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ACTIVE FOLDING ALONG A RIFT-FLANK: THE CATANIA REGION
CASE HISTORY (SE SICILY)

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1 Abstract

2 In this paper a new kinematic and dynamic model on the Recent and active contractional
 3 deformation of the Catania region, eastern Sicily, is discussed. The study area represents one of the
 4 most seismically active region of the Mediterranean, located at the intersection between the front of
 5 the Sicily collision belt and the seismogenic Siculo-Calabrian Rift-Zone. The analysed contractional
 6 tectonics form an active triangle zone that originated from the tectonic inversion of a Lower-Middle
 7 Pleistocene extensional basin, which was located at the northern edge of the African foreland. The
 8 triangle zone consists of two antithetic ENE-WSW oriented thrust-ramps that show evidence of
 9 motion during the Holocene and bound a folded belt that involves alluvial deposits as young as 40
 10 ka. These contractional structures represent the final product of the positive tectonic inversion of
 11 extensional features located, in the Hyblean Plateau in SE Sicily, along the flank of the active rift-
 12 zone. The Late Quaternary motions along the inverted structures was accommodated to the west by
 13 a major N-S oriented left-lateral fault zone, which separates the active contractional domains from
 14 the adjacent sectors of the African margin. As a whole, the Late Quaternary contractional tectonics
 15 of SE Sicily have been related to a NW-verging crustal stacking, related to a Mantle intrusion
 16 beneath the Hyblean Plateau that developed as effect of the rift flank deformation. The crustal
 17 lineaments, which compose the new kinematic model, represents potentially active seismogenic
 18 sources that might be considered in the frame of the seismotectonic picture of the Catania region.

19
 20 Keywords: active tectonics, contractional structures, morphological responses, eastern Sicily, rift-
 21 flank deformation and seismotectonics

22

23 1. Introduction

24 In the Catania region, in eastern Sicily (Fig. 1), several Authors (Labaume et al., 1990;
 25 Lanzafame et al., 1997; Monaco, 1997; Monaco et. al., 2002) have documented the growth of
 26 Middle Pleistocene (> 200 ka) contractional structures, along the southern margin of Mt. Etna

Volcano, at the front of the Maghrebian Collision Belt (Fig. 1). More recent studies (Catalano et al., 2004; 2007) described the occurrence of younger ENE-WSW oriented folds that, coherently with the active NNW-SSE oriented Nubia-Eurasia convergence, deform alluvial terraces as young as the 40 ka. This younger fold system developed along the western flank of the roughly N-S oriented Siculo-Calabrian Rift Zone (**SCRZ**) (Monaco & Tortorici, 2000; Catalano et al., 2008a), which consists of NNW-SSE trending major extensional faults located in the immediate Ionian off-shore area (Fig. 1). The seismological data (Neri et al., 2005) and stress-in-situ measurements along the western flank of the rift zone (Bousquet et al., 1988; Ragg et al., 1999) demonstrate the occurrence of a still active compressional regime, which is centred in the Mt. Etna region. This suggests that the growth of contractional structures can be still active and related to the seismicity of the Catania region. In this study, the geometry and the morphological evidence of the Late Quaternary contractional structures of the Catania region are analysed in order to define the displacement-rate and the mechanism of their evolution in the frame of the regional dynamics and seismotectonics of this densely populated area. The methodology includes morphometric analyses, applied on the Late Pleistocene alluvial terraces and the Holocene alluvial plain of the Simeto and Dittaino rivers (Catania Plain), and the study of channel morphology along the two main streams. The morphological data are augmented by surface geological information, derived from 1:10.000 scale field mapping, combined with the results of electrical resistivity tomography, performed across the Holocene alluvial plain.

2. Regional setting

Eastern Sicily is located along the Nubia-Eurasia convergent boundary (Dewey et al., 1989; Serpelloni et al., 2007), where the Neogene-Quaternary southeastern-verging Maghrebian Thrust Belt originated from the tectonic inversion of the former Africa continental palaeomargin (see inset in Fig. 1). The geometry of the collision belt consists of two imbricated continental blocks (Panormide and Pelagian blocks) and a thin-skinned Neogene-Quaternary accretionary wedge,

