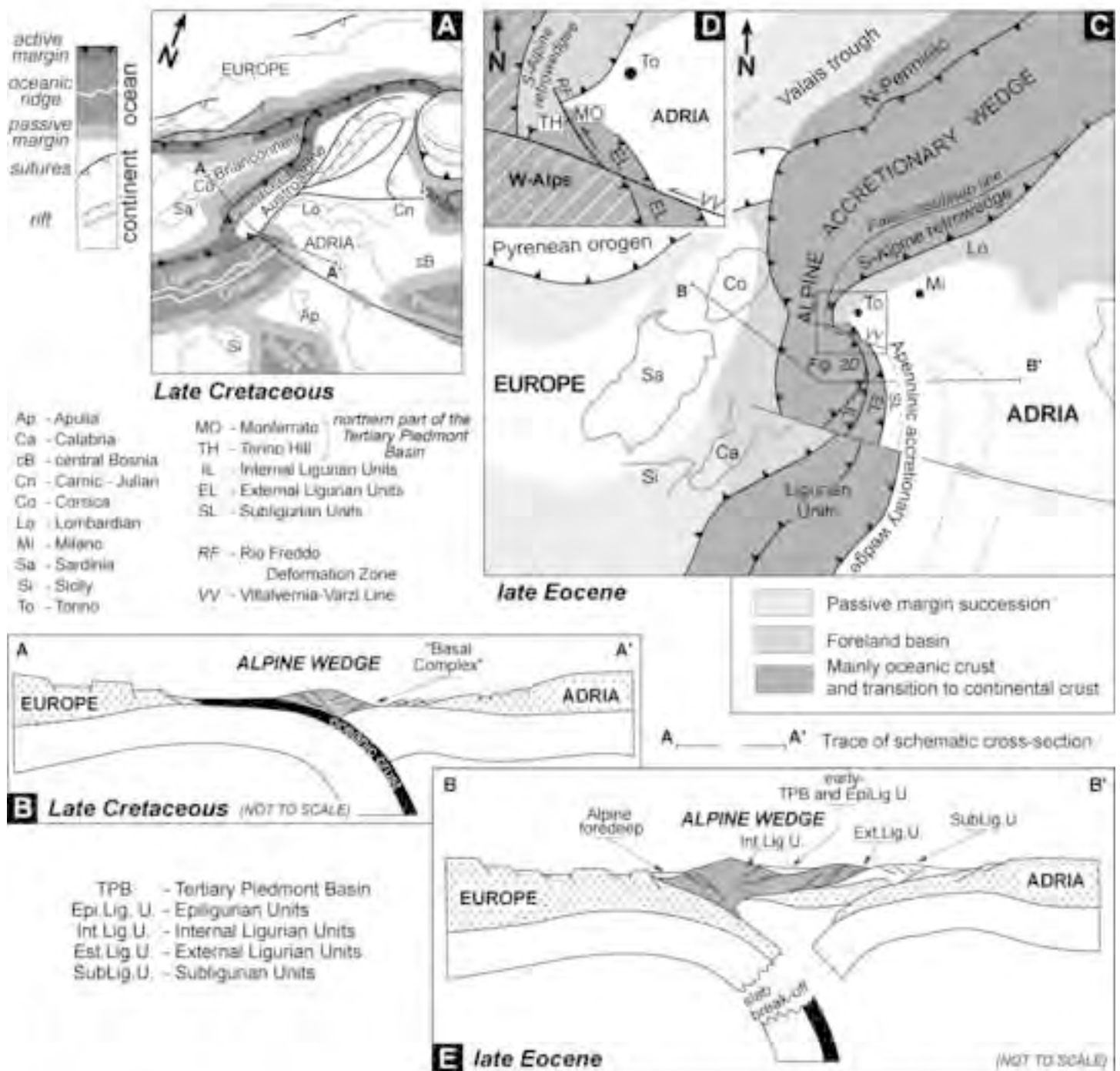


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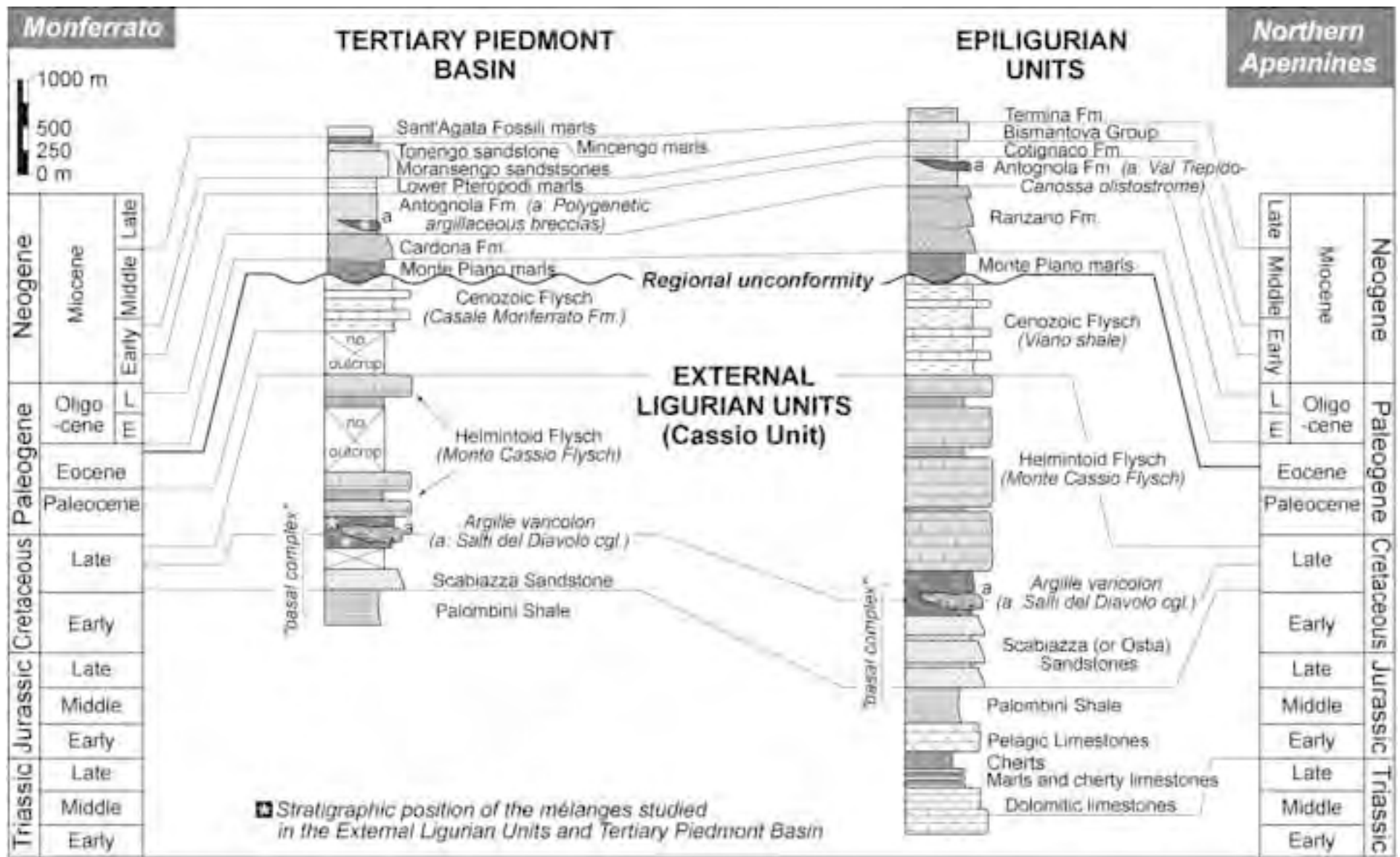


