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Abstract: In May 2012 widespread sand blows formed along buried channels in the eastern sector of the Po Plain as a consequence of a seismic crisis 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 18° century and was deposited starting from the 14° century (unit A); this sequence lie on Holocene muddy floodplain and scattered sandy channel deposits (unit B) and a Pleistocene channel sand unit (unit C). Sand inverse and direct grading, concave layering and vertical lamination coexisting along the dikes suggest multiple rhythmic opening and closing of the fracture borders that were injected and filled of slurry sand during the compression pulses end emptied during the extension phase. The pulse mechanism may have lasted for several minutes and formed well stratified structure of the sand volcanoes that formed on the top of some fractures. Sands from dikes and from the various units show well defined compositional fields from lithoarenitic to quartz-feldspar-rich compositions. Sorting related to sediment flux variations did not apparently affect the sand composition, across the sedimentary structures. Sands from the old Reno levee and channel fill (unit A) have abundant lithic fragments deriving from the erosion of Apennine sedimentary carbonate and terrigenous successions. Pleistocenic sands (unit C) are enriched in quartz and feldspars as a consequence of the different climatic weathering condition that prevailed during the last glacial stage. The Pleistocene sand were partially reworked during the Holocene (unit B). Composition of the sand filling the dikes show clear affinities with sand layer of the old Reno River channel (Unit A) and clearly differ from any sand from deeper layers (Unit B and C), which are richer in quartz and feldspar and poorer in sedimentary lithic fragments. 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.

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Dear Editors,

We are submitting the manuscript "Sedimentology and composition of sands injected during the seismic crisis of May 2012 (Emilia, Italy): clues for source layer identification and liquefaction regime", that we would like you to considered for publication on Sedimentary Geology.

The manuscript deals with the detailed facies texture and petrographic composition sands ejected during the 2012 Emilia earthquake (Italy) in order to identify the source layer and to provide a contribution to the understanding of earthquake-induced liquefaction mechanisms.

We think that our work could be of interest for the Sedimentary Geology readers.

Best regards,

D. Fontana, S. Lugli, S. Marchetti Dori, R. Caputo and M. Stefani

Highlights

Composition of injected sand of 2012 Emilia earthquake help pinpoint source layer

Fluvial sands at different stratigraphic have distinct petrographic composition

Sedimentology of dike sand suggest multiple rhythmic fracture opening-closing

Sorting due to flux variation did not affect sand composition

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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ABSTRACT

In May 2012 widespread sand blows formed along buried channels in the eastern sector of the Po Plain as a consequence of a seismic crisis 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 18° century and was deposited starting from the 14° century (unit A); this sequence lie on Holocene muddy floodplain and scattered sandy channel deposits (unit B) and a Pleistocene channel sand unit (unit C). Sand inverse and direct grading, concave layering and vertical lamination coexisting along the dikes suggest multiple rhythmic opening and closing of the fracture borders that were injected and filled of slurry sand during the compression pulses end emptied during the extension phase. The pulse mechanism may have lasted for several minutes and formed well stratified structure of the sand volcanoes that formed on the top of some fractures. Sands from dikes and from the various units show well defined compositional fields from lithoarenitic to quartz-feldspar-rich compositions. Sorting related to sediment flux variations did not apparently affect the sand composition, across the sedimentary structures. Sands from the old Reno levee and channel fill (unit A) have abundant lithic fragments deriving from the erosion of Apennine sedimentary carbonate and terrigenous successions. Pleistocenic sands (unit C) are enriched in quartz and feldspars as a consequence of the different climatic weathering condition that prevailed during the last glacial stage. The Pleistocene sands were partially reworked during the Holocene (unit B). Composition of the sand filling the dikes show clear affinities with sand layer of the old Reno River channel (Unit A) and clearly differ from any sand from deeper layers (Unit B and C), which are richer in quartz and feldspar and poorer in sedimentary lithic fragments. 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.

Keywords: Sand liquefaction, sand composition, 2012 Emilia Romagna earthquake, fluvial deposits, Po Plain.

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 crisis was triggered in correspondence of a portion of the Apennines thrust belt buried below the alluvial plain (Pieri and Groppi, 1981; Caputo et al., 2012). The first event produced relevant liquefaction phenomena, surface fracturing and sand ejection, in particular in the western sector of the Ferrara province (Papathanassiou et al., 2012). 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 18° century when it was artificially diverted.

Due to the destructive damage potentially produced on human structures and activities, sand boil and liquefaction phenomena are throughly studied to asses the geotechnical conditions for their recurrence (Chang et al., 2011). Less explored is the sedimentology of the liquefaction mechanisms and the selective processes acting on sand grains: 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 sediment composition: does sand retain the same petrograhic composition of the source layer while travelling 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 compostition may be used as a tool to pinpoint the source layers, provided that sands located at different stratigraphic layers have been petrographically characterized. This applies also to old sand blows buried by other deposits preserved in the geologic record.