which is sandwiched between them (Roure et al., 1990)(Fig. 2). A main E-W oriented, N-dipping crustal oblique (dextral) thrust (Mt. Kumeta-Alcantara Line of Ghisetti and Vezzani, 1982), which crops out in northern Sicily, represents the leading edge of the Panormide Block, also playing the role of back-stop of the Neogene-Quaternary accretionary wedge (Roure et al., 1990). This is emplaced on the Pelagian continental crust that, being buried beneath the entire eastern Sicily, culminates in the south-eastern sectors of the island, where it forms the Hyblean foreland domain (Ben Avraham et al., 1990). The present geometry of the Pelagian Block is the result of the Neogene-Quaternary flexure beneath the SE-verging orogenic belt. During Quaternary; this process was associated with the reactivation of a main N-S oriented dextral transform fault zone, the Scicli Line (Grasso & Reuther, 1988)(Fig. 1). To the west of this fault zone, the Hyblean Foreland sequences have also been flexured to form the Early Pleistocene NE-SW oriented Gela Foredeep (Grasso & Reuther, 1988; Grasso et al., 2000). To the east of the Scicli Line, the Hyblean Foreland sequences form a wide plateau, bordered to the north by two Middle Pleistocene collapsed basins, the Scordia-Lentini Graben and the Simeto Graben (Fig. 1)(Ghisetti & Vezzani, 1980) that are superimposed on the previous foredeep basin developed in the Catania region. Recent studies (Bousquet & Lanzafame, 2004; Catalano et al., 2008b) have documented a Late Quaternary tectonic inversion along both the Scicli Line, from right- to left-lateral, and along the margins of the associated Scordia-Lentini Graben, from extensional to contractional. As a consequence, during the Late Quaternary, the eastern portions of the Hyblean Plateau have been displaced to the northwest, towards the Catania Plain, at a rate estimated to be about 1.4 mm/a (Catalano et al., 2008b).

The entire collision belt of eastern Sicily is confined, to the east, by the Siculo-Calabrian Rift Zone (**SCRZ**) (Monaco & Tortorici, 2000); this is the tectonic expression of an incipient divergent margin, which separates the Adria-Ionian microplate from the colliding Tyrrhenian and Pelagian lithospheric domains (Serpelloni et al., 2007) (Fig. 1). The rift zone, in the Catania area, is composed of NNW trending oblique (dextral) extensional faults that are distributed from the eastern flank of Mt.Etna to the Ionian off-shore of the Hyblean Plateau, (Monaco et al., 1997; Monaco &

79 Tortorici, 2000; Catalano et al., 2008a).

80

81 **3. Late Quaternary deformation and seismotectonics of Sicily**

82 Sicily has been affected by intense Late Quaternary deformation, associated with high-level
 83 seismicity, which can be related to distinct seismogenic domains (Neri et al., 2005). Low to medium
 84 magnitude events ($4 < M < 6$) affect the deformation belt, which is related to the Eurasia-Nubian
 85 convergent boundary (see inset **a** in Fig. 1). The seismicity is concentrated along the Tyrrhenian
 86 off-shore and the northwestern sectors of the island, where available focal mechanisms constrain a
 87 stress field characterised by a $N130^\circ$ oriented maximum compression. Similarly, focal mechanisms
 88 indicating motions along NE-SW oriented thrust fault have been reconstructed for the 1968 Belice
 89 seismic sequence ($4.6 \leq M \leq 5.4$; Anderson & Jackson, 1987; Monaco et al., 1996) that affected the
 90 external areas of the orogen, in the southwestern Sicily (see inset **a** in Fig. 1).

91 In eastern Sicily, the present-day stress field has a different orientation because the σ_{hmax}
 92 follows the trend of the **SCRZ**, being NE-SW, in the Eolian Islands, and NNW-SSE, in the Mt.
 93 Etna region (Neri et al., 2005). A $N145^\circ$ oriented σ_1 has been obtained by the inversion of
 94 seismological data in the Hyblean region (Musumeci et al., 2005). This evidence is in good
 95 agreement with the focal mechanism of the 1990 Augusta earthquake (Amato et al., 1995), that
 96 indicates a NW-SE compression and a NE-SW tension (see inset **a** in Fig. 1).

97 Seismological data at a regional scale are consistent with the geodetic deformation that can be
 98 obtained by GPS-determined velocities with respect to stable Eurasia. Motions are constantly
 99 parallel to the maximum compression of the stress tensor. At sites LAMP and TRAP (see inset in
 100 Fig. 1; Hollestein et al., 2003) the measured NW-oriented GPS-velocities vs. Eurasia are parallel to
 101 the direction of the maximum compression measured in the western Sicily seismogenic domains.
 102 The slightly clockwise rotated NOTO vector (see inset **a** in Fig. 1) parallels the σ_1 orientation in the
 103 Hyblean-Mt. Etna subdomain. It is noteworthy that the difference between NOTO and LAMP
 104 vectors is largely accommodated by the left-lateral motions along the Scicli Line (Catalano et al.,

105 2008b).

106 Geodetic deformation also indicates that about 2.6 mm/a of shortening, representing the 63%
 107 of the entire NW-SE oriented Africa-Eurasia convergence, is accommodated by folding and
 108 thrusting within the Sicily collision belt (NOTO site vs. USTICA site; see inset **a** of Fig. 1), while
 109 the residual convergence (1.5 mm/a) measured at Ustica site must be accommodated further to the
 110 north.

111 In-situ stress measurements also fit well the seismological and geodetic data, as they indicate
 112 mean σ_{hmax} orientation of about N131°, in western Sicily, and N148° in the Hyblean foreland areas
 113 (Ragg et al., 1999).