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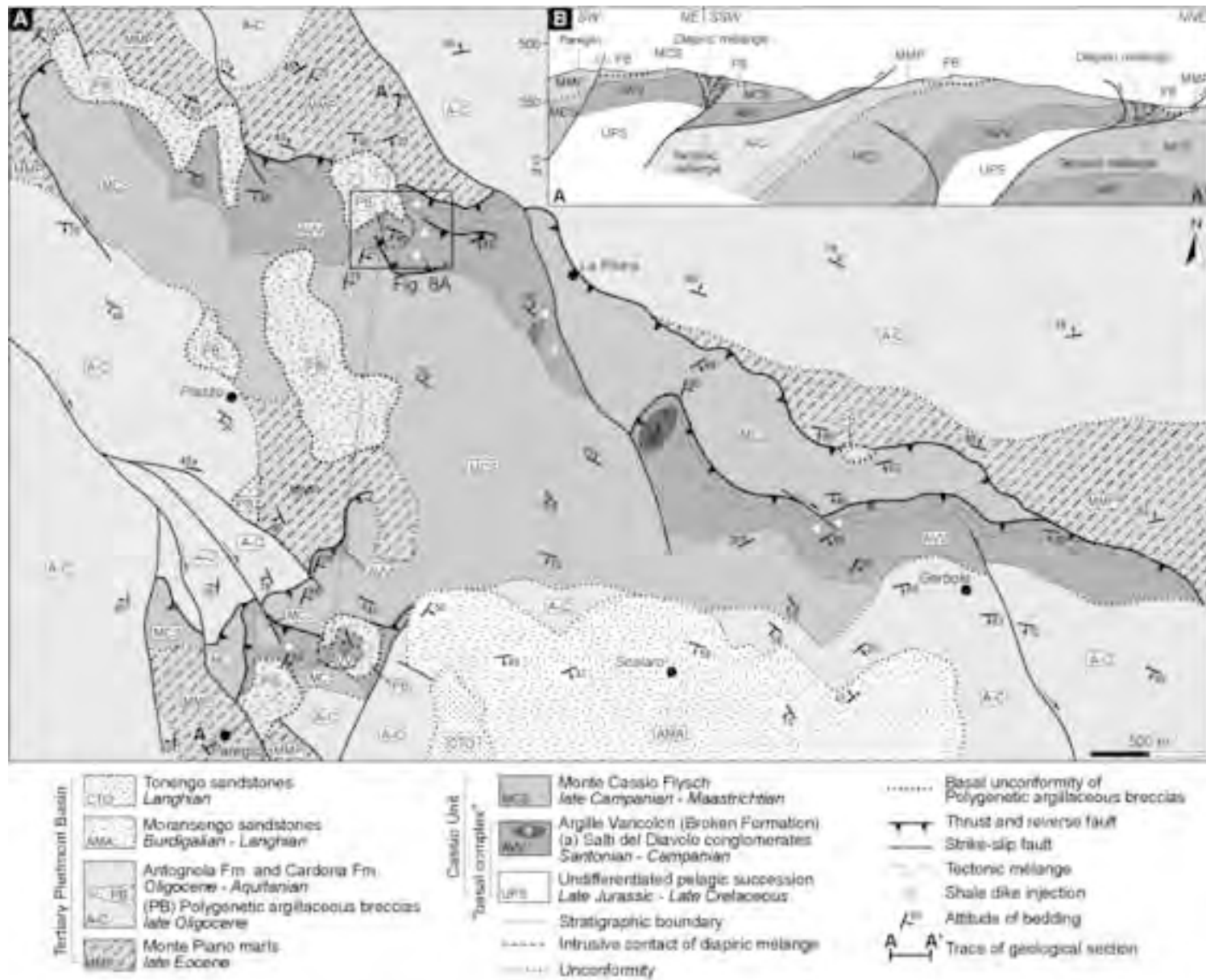