Fluvial sand composition studies have a particular significance in depositional settings such as the late Pleistocene–Holocene Po Plain, where distinct compositional fields characterize modern sands from different streams, as well as older sediments, back to the Pleistocene (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 crisis of 2012 along the paleo-Reno River body at San Carlo (Ferrara), and sands from subsurface deposits at different depths. The aim of the research was to provide a contribution to the understanding of earthquake-induced liquefaction mechanisms using texture 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 northern buried sector of the northern Apennines fold-and-thrust belt, where streams draining the chain flow northeastward into the Po River and the Adriatic Sea (Fig. 1). The Northern Apennines formed mainly during the Tertiary in the frame of the 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 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 subsidence average rates induced by the vertical motions of the blind thrusts buried under the foredeep deposits, such as the Ferrara faulf-fold 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 element, the Po River, was tectonically forced to shift northwards and human pressure on 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 to adjust the local tectonic pattern (Fig.1). The late evolution of the system has been successfully traced following the physical evidence of paleochannels on the alluvial plain surface, whereas the older sedimentary patterns are revealed by the provenance composition signal of buried Holocene channel sands wich match those of the present day rivers (Lugli et al., 2007).

3. **The recent evolution of the Reno River**

The synergic role 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 Age, 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 18° 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 southwestof 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 C.E. and its depositional morphology is still recognizable today. It consists of a concave belt oriented SW-NE (the former channel), bordered by two marginal ridges (the levees) rising up to 4-5 m above the surrounding floodplain. The topographic gradients created by the channel-levee ridge had a major role in the coseismic liquefaction dynamics, which was emphasized by lateral spreading phenomena (Papathanassiou et al. 2012).

The old Reno River channel-levee system was deposited on top of an alluvial sedimentary succession that was thoroughly investigated by boreholes, geotechnical and geognostic surveys. The shallow sequence (Calabrese et al., 2012) can be divided into three main units (A, B, C), from the top to the bottom (Fig. 2):

- unit A, Recent channel-levee unit consisting of medium sand belts (channels) and alternate fine sand-mud bodies (levees and proximal crevasse splays), spanning from the surface to about -13 m below the old channel ridge and -5 to – 6 m below the present-day floodplain; its base has been radiocarbon dated to a numerical age of 1450-1581 C.E.;

- unit B, Holocene paludal unit, consisting of floodplain mud and peat, with isolated channel and crevasse-splay sand bodies; this unit is 6 to 10 m-thick and was deposited starting roughly since the beginning of the Holocene;
- unit C, latest Pleistocene floodplain unit, consisting of floodplain mud, and channel and levee sand bodies deposited during and following the last glacial maximum.

The earthquake shaking produced an array of fractures roughly parallel to the old river ridge that were exposed for a few months by digging a trench opened a few weeks after the main schock. The sedimentary sequence exposed in the trench (Caputo et al., 2012) belongs to the upper part of the Recent channel-levee system of the unit A and consists of four main depositional facies associations (Fig. 2):

A1) distal levee to proximal alluvial plain silts and silty clays, with graded fine-sand overbank beds, which are partially amalgamated by bioturbation, contain root structures and show pedogenetic alteration, traces of agricultural activity and ceramic fragments;

A2) proximal levee sands and sandy silts, with direct gradation and tractive lamination structures;

A3) channel sediments consisting of medium sand, showing festoon cross stratification. The sand contains argillaceous rip-up clasts, rounded armored mud balls, wood and brick fragments;

A4) channel sands slightly older than A3, that were intercepted by drilling at the base of the trench (depth 6.8-7.5 m).

The above sequence is cross cut at high angle by several dikes which represent extension fractures infilled by sands injected upward from the trench bottom. Some of them reach the topographic surface and extend horizontally outside the trench for tens of meters, while others stop below the ploughed layer (about 0.5-1 m deep); the latter have been associated with the 1570 Ferrara earthquake (Caputo et al., 2012).

4. Materials and methods

The sampling of sand has been done in a trench dug immediately after the seismic event, which allowed the detailed observation of the fluvial sedimentary sequence across the Reno River down to the depth of about 6 m (Fig. 2). The sediments consist of cross-bedded sands from the paleo-channel of the Reno River and the laminated sand-mud leeve deposits cut by the liquifaction sand dikes. We sampled also cores from deeper sand horizons crossed by drillings down to the maximum depth of 50 m. A total of 41 sand samples were collected and analyzed: - 17 samples from the five dikes (named D 3, 4, 5, 6 and 7 in the trench section shown in Fig. 2), each dike sampled at different depths; - 4 samples from the modern sands of the present-day Reno River; - 10 samples from the levee (unit A1-A2) and channel fill (A3) of the paleo Reno River; - 4 samples from paleo-channel sands drilled at the bottom of the trench (unit A4), - 6 samples from cores outside the trench from unit B (borehole S2, 8.20 to10.45 m depth and borehole S3, 6.90 to 9.60 m depth) and the lower sand layer dating back to the uppermost Pleistocene (borehole S10, 22.50 to 24.50 m depth, unit C). Sample location is shown in Fig. 2.