114 Nevertheless, the main destructive ($M > 6.5$) historical earthquakes of Sicily (A.D. 1169, 1542,
 115 1693) have been localised along the Ionian coast of the island (Postpischl, 1985; Boschi et al., 1995;
 116 1997; Bianca et al., 1999; Monaco & Tortorici, 2000). They define a major seismogenic zone which
 117 is related to the occurrence of the active normal fault segments of the **SCRZ** (Fig. 1). Available
 118 crustal focal mechanisms in the Straits of Messina area (Anderson & Jackson, 1987; see inset **a** in
 119 Fig. 1), coupled with kinematic analyses on fault planes along the eastern flank of Mt.Etna (Monaco
 120 et al., 1997; Monaco & Tortorici, 2000), indicate that motion along the normal fault belt occurred in
 121 response of a N100° oriented maximum extension. The analysis of seismic lines across the off-
 122 shore active fault segments (Bianca et al., 1999) and morpho-structural investigations carried out
 123 along the on-shore fault planes (Monaco et al., 1997) suggested Late Quaternary average
 124 extensional-rates ranging from 1.7 to 3.7 mm/a. These data are in good agreement with GPS
 125 measurements carried out in southern Italy (Hollestein et al., 2003). In more detail, a mean active
 126 extension of about 3.5 mm/a has been calculated in the Messina Straits Region (D'Agostino &
 127 Selvaggi, 2004).

128

129 **4. Late Quaternary evolution of the Catania region**

130 The town of Catania is located on the northern margin of the NE-SW oriented Middle

131 Pleistocene Simeto Graben (Fig. 1) that originated at the front of the Maghrebian Thrust Belt and is
 132 filled by more than 1000 m of pelagic sediments (1.2 to 0.6 Ma-old; Di Stefano and Branca, 2002).
 133 The seismic lines across the basin and bore-hole data (Torelli et al., 1998; Fig. 3) emphasize that the
 134 Simeto Graben sequence seals the tectonic contact of the frontal nappe of the allochthonous edifice
 135 (Gela Nappe) upon the Early Pleistocene horizons of the Catania Foredeep (P-Q in Fig. 3)(Lentini
 136 and Vezzani; 1978; Bianchi et al., 1987; Lentini et al., 1996 and references therein), which are
 137 located at the top of the flexured Hyblean carbonate sequences (Roure et al., 1990; Lentini et al.,
 138 1994)(Fig. 3). The southern margin of the Simeto Graben is represented by the Primosole Horst
 139 (Fig. 3), where Middle Pleistocene extensional features are still preserved (Torelli et al., 1998).
 140 Conversely, the northern border of the basin has been completely obliterated by younger (200 ka)
 141 ramp-thrusts that bound the Dittaino-Simeto and the Terreforti highs (Monaco, 1997; Catalano et
 142 al., 2004). Seismic lines across the deposits of the Simeto Graben image an incipient NW-ward
 143 gently dipping detachment that ramps from the base of the allochthonous units through the Middle
 144 Pleistocene horizons. This detachment has been recognised at a depth of about 2000 m, beneath the
 145 Catania Plain and it approaches the surface near the coast (Fig. 3; Torelli et al., 1998). The deposits
 146 of the Simeto Graben are now covered by the alluvial plain of the Simeto and Dittaino Rivers
 147 (Catania Plain).

148 The Simeto Graben sequence is extensively exposed in the hangingwall of the thrust bordering
 149 the basin to the north. Along the Terreforti High (Fig. 3), Late Quaternary clastic deposits engrave
 150 several orders of terraced abrasion platforms, which have been modelled at the top of the Middle
 151 Pleistocene clay sequence. The terraced deposits represent regressive marine sequences (**S₁-S₇** in
 152 Catalano et al, 2004), upward grading into alluvial conglomerates (**T₁-T₇** in Catalano et al, 2004;
 153 see also Chester and Duncan, 1982; Monaco, 1997; Monaco et al., 2000)(Tab. 1), that were
 154 accumulated during successive periods of highstand, under the control of active tectonic uplift and
 155 deformation (Fig. 3). The fluvial terraces along the left side of the Simeto River (Chester and
 156 Duncan, 1982) can be, thus, interpreted as cyclic features, strictly related to the eustatically

157 controlled marine sequences distributed along the coastal slope of the town of Catania. This implies
 158 that the age of the marine deposits can be extended also to the correlative alluvial deposits (Caputo
 159 et al., 2008).

160 The older terraced sequence (**S₁** and **T₁** in Catalano et al, 2004)(Tab. 1) rests on an abrasion
 161 platform undercutting 320-250 ka-old subaerial subalkaline lavas (Gillot et al., 1994) and is
 162 intruded by 200 ka-old sub-volcanic rocks (Del Negro et al., 1998), while the youngest sequence (**S₇**
 163 and **T₇** in Catalano et al, 2004)(Tab. 1) is largely covered by subaerial lava flows from the modern
 164 central volcano (< 35 ka-old; Gillot et al., 1994). Taking into account the relation between eustacy
 165 and terracing, the age of the terraced sequences is thus constrained within the OISs (Oxygen Isotope
 166 Timescale Stages) to have occurred since 250 ka B.P., as also demonstrated by occurrence of
 167 volcanic pebbles from the Etnean sub-alkaline lavas (320-250 ka old; Gillot et al., 1994) in the
 168 coarse grained levels (Monaco et al., 2002).