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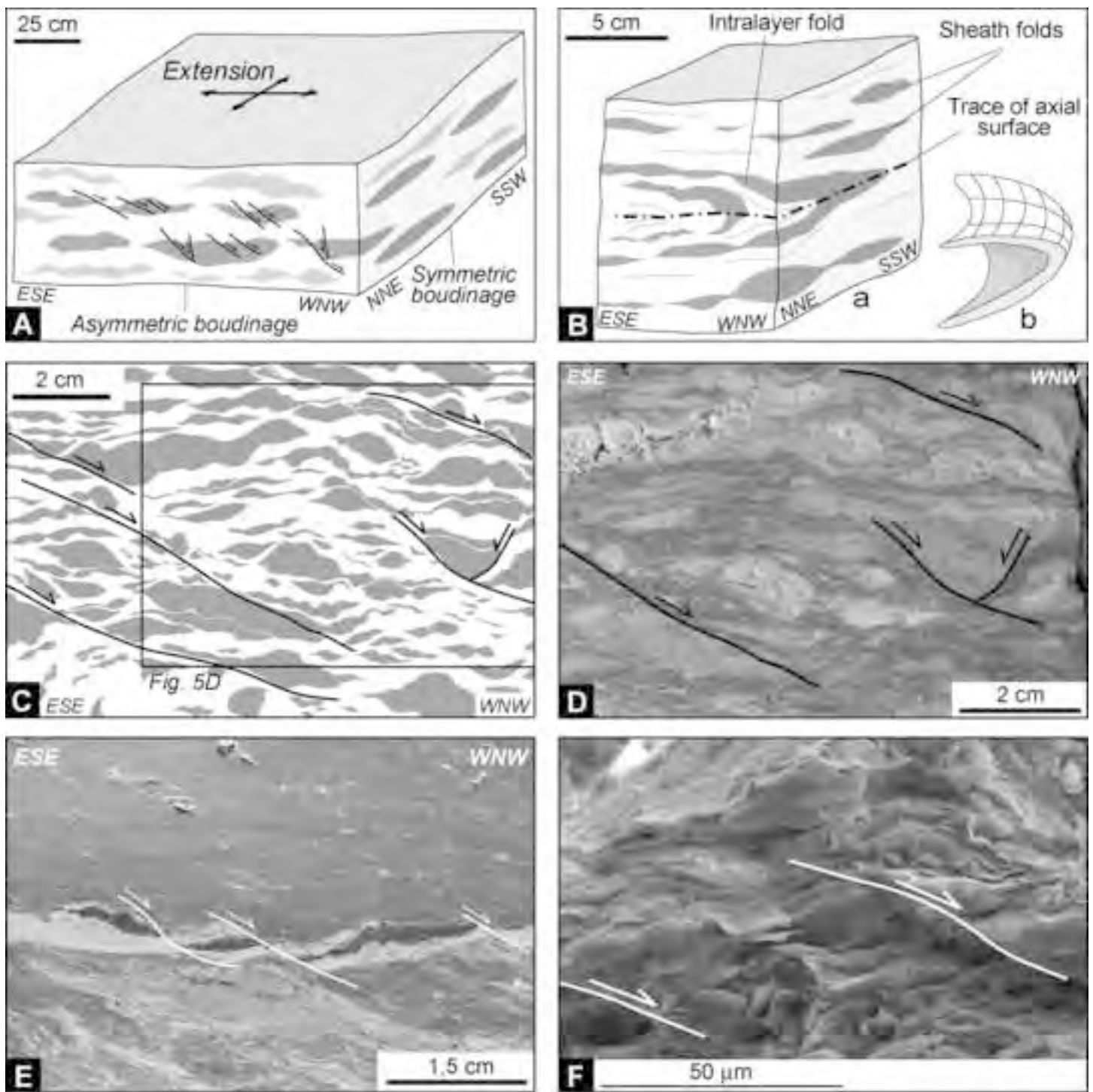


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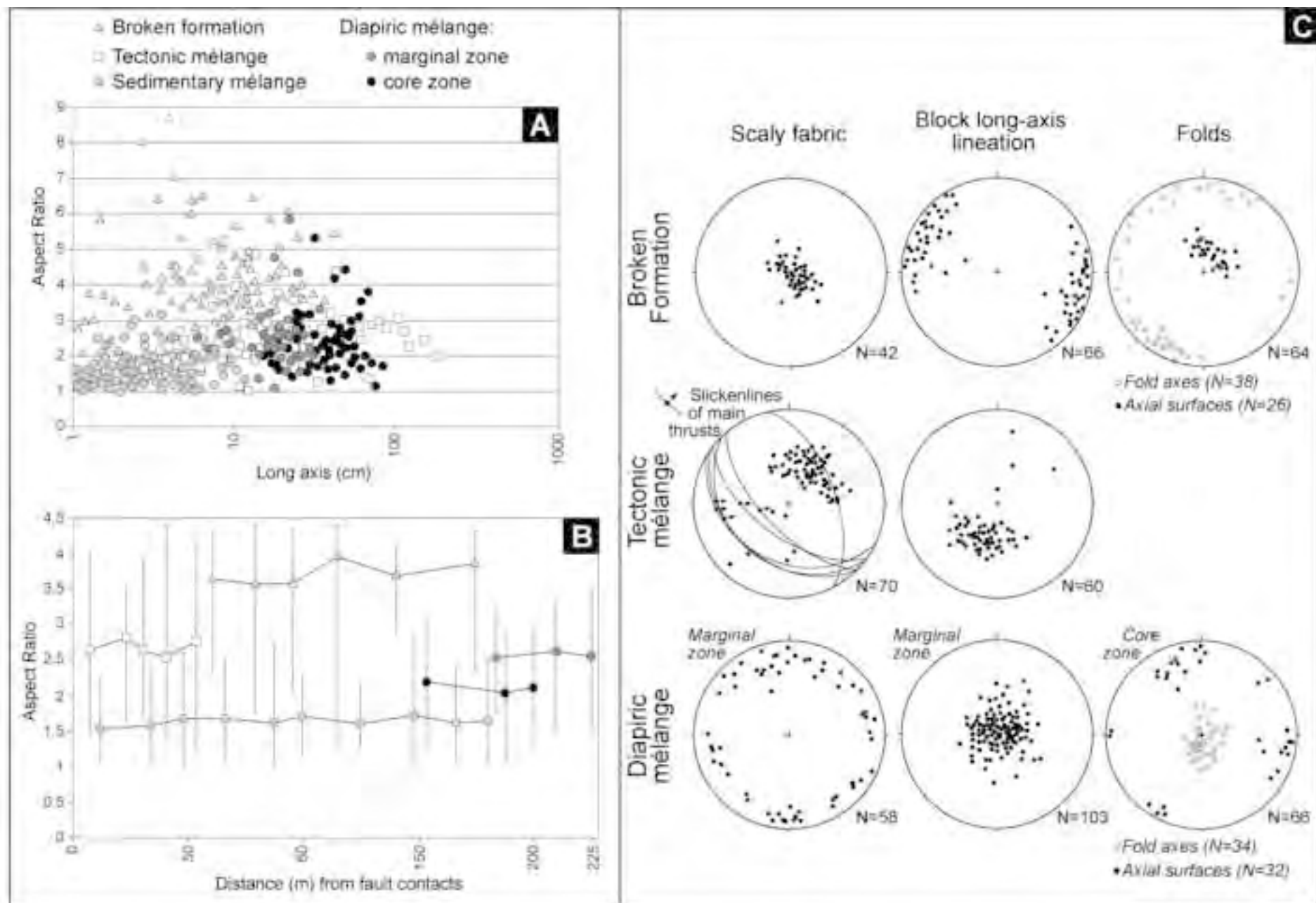


