Liquefaction structures induced by historical earthquakes along the Ionian coast of Sicily (southern Italy)

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Liquefaction is one of the most common secondary effects induced by earthquakes and, because sites affected by liquefaction are susceptible to liquefy again, it is widely used as geological marker of paleoseismicity. For a site affected by liquefaction, earthquake magnitude and epicentral distance are related by empirical relationships (Ambraseys, 1988; Galli *et al.*, 1999; Galli, 2000; Pirrotta *et al.*, 2007). The field survey of liquefaction structures is very difficult since they develop underground, to a depth of 10 m, and, occur mainly in highly dynamic depositional environments such as beaches or alluvial plains, which are often affected by important human activity. Even if liquefaction split off the surface, it is difficult to be preserved.

The aim of this work is to present geological evidence of liquefactions triggered by earthquakes in eastern-Sicily and to analyze their characteristics. Liquefaction prone areas have been selected on the basis of the historical observations and by using aerial photographs, geological maps and field investigations.

Only from the latest decennia the Italian bibliography can offer catalogues reporting accounts of historical earthquakes secondary effects as the result of a modern, strongly focused, historical seismological research (Fig. 1). In fact, Berardi *et al.* (1991; 1998) reported 158 liquefaction events occurred during 31 quakes. ISMES (1991) and Galli and Ferreli (1995) compiled catalogues with high liquefaction potential earthquakes, selected from the ENEL Seismic Catalogue (1991). Galli and Meloni (1993), updating the previous work, created a catalogue, for the Italian country, including 307 liquefactions occurred during 63 earthquakes, subsequently inproved by Galli *et al.* (1999) which considered all the events occurred in Italy since AD 1117. Finally Galli (2000) creates a catalogue which is a completely reviewed and updated version of previous compilations.

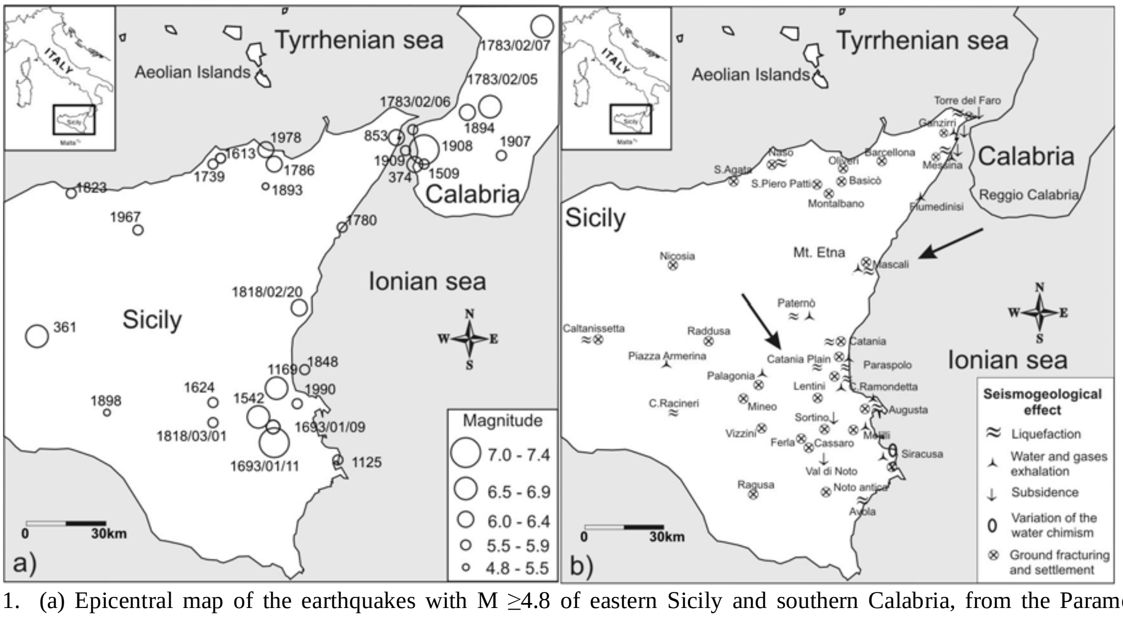

Fig. 1. (a) Epicentral map of the earthquakes with M ≥4.8 of eastern Sicily and southern Calabria, from the Parametric Italian catalogue (Working Group CPTI, 2004); (b) Map of the most important seismically-induced secondary effects of eastern Sicily and southern Calabria, retrieved from historical sources (After Pirrotta *et al.*, 2007, modified).