169 In more detail, the lowermost five terraced sedimentary wedges and the correlative alluvial
 170 terraces (**T₃-T₇** in Catalano et al, 2004) (Tab. 1) undercut the 180 ka-old alkaline volcanics and can
 171 be thus related to the five main highstands between the OIS 5.5 (125 ka) and 3.1 (40 ka)(Tab. 1).
 172 This indirect dating, based on geomorphic evidence, is also supported by the occurrence of volcanic
 173 pebbles from the ancient alkaline lavas in the coarse-grained levels (Monaco, 1997). This implies
 174 that the lowermost fluvial terrace (**T₇**; Tab. 1), flanking the courses of the Simeto and Dittaino
 175 Rivers, can be assigned to the OIS 3.1 (40 ka).

176 The Middle Pleistocene (240-200 ka) terraced deposits are severely deformed by the
 177 contractional structures developed by the positive tectonic inversion of the northern margin of the
 178 Simeto Graben as a result of the propagation of a dextral shear zone from the collision belt. These
 179 structures are mostly represented by E-W oriented ramp-thrusts associated with major NW-SE
 180 oriented dextral strike-slip fault zones (Fig. 3 and Tab. 1; Catalano et al., 2004). In contrast, the
 181 Upper Pleistocene deposits, ranging in age from 125 to 40 ka, have been severely uplifted, as a
 182 consequence of the deformation along the extensional faults of the **SCRZ**, located in the Ionian off-

183 shore region (Tab. 1; Monaco et al., 2002; Catalano et al., 2004). During the last 40 ka, the syn-rift
 184 deformation has been accompanied by the propagation through the Catania Plain of a set of ENE-
 185 WSW oriented gentle folds (Contrada Agnelleria, Contrada Rotondella and Sigonella anticlines in
 186 Fig. 3; Catalano et al., 2004), that has deformed the most recent alluvial terrace (T_7 ; 40 ka)(Tab. 1).

187

188 **5.** The most impressive contractional structure of the Catania region is represented by a N70
 189 oriented, northwest-dipping ramp thrust. It involves terraced deposits as young as 80 ka (Monaco et
 190 al., 2002), as observed in the southern sector of the town of Catania, in a quarry (Fig. 4). In this
 191 area, the alluvial conglomerates belonging to terrace T_5 (OIS 5.1; Monaco et al., 2000) (Tab. 1)
 192 unconformably cover the 200 ka-old marine sandy sequence (S_2)(see inset **a** of Fig. 4), which is
 193 severely tilted towards the south, at the eastern termination of the Terreforti High (Fig. 3; Catalano
 194 et al., 2004). The syn-rift thrust-ramp is responsible for the local overthrusting of the marine
 195 terraced sequence (S_2 ; 200 ka) onto the alluvial conglomerates of the T_5 (80 ka)(see inset **b** of Fig.
 196 4). The total vertical displacement along the structure has been estimated at about 10 m, considering
 197 the off-set of the 80 ka-old unconformity across the ramp. In the hanging-wall of the structure, the
 198 motion along the ramp has produced the propagation of a fan of minor slip planes that isolate a
 199 N70° oriented kink band, which has further tilted the S-dipping strata (Fig. 4).

200 The described thrust-ramp developed at the forelimb of the N70° oriented Sigonella Anticline
 201 (Fig. 3), a wide box-fold that extends towards the SW, as far as 13 km from the urban area of
 202 Catania. The anticline is well exposed in the area of the village of San Giorgio, on the northern
 203 margin of the Catania Plain, where it deforms 60 ka-old terraced alluvials (T_6 in Catalano et al.,
 204 2004) (Tab. 1) as well as several older (125 to 80 ka) marine terraced deposits (S_3 - S_5 in Catalano et
 205 al., 2004) (Tab. 1). The marine strandline of the OIS 5.5 (125 ka) is involved in the inner flank of
 206 the box-fold, along which is regularly increasing in elevation from 120 to 150 m a.s.l.. The 100 ka-
 207 old (OIS 5.3) marine strandline crosses the crest of the structure, showing a change in elevation
 208 from about 80 m a.s.l., at the base of the inner flank, to 120 m a.s.l., at the crest of the anticline. The

209 younger marine strandlines, as well as the 60 ka-old alluvial deposits, are confined to the forelimb
 210 of the anticline, being deformed as far as 2 km from the crest of the structure. The morphological
 211 features of different ages that are involved in the structure, as a whole, suggest a wavelength of the
 212 fold of about 4 km with an estimated amplitude of about 40 m.