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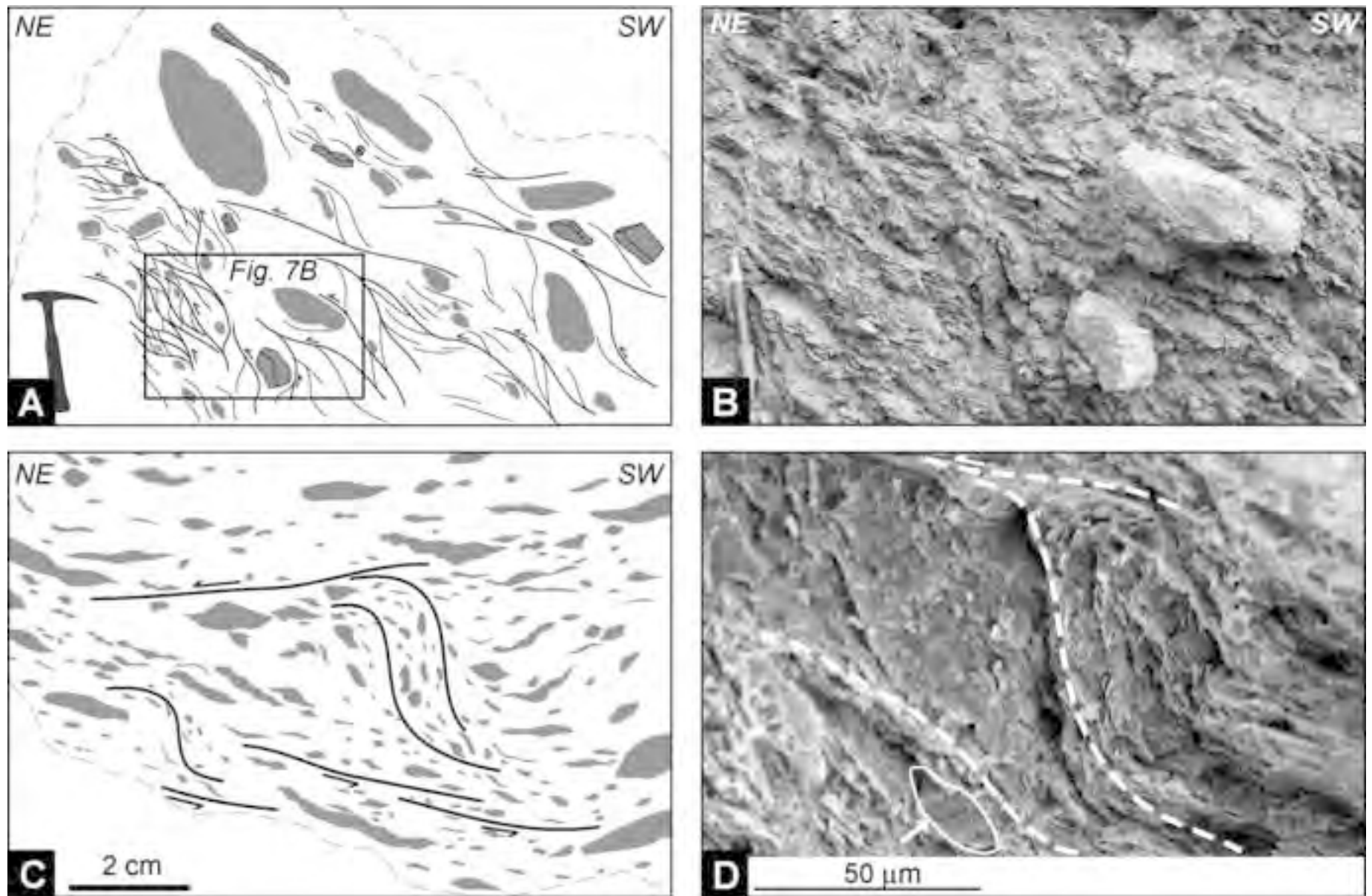


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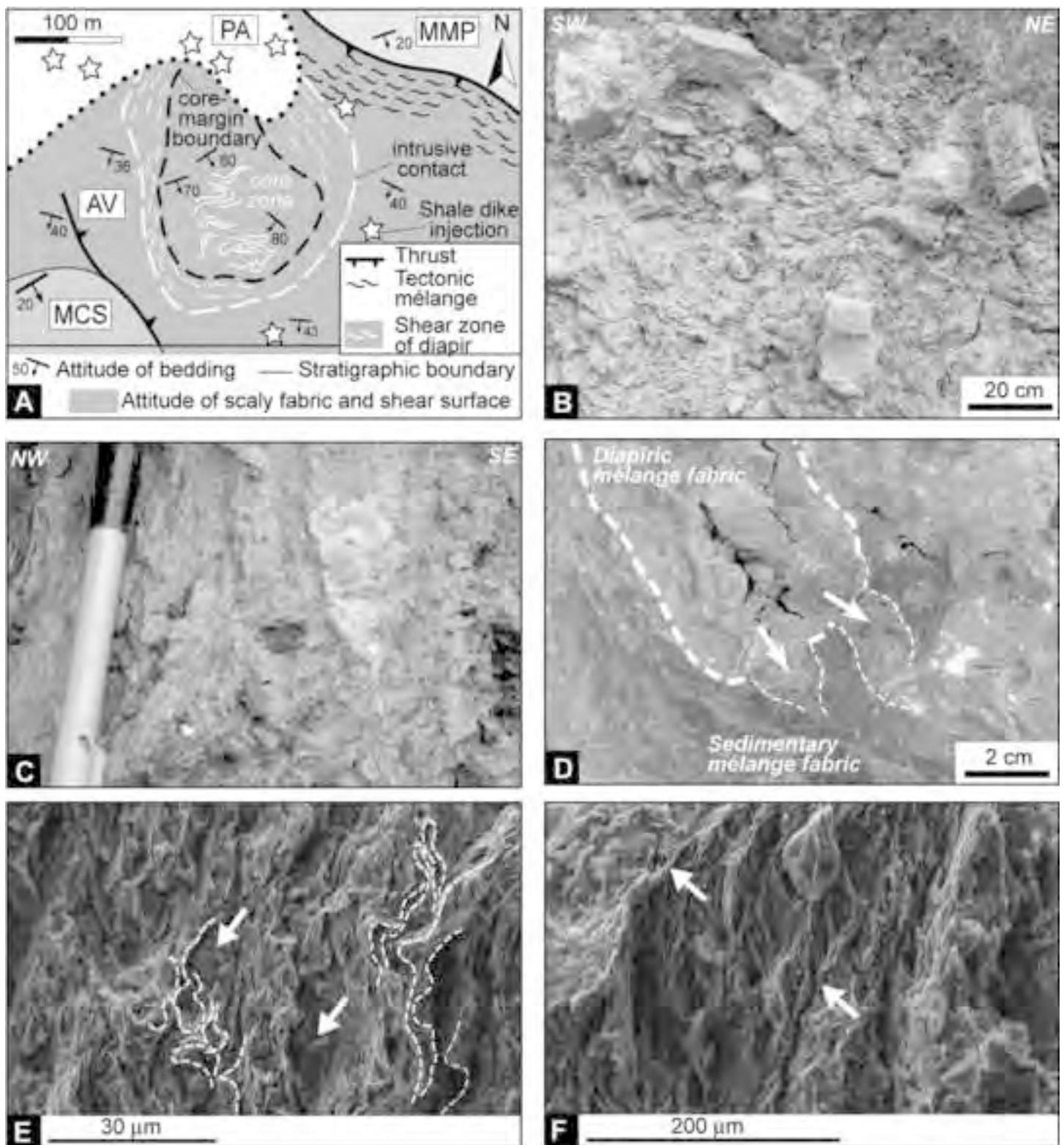


