Sedimentary Geology 325 (2015) 158–167

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Sedimentology and composition of sands injected during the seismic crisis of May 2012 (Emilia, Italy): clues for source layer identification and liquefaction regime

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ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form 1 June 2015
Accepted 2 June 2015
Available online 12 June 2015

Editor: J. Knight

Keywords:
Sand liquefaction
Sand composition
2012 Emilia Romagna earthquake
Fluvial deposits
Po Plain

ABSTRACT

In May 2012 widespread sand blows formed along buried channels in the eastern sector of the Po Plain (Northern Italy) as a consequence of a series of seismic events with main shocks of Mw 6.1 and 5.9. At San Carlo (Ferrara) a trench dug a few week after the earthquakes exposed sand dikes cutting through an old Reno River channel–levee system that was diverted in the 18th century and was deposited starting from the 14th century (unit A). This sequence overlies a Holocene muddy floodplain deposits and contains scattered sandy channel deposits (unit B) and a Pleistocene channel sand unit (unit C). Sands with inverse and normal grading, concave layering and vertical lamination coexisting along the dikes suggest multiple rhythmic opening and closing of the fractures that were injected and filled by a slurry of sand during the compression pulses, and emptied during the extension phase. The pulse mechanism may have lasted for several minutes and formed well stratified sand volcanoes structures that formed at the top of the fractures. Sands from dikes and from the various units show well defined compositional fields from lithoarenitic to quartz-feldspar-rich compositions. Sands from the old Reno levee and channel fill (unit A) have abundant lithic fragments derived from the erosion of Apennine sedimentary carbonate and terrigenous successions. Composition of the sand filling the dikes show clear affinities with sand layers of the old Reno River channel (Unit A) and clearly differ from any sand from deeper Holocene and Pleistocene layers (Unit B and C), which are richer in quartz and feldspar and poorer in sedimentary lithic fragments. Sorting related to sediment flux variations did not apparently affect the sand composition across the sedimentary structures. Textural and compositional data indicate that the liquefaction processes originated from a relatively shallow source consisting of channel sands located within Unit A at 6.8.to 7.5 m depth.

1. Introduction

In May 2012 the eastern sector of the Po Plain (Northern Italy) was affected by two earthquakes (Mw 6.1 and 5.9; Pondrelli et al., 2012) followed by several aftershocks (up to Mw 5.1). The seismic activity was triggered along a portion of the Apennines thrust belt buried below the alluvial plain (Pieri and Groppi, 1981). The first event produced liquefaction phenomena, surface fracturing and sand ejection, in particular in the western sector of the Ferrara province (Papathanassiou et al., 2015). In this area, the liquefaction processes were concentrated along an elongated topographic ridge corresponding to an old channel of the Reno River that was active until the end of the 18th century when it was artificially diverted.

Because of the potential destruction and damage to structures and human activities, sand-boil and liquefaction phenomena require thorough studies to assess the geotechnical conditions that may lead to their recurrence (Chang et al., 2011). Sedimentology of the liquefaction mechanisms and the selective processes acting on sand grains are, however, less commonly explored (Ricci Lucchi, 1995; Hurst et al., 2011). This is particularly interesting because, although the phenomenon is mostly limited to sands, even gravelly sediments can be susceptible to liquefaction (Chen et al., 2008). No data are available on the possible influence of the liquefaction phenomena on the composition of sediments: does the liquefied sand retain the same petrographic composition of the source layer while traveling through the fractures? Is there any selective mechanism that may shift the sediment composition when the pressurized slurry of water and sand erupts to the ground surface? These questions are particularly significant as the sand composition may be used as a tool to pinpoint the source layers, provided that sands located at different stratigraphic layers have been

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http://dx.doi.org/10.1016/j.sedgeo.2015.06.004
0037-0738/

petrographically characterized. This applies also to old sand blows buried by other deposits and preserved in the geologic record.

Fluvial sand composition studies have a particular significance in the late Pleistocene–Holocene Po Plain, where distinct compositional fields characterize modern sands from different streams, as well as older sediments (Lugli et al., 2007; Garzanti et al., 2011). Several key petrographic components provide diagnostic features to distinguish sand bodies buried beneath the floodplain (Johnsson et al, 1991; Arribas and Tortosa, 2003; Critelli et al., 2003; Weltje and Von Eynatten, 2004: Basu et al., 2013). In this context, we analyzed the texture and petrographic composition of sands injected during the seismic events of 2012 along the paleo-Reno River channel at San Carlo (Ferrara), and sands from subsurface deposits at different depths. The aim of the research was to provide a better understanding of earthquake-induced liquefaction mechanisms using textural and petrographic parameters to identify the possible source layers of the sand blows.