213 Towards the southwest, the crest of the anticline has been buried by the Holocene deposits of
 214 the Catania Plain. The stratigraphy of the uppermost 60 m thick levels of the alluvial plain have
 215 been investigated, by a series of electrical resistivity surveys, across the southwestern prolongation
 216 of the Sigonella Anticline, near the confluence between the Simeto and Dittaino rivers. North and
 217 south of the structure (cross-sections 1 and 3 in Fig. 5), the reconstructed resistivity pseudocross-
 218 sections have imaged three well defined superimposed electrostratigraphical units, each
 219 corresponding to as many sedimentary units: the shallower 15-25 m thick level ($R = 8 - 4 \text{ Ohm}\cdot\text{m}$)
 220 is represented by the Holocene alluvial sands and conglomerates, the intermediate 35 m thick level
 221 ($R = 10 - 30 \text{ Ohm}\cdot\text{m}$) corresponds to the Late Pleistocene sands and conglomerates (T_7 ; 40 ka),
 222 while the deeper very low-resistivity ($R < 4 \text{ Ohm}\cdot\text{m}$) layer corresponds to the top of the Middle
 223 Pleistocene marly-clay levels of the Simeto Graben. The tomographic model to the north of the fold
 224 crest (profile 1 in Fig. 5) shows a slight N-ward tilting of the layering, with the consequent S-ward
 225 narrowing of the Holocene alluvial deposits from 25 to 15 m, on a distance of about 300 m
 226 ($\text{dip} = 2^\circ$). The tomographic model crossing the buried crest of the Sigonella Anticline (profile 2 in
 227 Fig. 5) reveals a further narrowing ($< 5 \text{ m}$) of the Holocene alluvial deposits. In the resistivity
 228 pseudo cross-section, the forelimb of the fold is also marked by the occurrence, at depth, of a NE-
 229 dipping body that, characterised by higher resistivity values (20 to 35 $\text{Ohm}\cdot\text{m}$), cutting at high angle
 230 the sub-horizontal layering. The geometry of this resistivity anomaly is consistent with the
 231 occurrence, as well as in the Catania area, of heavy fractured fault-rocks, associated with a NE-
 232 dipping thrust-ramp. As similar to the Catania town section, the tomographic model across the
 233 structure suggests a very small vertical displacement that can be estimated at about 10 m, if

measured on the offset of the base of the sandy levels, while it is reduced to about 5 m, considering only the offset of the base of the Holocene alluvial deposits.

In the northwestern sector of the Catania Plain and in the adjacent Terreforti High, further two Late Quaternary N70 oriented anticlines (Contrada Rotondella and Contrada Agnelleria anticlines of Catalano et al., 2004) can be recognised (Fig. 3). These two gentle folds show very low amplitude (20 and 40 m) and long wavelength (3 to 4 km, respectively). The Contrada Agnelleria and Contrada Rotondella folds appear as slight flexures of the top-surface of the youngest terraced alluvial deposits (T_7 ; 40 ka) (Tab. 1), showing interlimb angles that approximate the 180° (Fig. 6). The geometry of these folds shows almost uniform amplitude and length on surface of different age, where they deform the older terraced alluvial deposits (T_1 - T_6 ; Tab. 1). The morphology of the folds is completely absent in the Holocene floodplain, which shows a very low-gradient (0,3%) longitudinal profile, almost parallel to that of the active channel of the Simeto River.

Out of the folded area, the T_7 terrace (Tab. 1) is regularly dipping, at very low-angle (0.34°), towards the Ionian sea. In contrast, in the folded area, the T_7 terrace shows evident undulations, as it culminates to form ENE-WSW elongated ridges, corresponding with the well-rounded hinge zones of the anticlines, which are separated by wide U shaped topographic depressions that have developed where the terraced surfaces have been subsided at the core of the synclines (Fig. 6). Approaching the crest of the Contrada Agnelleria and Contrada Rotondella anticlines, the T_7 terrace (Tab. 1) shows a slight divergence (1.34°) from the alluvial plain, coupled with convergence (0.40°) towards the intermediate synclines. The steeper and shorter NNW-dipping limbs suggest a NNW vergence of the folds. To the southeast of the Rotondella anticline, the 40 ka-old fluvial deposits have been covered by the Holocene deposits of the Catania Plain.

The syn-rift contractional deformation has also controlled the evolution of the Holocene fluvial morphology of the Catania Plain, which formed by the merging of the Simeto and Dittaino river floodplains (Fig. 3). The final tract of the Simeto River is characterised by an arcuated meandering course that, varying in direction from the N-S to the NW-SE, crosses at high-angle the

260 Late Quaternary anticlines of the Catania region (Fig. 3). At a distance of about 25 km from the
 261 mouth, the active channel of the Simeto River as well as the top of the Holocene floodplain show a
 262 very low-gradient (about 0.3 %), crossing undisturbed the folds that deform the 40 ka-old alluvial
 263 terrace (T_7).

264 In the Catania Plain, a very impressive change in the sinuosity index (S) of the river channel
 265 occurs at the intersection with the Sigonella Anticline (from the reach 6 to 7; Fig. 7). This variation,
 266 even if partly obliterated by modification due to the human activities, has been estimated taking into
 267 account the topographic data from the 1867 1:50.000 topographic map, the 1:100.000 topography
 268 reported in the geological map of the end of the XIX century (Gemmellaro and Travaglia, 1885;
 269 Gemmellaro et al., 1885) and, finally, the 1960 edition of I.G.M.I. 1:25.000 topographic map. If
 270 measured on the XIX century topography, the variation of the sinuosity can be estimated from 1.75
 271 to 3.75. A reduced change of the sinuosity (from 1.75 to 2.5) is imaged in the 1960 topography, as a
 272 consequence of the cut-offs of meanders that occurred in the last century.