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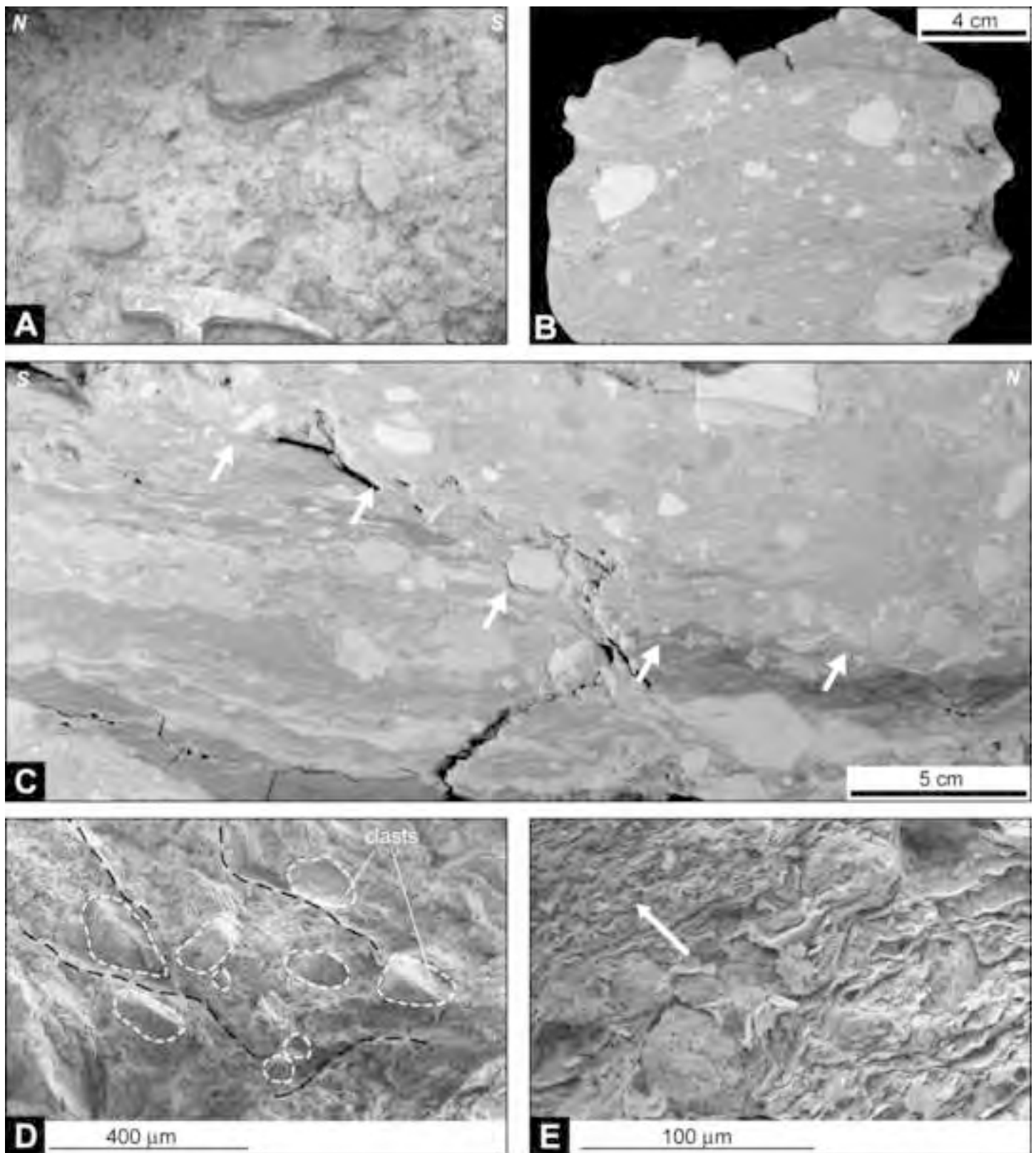