Though the difficulties caused by the intense human activity (urban settlement, industrial development, fluvial regimentation etc.), field investigations allowed us to recognize evidence of

liquefaction at several sites in the eastern flank of Mt. Etna and in the Catania plain to the south, where these phenomena are described by historical reports.
In two sites we analyzed in details artificial exposures showing evidences of liquefaction features in the outcropping Holocene deposits: (1) the Minissale trench, in the Mascali area, and (2) the Agnone trench, in the Catania plain both placed onto the Gela foredeep.
The most frequent structures found in our analysis are:
a) Lateral spreading: a breakage and lateral/vertical drag of the fine grained brittle cap. This feature is caused by the direct action of the seismic shaking and liquefaction of the underlying layers.
b) Dikes: intrusion of sand layers vented upward under the influence of the hydraulic force.
c) Faults: brittle mesostructures developed in the uppermost sandy layer as consequence of the dike intrusion.
d) Drag folds: developed in some clayey layers alternated with sands, as consequence of the upward dragging of the dike.
e) Recumbent folds and sheet slumps: developed in the uppermost sandy layer as consequence of the seismic shaking.
f) Warped top level: up-warping of the low permeability cap in response to the dike intrusion.
g) Boudinage: developed in low permeability layers horizontally stretched in consequence of the seismic shaking.

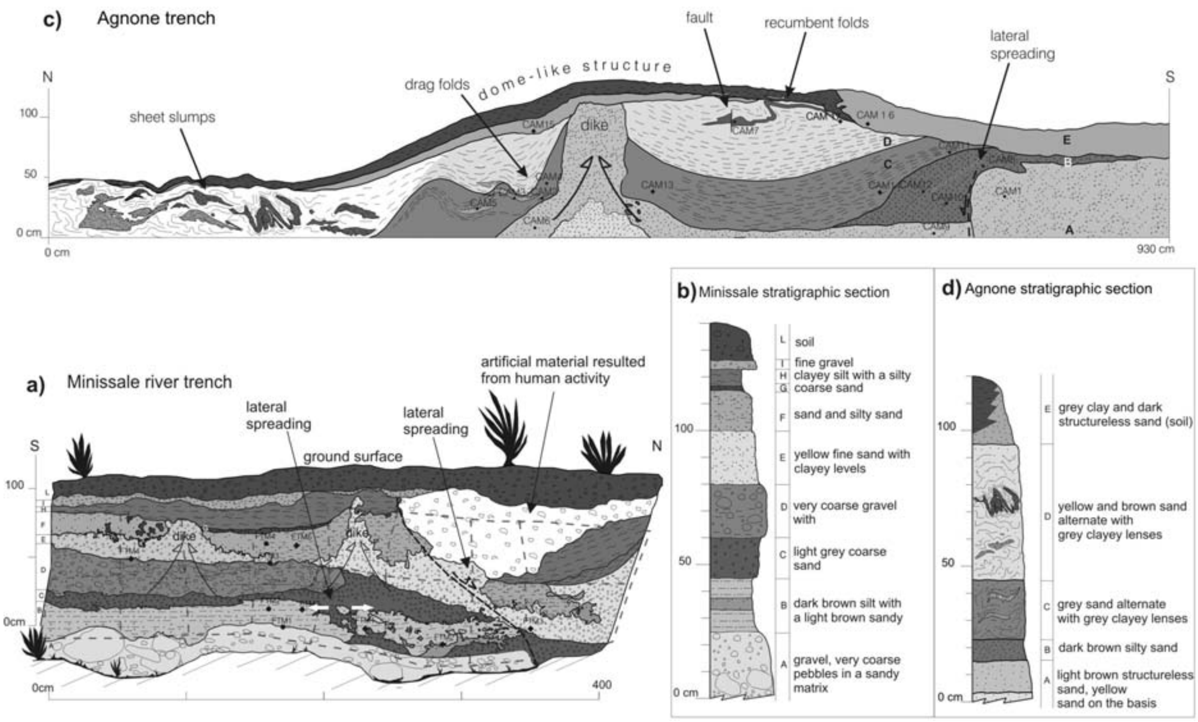

Fig. 2 (a) Line drawing of the Minissale exposure. The arrows represent the flow direction of the liquefied sand. The polygons indicate the samples for stratigraphic and micro-paleontological analysis and for ^{14}C dating; (b) Stratigraphic log of the fluvial terrace outcropping in the Minissale exposure. (c) Line drawing of the Agnone exposure. The arrows represent the flow direction of the liquefied sand. The polygons indicate the samples for stratigraphic and micro-paleontological analysis and for ^{14}C dating; (d) Stratigraphic log of the alluvial sequence outcropping in the Agnone sand quarry.