273 To the west of the Simeto River, the Dittaino River is characterised by a prevalent NW-SE
 274 oriented meandering course, which flows from the external areas of the Maghrebian Orogen to the
 275 Catania Plain, crossing roughly perpendicular the NE-SW oriented termination of the Scicli Line.
 276 At the intersection with the structure, which is located between the reach 2 and the reach 3 (Fig. 7),
 277 the Dittaino River shows an evident increase of the sinuosity, of about the 100% (from 1.5 to 3),
 278 that was attenuated at about 60%, due to the cut-off of meanders in the reach 3 during the last
 279 century. From the Scicli Line to the mouth, the sinuosity of the river remains almost uniform and
 280 constant in the time. Nevertheless, the Dittaino displays a large scale deflection, which bounds the
 281 western terminations of the Rotondella and Sigonella anticlines, as it enters in the Catania Plain
 282 (Fig. 7).

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284

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6. Discussion and conclusions

A Late Quaternary fold and thrust system that developed along the flank of an active rift zone in the Catania region has been described. The Late Quaternary contractional structures as a whole generate a triangle zone, involving the Lower-Middle Pleistocene deposits of a former extensional basin (Simeto Graben) and deforming Upper Pleistocene and Holocene morphological features (Fig. 3). The south-verging active boundary of the triangle zone is represented by the ramp-thrust outcropping in the town of Catania, here referred to as Catania-Sigonella Thrust (**CST**), responsible for adjustments in the fluvial morphology along the Simeto River. At the intersection between the river and the structure, a dramatic change in the sinuosity is documented by several historical topographic maps (Fig. 8). The synoptic analysis of the 1:50.000 scale topographic map, edited in the 1867, of the topography reported in the 1:100.000 scale geological map of the end of the XIX century (Gemmellaro and Travaglia, 1885; Gemmellaro et al., 1885) and of I.G.M.I. 1:25.000 topographic map, edited in 1960, demonstrates that the difference in the sinuosity, between reaches 6 and 7 (Fig. 8), has in about 100 yrs progressively decreased from 2 to 0.75. The **CST** accumulated a total vertical displacement of about 10 m, half of which is related to Holocene motions as suggested by the clear control on the fluvial morphology. This implies that the structures developed in the last 20 ka, with an averaged vertical displacement-rate of about 0,5 mm/a.

The opposite north-verging tectonic boundary of the active triangle zone can be located along the northern limb of the Agnelleria Fold, on the prolongation of the active NE-SW oriented splay of the Scicli Line, here designated as the Sferro-Paternò Thrust (**SPT**), displacement on which has caused the morphological responses recognised along the Dittaino River. The intersection between the river and the structure is also in this case marked by a well defined change in sinuosity, only partially attenuated in the last century. The recognised responses of the fluvial morphology, which have been modelled in the literature by Holbrook & Schumm (1999), document very recent longitudinal tilting of the active channels of the Simeto and Dittaino Rivers, at the intersection with

the two tectonic boundaries of the triangle zone and, thus, directly related to recent motion along the **SPT** and the **CST**.

Conversely, the undeformed Holocene morphological features, which are incised into the entire fold belt, and the geometry of the Late Pleistocene fluvial terraces suggest that the folding is restricted to the time interval from 40 to 10 ka. Considering the evolution of these contractional structures, the Late Pleistocene anticlines can be interpreted as fault-propagation folds affected by opposite vergences, that deactivated when the thrusts reached the surface. Thereafter, the entire triangle zone was uplifted, confined to the west by the large scale deflection of the Dittaino River.

The cumulative shortening across the entire triangle zone can be estimated taking into account the vertical displacement of the Late Quaternary terraces and the shortening due to the gentle folding (< 3 m). The terracing of the 40 ka-old fluvial deposits is confined at the hangingwall of the **SPT**. These old alluvial sediments were deposited during OIS 3.1, when the base level was about 40 m lower than Present (Bassinot et al., 1994). Considering an average elevation of the terrace of about 30 m above the modern Simeto River, a cumulative uplift of about 70 m is implied. A large portion of this uplift can be related to the regional signal that has been estimated to be about 0.8 mm/a (Catalano et al., 2004). The residual amount of uplift (38 m) can be interpreted as the tectonic contribution of the **SPT**. Considering that the reverse faulting developed along a former extensional margin, a dip of 60° for the inverted fault-plane can be tentatively assumed. This would imply a conversion of the vertical motion into a shortening of about 22 m. Taking also into account the motion along the **CST** and the gentle fold deformation, a shortening of about 35 m has been accommodated by the entire triangle zone in the last 40 ka, at a deformation-rate of about 0.8-0.9 mm/a. A rough estimate of the depth of the sole-thrust of the triangle zone can be obtained comparing the amount of the relief produced at the surface by the Late Quaternary thrust motion with the related cumulative shortening. Assuming plane-strain deformation, a depth of the sole-thrust of about 7500 m is obtained by analysing the deformation of the 40 ka-old alluvial terrace (**T₇**) along the topographic profiles, drawn perpendicular to the trend of the contractional structures

(Fig. 6). This implies, considering a depth of about 2000 m of the sole-thrust of the allochthonous units beneath the Catania Plain (T_1 in Fig. 3), that the relation between the Late Quaternary deformation of the triangle zone and the migration of the front of the orogen is unrealistic.