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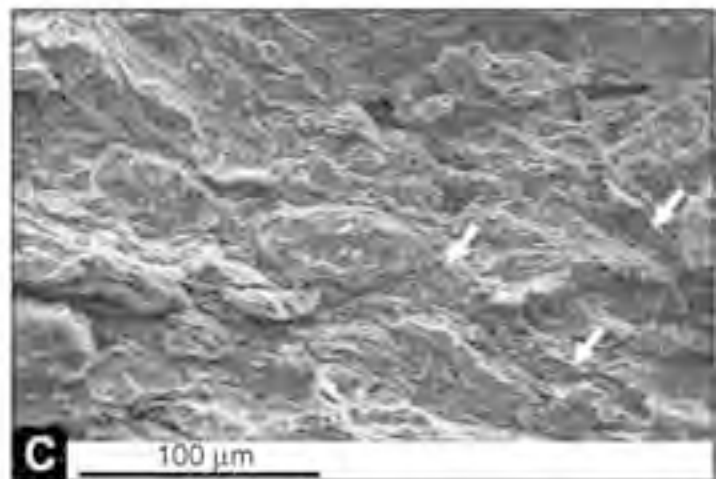
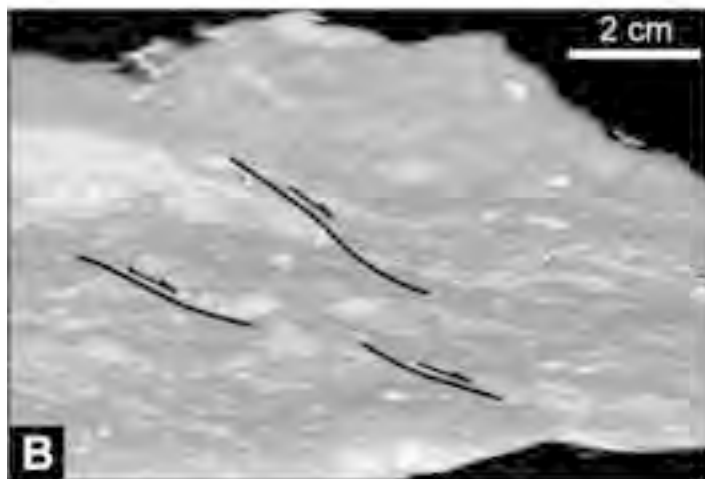
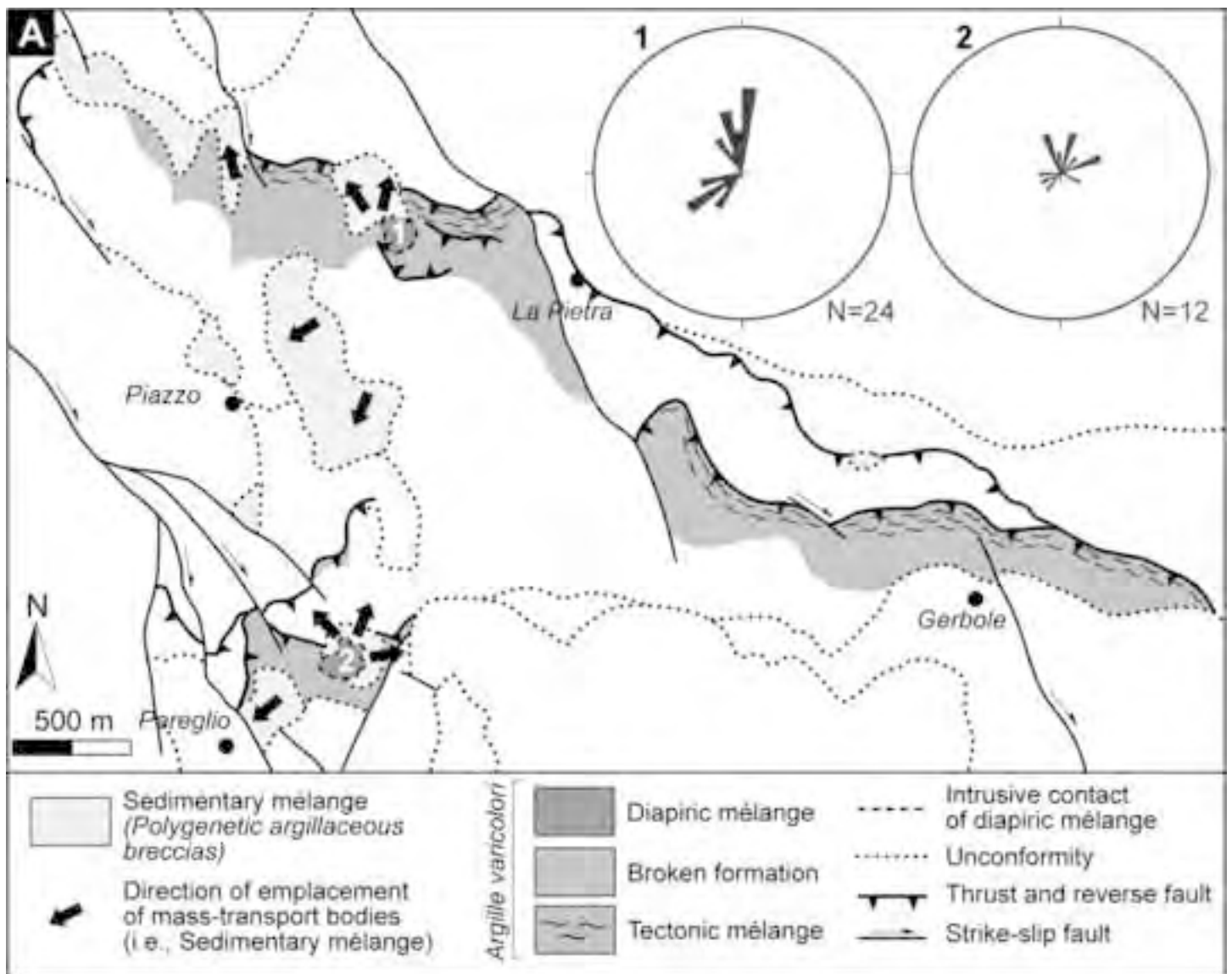