2. Geological setting

The Ferrara alluvial plain area is located on the buried sector of the Northern Apennine fold-and-thrust belt, Italy, where streams flow northeastward into the Po River and the Adriatic Sea (Fig. 1). The Northern Apennines formed mainly during the Tertiary convergence between the European and the Adria plates. The plate movement consumed the interposed Tethyan oceanic crust with the formation of an accretionary prism, which during the subsequent collisional phase produced a complex orogenic wedge (Ricci Lucchi, 1986; Bettelli and De Nardo, 2001; Argnani et al., 2004). On the northern side of the Apennine chain, these units are unconformably overlain by Miocene–Pliocene and Quaternary terrigenous deposits of the Po Plain.

The Po Plain is the syntectonic sedimentary wedge filling the Pliocene–Pleistocene Apennine foredeep. The total basin infill is up to 4 km-thick, and the Quaternary deposits reach a thickness of 1.5 km. The factors controlling the architecture of the sedimentary filling (Amorosi et al., 2008) were the contrasting rates of subsidence induced by the vertical motions of the blind thrusts buried under the foredeep deposits, such as the Ferrara fold-fault system (Pieri and Groppi, 1981). This long-term effect combined with the Holocene rise of the Adriatic Sea level reduced the gradient along a west-east drainage axis. The main drainage, the Po River, was tectonically forced to shift northwards and human pressure on the forest cover since the Bronze Age produced a generalized increase in fine bedload discharge into the Apennines tributaries (Ravazzi et al., 2013). The river network continuously shifted laterally as a consequence of climate changes and local tectonic events (Fig. 1). The late evolution of the system has been successfully traced following the physical evidence of paleochannels on the alluvial plain surface, and the older sedimentary patterns are revealed by the provenance composition signals of buried Holocene channel sands which match those of the present day rivers (Lugli et al., 2007).

3. The recent evolution of the Reno River

The synergic roles of fast subsidence and large sedimentary input have produced very high sedimentation rates and frequent changes in the fluvial drainage framework of the central part of the eastern Po plain (Fig. 1). The evolution of the river network can be reconstructed and dated in great detail, through the correlation of the stratigraphic sedimentological evidence with compositional data (Lugli et al., 2007) and a large amount of historical information and accurate ancient maps (e.g., Bondesan, 1989; Caputo et al., 2015).

In the late Middle Ages, the Reno River was neither able to reach the Adriatic Sea nor to directly flow into the Po River, which was running about 10 km to the north of the study area. At that time the Reno River was mostly feeding a large paludal area and only at the end of the 18th century it was successfully forced to reach the sea, through an abandoned southern distributary channel of the Po River. The diversion point is located just to the southwest of the investigated site (Fig. 1). The investigated sector of the channel–levee system was already built in its present form at the beginning the 15th century and its depositional morphology is still recognizable today. It consists of a concave belt oriented SW–NE (the former channel), bordered by two

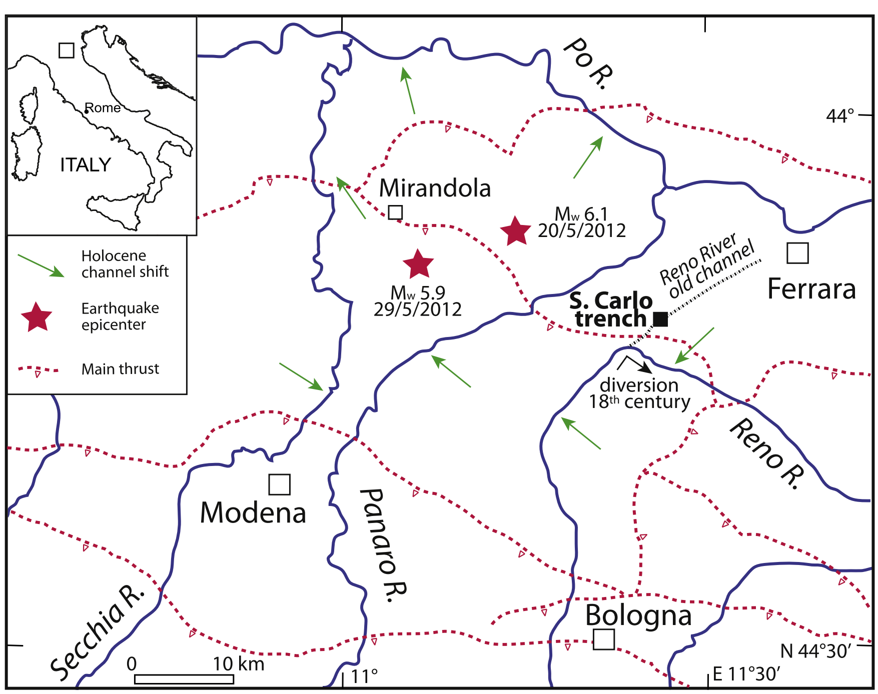

Fig. 1. Sketch map of the alluvial plain in the Emilia area affected by the May 2012 earthquakes (location of the two major epicenters are indicated with stars). The studied trench is located at San Carlo, along an old Reno River channel abandoned as a result of the 18th century diversion. Arrows indicate the river channel shift trends during the Holocene (modified from Burrato et al., 2012).