The geometry, the estimated depth of the basal detachment and the deformation-rate of the triangle zone are, however consistent with the Late Quaternary contractional deformation affecting the Hyblean crustal block, which is bounded to the west by the Scicli Line. In this region, the Early Pleistocene extensional features (e.g. Scordia-Lentini Graben) experienced a diffuse Late Quaternary positive tectonic inversion, associated with the inversion of the sense of motion along the Scicli Line (Catalano et al., 2008b). The authors have constrained the positive tectonic inversion of the Scordia-Lentini Graben, connected to the left-lateral motion along the southernmost segments of the Scicli Line, at about 850 ka. Recent studies (Catalano et al., 2010) have interpreted the inversion tectonics as related to a rift-flank deformation, affecting the eastern sectors of the Hyblean Plateau, located at the footwall of the **SCRZ**. The authors have related the surface inverted tectonics of the southern margin of the Scordia-Lentini Graben to the emergence of a NNW-verging crustal ramp that originated from a Mantle intrusion, which has been inferred at a depth of about 25 km.

It is worth noting that the described surface inverted structures have accommodated only a small amount (30%) of the sinistral strike-slip motion along the Scicli Line, thus suggesting that part of the contraction should be taken up along blind structures, located more to the north. The present study suggests that a NNW-ward propagation of the inverted contractional structures may have migrated for about 30 km in the last 850 ka (Fig. 8). The overall surface geometry of these younger inverted structures is compatible with a detachment, located at depth of about 7500 m, along the Permo-Triassic levels at the base of the sedimentary succession of the Hyblean Plateau (Bianchi et al., 1987), that ramps to form the **SPT**, since about 40 ka. In this context, the **CST**, which forms the opposite boundary of the triangle zone would represent a secondary back-thrust, characterised by a very low cumulative displacement. The measured shortening-rate (0.8-0.9 mm/a) along the inverted triangle zone of the Catania Plain is comparable with the residual left-lateral

deformation-rate (≈ 1 mm/a), affecting the northernmost segments of the Scicli Line, to the north of the Scordia-Lentini Graben. According to this new kinematic model, the active contractional deformation of the Catania region can be related to the dynamics affecting the whole of southeastern Sicily, driven by mantle intrusion triggered by the rift-flank deformation along the **SCRZ**, rather than to the late evolution of the collision belt (Catalano et al., 2010).

This new kinematic and dynamic model has consequences for the regional seismotectonic picture, if the contractional deformation of the Catania region is to be related to motion along the northern segments of the Scicli Line and the southern inverted margins of the Scordia-Lentini Graben. These tectonic alignments represent major crustal structures that must be considered as potential seismogenic sources for locating historical earthquakes. As well, the measured deformation rates are significant and should be accounted for when evaluating the recurrence-time of seismicity in the area.

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501

502 **Figure captions**

503 **Fig. 1:** Geological sketch map of the Catania region, eastern Sicily.

504 Key: (1) Holocene deposits (a) Late Würmian-Holocene alluvial fan (b); (2) Etnean Lavas: recent
505 alkaline products (80 ka to Present) (a); ancient alkaline products (180-100 ka) (b) (chronological
506 data from Gillot et al., 1994); (3) sub-alkaline products of Mt. Etna volcanic district (320-200 ka)
507 (chronological data from Gillot et al., 1994); (4) Middle Pleistocene deposits of the Simeto and
508 Scordia-Lentini Graben and Late Quaternary marine terraces; (5) Early-Middle Pleistocene deposits
509 of the Gela Foredeep; (6) Undifferentiated Meso-Cenozoic Maghrebian allochthonous units; (7)
510 Pliocene-Early Pleistocene volcanics of the Hyblean Plateau; (8) Meso-Cenozoic foreland
511 sequences of the western Hyblean Plateau; (9) Meso-Cenozoic foreland sequences of the eastern
512 Hyblean Plateau; (10) buried front of the Maghrebian allochthonous units; (11) Pliocene- Early
513 Pleistocene fault; (12) Middle Pleistocene extensional fault (Simeto and Scordia-Lentini Graben);
514 (13) Late Quaternary and active tectonics and volcano-tectonics: strike-slip fault (a); normal fault of
515 the “Siculo-Calabrian Rift Zone” (b), thrust (c), anticline (d) dry and eruptive fissure (e); (14) main
516 transform fault zone; (15) maximum horizontal extension in the Etnean area and in the Ionian

517 offshore; (16) maximum horizontal compression in the Catania Plain area; (17) main earthquake
 518 (a): in the map the major ($M \geq 7$) historical earthquakes are reported; the inset also shows the main
 519 instrumental events, with available focal mechanisms (b) (the location of epicentres are from
 520 Postpischl, 1985; Boschi et al., 1995 and 1997; Bianca et al., 1999; Monaco & Tortorici, 2000;
 521 Focal mechanisms are from Anderson & Jackson, 1987; Amato et al., 1995; Pondrelli et al., 2002;
 522 2004); (18) GPS vector; (19) rift-flank volcanoes (see in the inset **a**).