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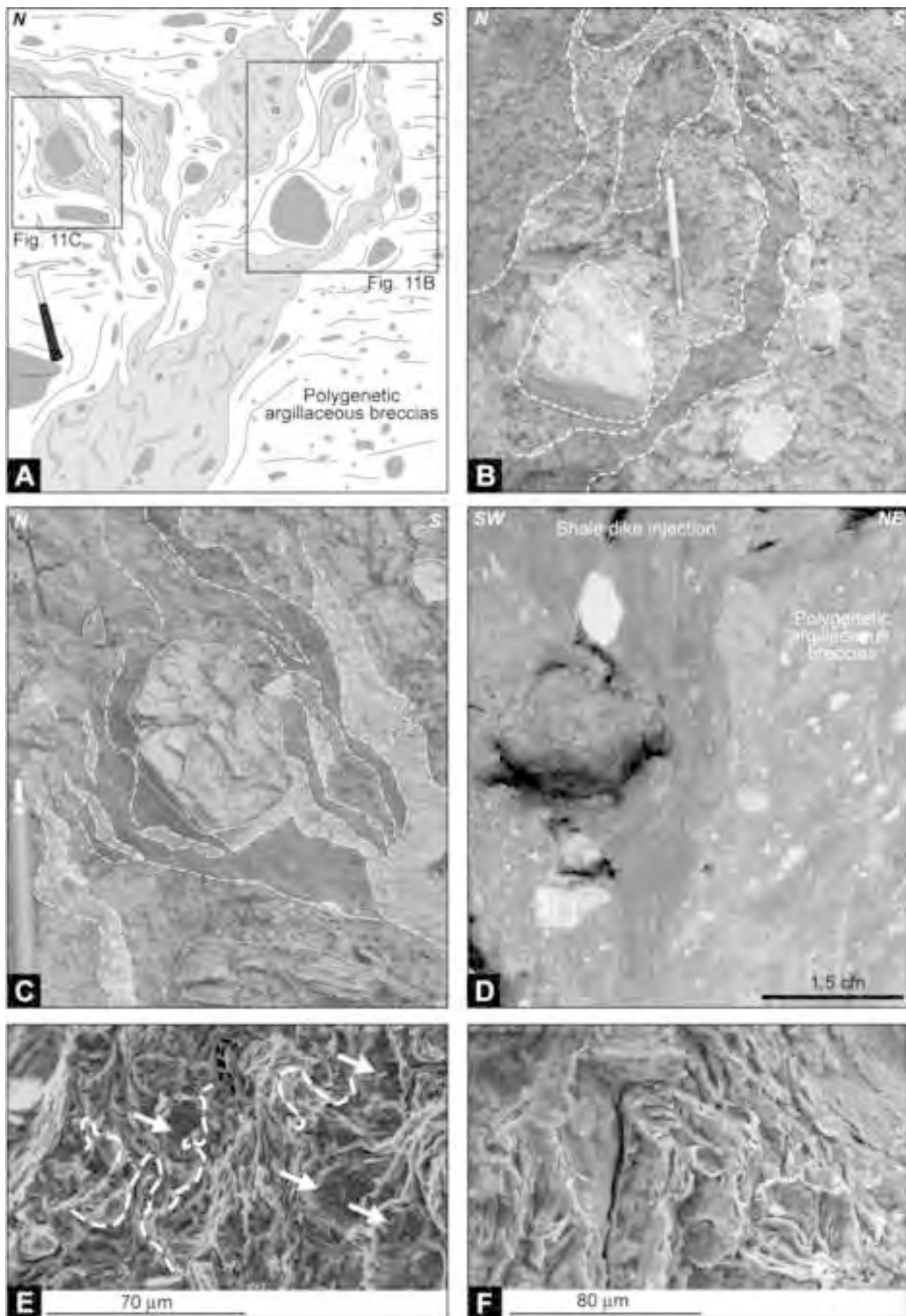


Figure 11 - Festa et al. (\*.jpg)

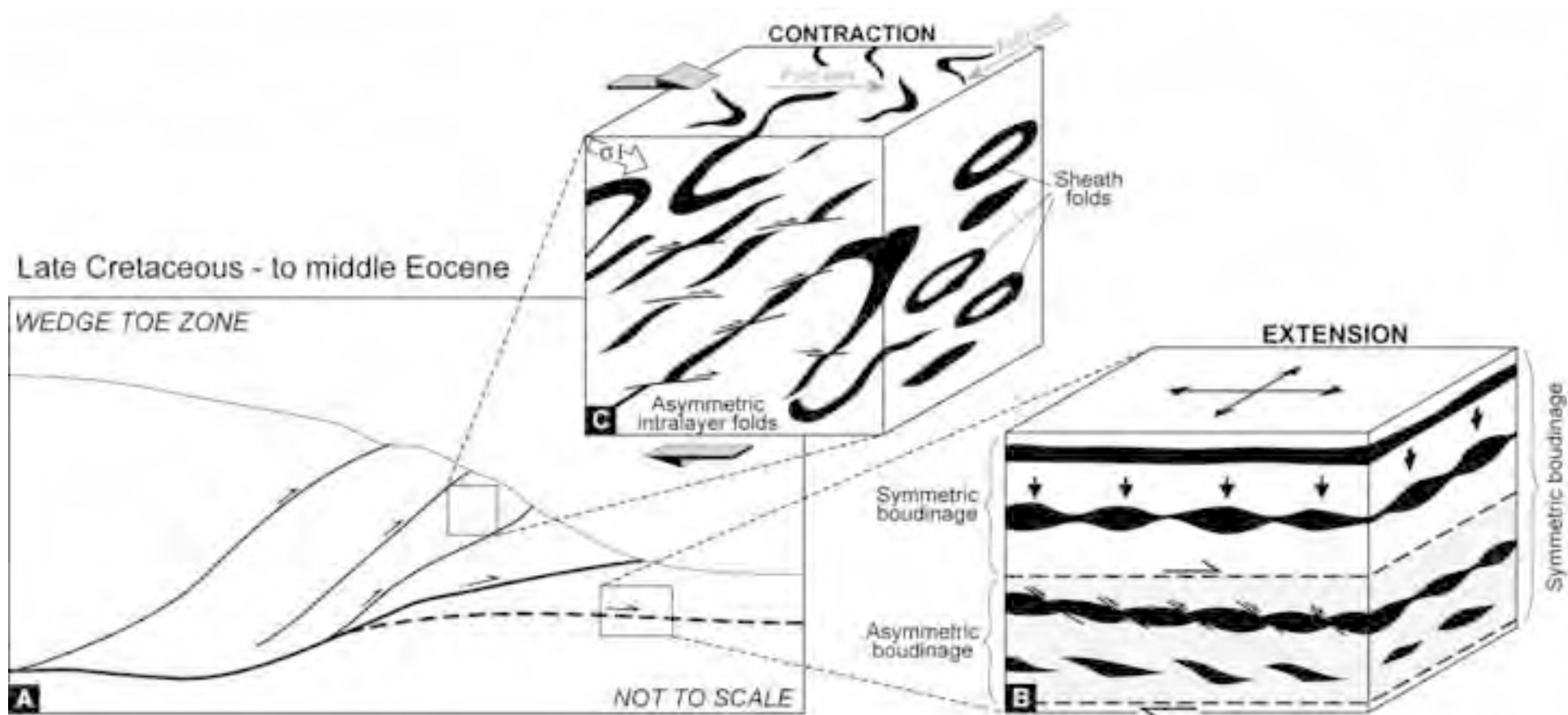


Figure 12 - Festa et al. (\*.jpg)