The Minissale Site.
The Minissale trench is part of an anthropic ditch, dug for agricultural purposes, up to 3 m deep, exposing the sedimentary sequence of a fluvial terrace developed on the right side of the Minissale river in the Mascali area (Fig. 2b). The most clear deformational features observed on the trench wall are the interruption of the A and B-Units and the downthrowing of the F and H-Units. This is interpreted as lateral spreading since the absence of an evident fault plane (Fig. 2a). Other features are two dikes formed by vented yellow fine sands (E-Unit) : the southernmost dike intrudes the F-Unit, while the northernmost one cuts the layers up to the middle part of H-Unit. Below the dikes the pebbles of the D-Unit are clustered and iso-oriented. Moreover, the breakage of B-Unit, with stretched beds and cracks overfilled by sands, associated with the interruption of the coarse gravel

layer (D-Unit), suggests the presence of a previous lateral spreading sealed by the sands of E-Unit (Fig. 2a).
We dated two samples collected on the trench wall at different depths, in order to get an age control on the hypothesised deformational events (Table 1). Sample FTM5, a piece of charcoal collected within Unit F that should predate the last event, gave a 2 sigma age of AD 1650-1950, with the older part of the interval statistically preferred. A bulk sample (FTM7) collected from the dark brown silty B-Unit, predating the older event gave a 2 sigma age of AD 825-995.

The Agnone Site
The Agnone trench is part of a quarry located in the Agnone area, behind a wide littoral dune about 1 km far from the coastline of the Ionian Sea (Fig. 2d). The most prominent deformational structure is a 100 cm high and 50 cm wide sand dike located in the central sector of the exposure (Fig. 3b). The dike, developed by the light brown sand (A-Unit) upward migration, cuts through the sequence intruding up to the top levels (Fig. 3c). The alternated sand and clay layers of C-Unit show the presence of drag-folds most likely caused by the dike development (Fig. 3d). D-Unit, a 50 cm thick layer of yellow sands alternated with brown silt and clay, appears intensely deformed by boudinage, recumbent folds (Fig. 3e) and sheet-slumps (Fig. 3f), probably as its heterogenic lithology responds to the dike intrusion.