523 The inset **a** shows the deformation belts connected to the active Nubia-Eurasia convergent boundary
 524 and the SCRZ respectively. The inset **b** refers to the relative motion between the plates.

525

526 **Fig. 2:** Schematic geological profile across the eastern portion of the Sicily collision belt.

527 (for the location see inset **a** in Fig. 1)

528

529 **Fig. 3:** Geological map of the Simeto Graben (for location see box in Fig. 1). Note that the southern
 530 border of the collapsed basin (Primosele Horst) still shows the original (Middle Pleistocene)
 531 extensional features, while the northern margin (Dittaino-Simeto Horst) has been completely
 532 replaced by the Late Pleistocene contractional structures of the Terreforti High. In addition, within
 533 the basin Recent (< 40 ka) to active ENE-WSW oriented folds and thrusts developed.

534 Key: (1) Holocene alluvial deposits; (2) Recent etnean lava flows (< 80 ka); (3) 40-ka old alluvial
 535 terraced deposits; (4) Middle-Late Pleistocene alluvial terraces; (5) Middle Pleistocene marine
 536 terraced sequences; (6) Ancient alkaline lavas (180-100 ka); (7) sub-alkaline lavas (320-200 ka); (8)
 537 Middle Pleistocene deposits of the Simeto Graben (1,2-0,6 Ma); (9) allochthonous units; (10)
 538 Pliocene-Early Pleistocene volcanics of the Hyblean Plateau; (11) Carbonate foreland sequence of
 539 the Hyblean Plateau; (12) Late Quaternary tectonics: (a) normal fault, (b) strike-slip fault, (c) thrust;
 540 (13) Recent and active anticline (a), inverted reverse fault (b).

541 Dashed boxes in the figure refer to the location of Fig. 5 and Fig. 6, respectively.

The stereoplots (Schmidt net, lower hemisphere projection) in the inset refers to measured bedding of marine terraces of the following Oxygen Isotope Stages (OISs): a) OIS 7 (240-200 ka); b) OIS 5.5 (125 ka); c) OIS 5.3 (100 ka); d) OIS 5.1 (80 ka); e) OIS 3.3 (60 ka); f) OIS 3.1 (40 ka).

In the geological profiles, which has been drawn on the basis of surface data, supported by bore-hole logs and seismic lines (Torelli et al., 1998), the tectonics related to distinct deformation stages are reported: **T₁**) sole thrust of the allochthonous nappe; **T₂**) Middle Pleistocene (> 850 ka) normal faults of the Simeto Graben; **T₃**) Middle Pleistocene (600-200 ka) ramp thrust; **T₄**) reactivated portion of **T₁** (< 40 ka).

Fig. 4: Photo showing the Late Quaternary (< 80 ka) thrust ramp (**CST**) exposed in the Catania Town. For details on the involved deposits, see the schemes **a** and **b** in the inset.

Fig. 5: Geoelectric tomographies in the Catania Plain, across the southwestern prolongation of the Sigonella Anticline. For location of the area see dashed box in Fig. 3. For locating the resistivity pseudocross-sections with regards to the investigated tectonics, see the inset.

Fig. 6: Digital elevation model (DEM) of the topography across the Sigonella, Rotondella and Agnelleria anticlines. In the model, the 40 ka-old alluvial terrace is evidenced. The cross-sections evidence the geometry of the surface at the top of the alluvial terrace (dashed grey line) compared with the reconstructed longitudinal profiles of modern rivers (dashed black line).

Fig. 7: Evolution of the sinuosity along the Simeto and the Dittaino rivers, across the Late Quaternary tectonics of the Catania Plain.

In the diagrams, the variation of sinuosity within successive reaches of the Simeto and the Dittaino rivers has been plotted, with reference to the 1867 and 1960 topographic maps, respectively.

568 **Fig. 8:** Evolution of the Late Quaternary positive tectonic inversion at the flank of the **SCRZ**, in the
569 Catania region.

570

571 **Tab. 1:** Chronostratigraphic scheme of Upper and Middle Quaternary terraced sequences of the
572 northern margin of the Simeto Graben. For each sequence, the correlative OIS and the age are
573 reported.

Table 1

Terraced sequence	OIS	Age (ka)
(S ₁) (T ₁)	7.5	240
(S ₂) (T ₂)	7.1	200
(S ₃) (T ₃)	5.5	125
(S ₄) (T ₄)	5.3	100
(S ₅) (T ₅)	5.1	80
(S ₆) (T ₆)	3.3	60
(S ₇) (T ₇)	3.1	40

Figure 2

Figure 5