Figure 13 (Revised)  
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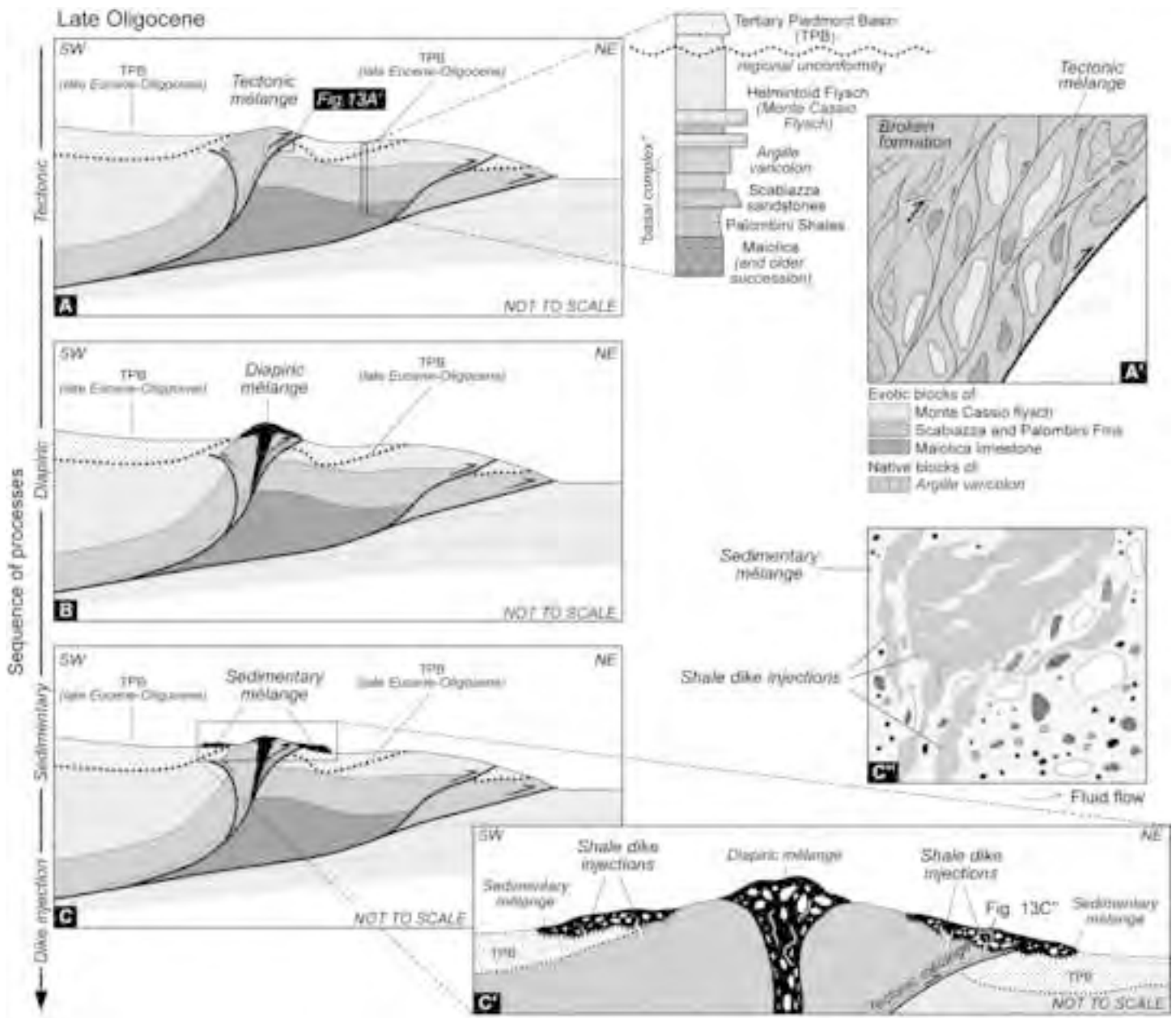


Figure 13 - Festa et al. (\*.jpg)

TABLE 1.

		Broken Formation	Tectonic Mélange	Diapiric Mélange	Sedimentary Mélange
Process of formation			Tectonic	Diapiric	Sedimentary (gravitational)
Map-scale features	<b>Shape of chaotic unit (in map view)</b>	Aligned to conformable stratigraphic contacts of bounding lithostratigraphic units	Narrow and elongated; aligned to thrusts	Circular to elliptical	Irregular
	<b>Nature of bounding surface</b>	No bounding surface: gradual transition to both Tectonic Mélange and coherent lithostratigraphic units	Fault (i.e., thrust)	High angle intrusive contacts	Lower and upper depositional contacts as discontinuity surfaces
Meso-scale features	<b>Block-in-matrix fabric</b>	Progressive distribution from continuous layering to boudinage up to isolated blocks aligned to the original coherent bending (i.e., pseudo-bedding) Non-cylindrical, flattened intralayer folds with curvilinear axial surfaces	Structurally ordered fabric (S-C and/or P-T shears) consistent with the regional shortening direction	Zonation of deformation: - <b>Core zone:</b> plurimetric, irregular non-cylindrical folds with steeply dipping axes and irregular axial trends; - <b>Marginal zone:</b> pervasive vertical scaly fabric and fluidal features which wrap around the blocks	Random distribution of blocks in a brecciated isotropic matrix
	<b>Nature of blocks</b>	Native (i.e., intra-formational)	Native (i.e., intra-formational) and exotic (i.e., extra-formational)		
	<b>Shape of blocks</b>	From flat to ellipsoidal shape (aspect ratio: 3,5-4)	Phacoidal and tabular blocks (aspect ratio: 2,5-2,8)	- <b>Core zone:</b> irregular blocks (aspect ratio: 2,1-2,3) - <b>Marginal zone:</b> phacoidal blocks (aspect ratio: 2,5-2,6)	Angular to rounded and irregular blocs (aspect ratio: 1,5-1,7)
	<b>Size of blocks</b>	mean: 33 cm max: 50 cm	- Native blocks: mean: 33 cm; max: 50 cm - Exotic blocks: mean: 35 cm; max: 125 cm	- <b>Core zone:</b> mean: 60 cm; max: 90 cm - <b>Marginal zone:</b> mean: 25 cm; max: 40 cm Sub-vertical flow fabric.	mean: 4 cm max: 15 cm
Micro-scale features	<b>Matrix fabric</b>	Anastomosing domains of clays aligned to bedding. Locally, the fabric is transected by C' and/or R shears	Clays rotated and aligned to S-C fabric which isolate sigmoidal to lenticular shaped micro-lithons. Occurrence of striation.	- <b>Core zone:</b> alignment of irregularly anastomosing and folded clays (sub-vertical axial fold); - <b>Marginal zone:</b> sub-vertical S-C fabric	Anastomosing domains of clays that, close to the basal erosional surface, are transected by C'-type shears
	<b>Clast arrangement</b>	Planar orientation of elongated clasts, locally transected by R-shears	Alignment of elongated clasts to the S-C fabric	Alignment of elongated clasts to the fluidal fabric	Random distribution of equidimensional and irregular clasts. Close to the basal surface, elongated clasts are aligned to the clays

Table 1 – Festa et al. (\*.doc)