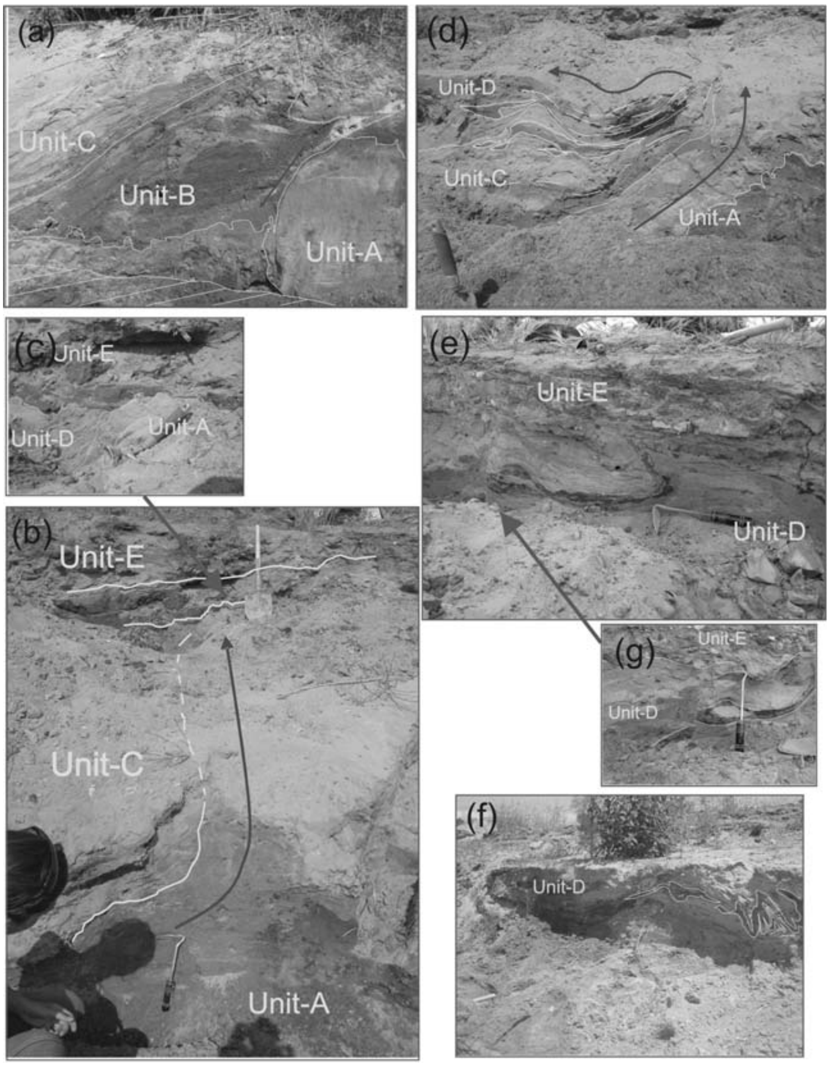

Fig. 3 Agnone trench pictures: (a) Slumping in the Unit-D, northern sector of the trench; (b) Dike of the sand of Unit-A and drag folds associated in the Unit-C and D; (c) Dike intrusion in the Unit-E, the detail is in picture (f); (d) recumbent fold in Unit-D offset for 7cm by a little fault, the detail is in picture (e); (g) lateral spreading involving the Unit-A and B.

In the upper part of the section, south of the sand dike, we can observe a little fault with a near vertical plane, 7 cm offset, cross-cutting the recumbent fold of D-Unit (Fig. 3g). Finally, the dome-like morphology of the top level (E-Unit) has been interpreted as result of the up-warping mechanism caused by the sand dike intrusion.
In the Agnone trench we have collected two bulk samples (CAM15 and CAM16 in Figure 2c), for radiocarbon dating, both from the dark brown silt of the top level, the age of which should predate the last event (dike intrusion). Sample CAM15 gave a 2 sigma age of AD 1660-1950 (Table 1), while the 2 sigma age of CAM-16 is AD 1460-1635. We also collected bulk sample CAM12 from the dark brown silty sand B-Unit, predating the lateral spreading event. Sample CAM12 gave a 2 sigma age of AD 1430-1620.
In both the studied trenches the relationships between deformational and sedimentological structures suggest the occurrence of more than one liquefaction event.
The Minissale trench study highlights the occurrence of two events: the first deformation is testified by the lateral spreading affecting up to D-Units, the second one by the dikes and the lateral spreading involving the sequences up to the H-Unit (Fig. 2a). Since the lateral spreading is linked to a sinking mechanism and the dike intrusion is driven by an upward venting, the overlapping of the dike upon the first lateral spreading suggests that the two events are not coeval. Considering that the lowermost liquefaction structures affected the sequence up to D-Unit and that B-Unit age is AD 825-995 (FTM7 in Tab. 1), this deformational event could be tentatively associated to the AD 1169 earthquake. For the younger liquefaction structures, the calibrated age of the unit that predates this event ranges between AD 1650-1950, with the interval AD 1650-1815 more probable (78% of 2 sigma probability, Tab. 1). Since three large earthquakes occurred in this time interval (1693, 1818 and 1908), it is difficult to substantiate a direct correlation with one of them, however, considering the Magnitude vs Epicentral distance relation available for eastern Sicily (Pirrotta et al., 2007) the best candidates are the AD 1693 and 1818 earthquakes.

Tab. 1 Measured and calibrated ages (according to Calib REV5.0.2 by Stuiver and Reimer (2005) of the samples collected in the excavation walls).

Sample	**Type**	**Measured age B.P.**	**Calibrated age 2 σ**
FTM5	Charcoal	185 ± 30 BP	1650-1950 AD
FTM7	Bulk	1120 ± 30 BP	825-995 AD
CAM12	Bulk	410±30	1430-1620 AD
CAM15	Bulk	165 ± 30 BP	1660-1950 AD
CAM16	Bulk	350 ± 30 BP	1460-1635 AD

Also the Agnone trench study clearly proves the repeatability of the liquefaction phenomena in a site subject to this type of deformation. In fact, the Agnone site suffered at least two distinct seismic events, as testified by the liquefaction study: (1) in response to the first event, a lateral spreading caused subsidence with a slight deepening to the north and the accommodation space for the sedimentation of C and D-Unit (Fig 3a); (2) the last and more recent event induced the sand dike venting (Fig. 3b) and the intrusion of the low permeability cap (Fig. 3c), that caused the dome-like structure of the top levels and the occurrence of drag and recumbent folds (Figs. 3d, 3e) and sheet slumps (Fig. 3f) in D and C-Unit. Since the paucity of datable material in these fluvial deposits, this trench is supported by two samples collected on the top level (CAM16 and CAM15 in Tab. 1) that gave incompatible results probably because of sample contamination from the surface. Thus we decided to rely mostly on the CAM16 age (AD 1460-1635). Since the age of the top level pre-dates the last deformational event we can tentatively associate the development of the sand dike and related structures to the AD 1693 earthquake. The older event is pre-dated by the sample CAM12 (AD 1430-1620, with the interval AD 1430-1520 comprising 88% of 2 sigma probability, see Tab. 1) which may suggest the 1542 earthquake to be the causative event.

Acknowledgments
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