Grain-size analyses were performed using standard techniques: mechanical sieving for the sandy fraction and hydrometer analysis for fine-grained sediments. Sand samples consisting of a few hundreds of grams were washed with dilute H_2O_2 to remove organic matter and were air dried and mechanically sieved for granulometric and compositonal analyses. The result of grain size analyses for most of the samples is a mean value of multiple bands that are a few millimeters to centimeters in thickness, as sampling encompassed many of these vertical features (see sedimentological description).

For the compositional analyses, two sub-samples were prepared for each samples: the whole sandy fraction (for qualitative observations) and the fine sand fraction (0.125–0.250 mm) for point counting. The necessity to analyze the fine sand fraction was dictated by the lack of medium-coarse sand at some of the sampling sites and for comparison with the same grain-size fraction used in Lugli et al. (2007). Sands were impregnated in epoxy resin under vacuum, thin-sectioned, and stained for carbonate identification. Point counting under transmitted light microscopy was performed on the 0.125–0.250 mm fraction, according to the Gazzi-Dickinson method (Zuffa, 1985; Weltje, 2002). At least 300 grains were point counted for each section to achieve modal composition. Results of point counting are presented in Table 1. Components not related to the original sand composition, such as authigenic carbonate nodules, penecontemporaneous shell fragments, soil and organic fragments were excluded from the final calculations.

5. Results

5.1 Sedimentology of the sand blows

The coseismic sand dikes represent vertical straight, planar or curved extension features crosscutting the sequence at high angles from the base of the trench to the topographic surface with a vertical extension of at least 5 m. In several cases (dikes D 5, 6, 7) they stop 1 m or a few decimetres below the surface, but the main fracture may have reached the surface elsewere. The width of the fractures varies from a few centimetres to about 30 cm. Most fractures are single, but tapering and bifurcation are also present (Fig. 3 and 4). Some fracture margins are closely spaced locally and are partially filled by muddy fragments from the host sediment (Fig. 3).

The sand injected into the fractures shows complex sedimentary structures similar to those described by Nichols et al (1994) and Hurst et al. (2011; see also references therein). The most common feature is a distinct banding, that ranges in thickness from 0.3 to 3 cm (Fig. 5), and can be longitudinal to the dike length, or perpendicular to the dike margins (Figs. 3, 4, 5). The bands oriented parallel to the dike are bounded by sharp contacts marked by thin clay veneers and are defined by differences in grain size and grain alignment. The multiple sets of graded layers that form the banding may show variable thickness along the dikes and some bands scoured into adjacent layers (Fig. 3 and 4). The largest fractures are filled by massive sand which graded along the vertical fissures (Fig. 5) and show an internal stratification consisting of multiple superimposed concave fine-grained veneers (Fig. 3). We observed both direct and inverse vertical grading of the sand from medium sand to mud. Similar well-laminated structures are observed in sand volcanoes that formed on the top of the fractures in many of the liquefaction sites around San Carlo (Fig. 6).

5.2 Grain-size distribution

Results of grains size analysis are reported in Fig 7. The content of sand, silt and clay for all samples is shown in the triangular plot of Fig. 8. The samples range from almost pure sands to silt, with a content of clay less than 20%. Samples from the levee facies are the finest, made up of coarse silt to very fine to fine sands. Samples from the paleo-channel and from deeper layers are predominantly medium and medium-coarse grained sands. The dikes consist mainly of very fine to fine and medium sands. In four samples the amounts of coarse-grained sand is higher than 10 %. One dike sample is made up of silt. In all dikes the amount of clay is less than 10 %. The grain-size distribution along the same dike shows no systematic trends, as samples located nearby each other may have different grain-size. This is shown by the diagram of Fig 9 that plots the mean diameter for each dike at different dephts: dike D 3 is characterized by a slight grain size increase from the lower portion to the top, while an opposite trend is observed in dike 5.

Sorting of all sands is moderate to poor and for dikes ranges from 1.22 to 2.46.

5.3 Sand Composition

5.3.1 The modern Reno River fluvial sands.

Among the examined samples, the sands from the modern Reno River are the most lithoarenitic; they are made up of quartz (ranging from 29.7 to 35.19%, Table 1), feldspars (15.2 -21.7%) and sedimentary fine-grained siliciclastic and carbonate lithics. Shales are the dominant lithic grains (12.4 to 18.6%); they are well lithified, well rounded, with an evident iso-orientation of clay minerals, and for these characters they appear to have a detrital origin, derived from older pelitic successions of the Northern Apennines. Minor intrabasinal muddy components consisting of penecontemporaneous rip-up clasts have also been observed. Sands of the modern Reno River are well distinguishable from the other rivers of the Po plain, as defined by Lugli et al. (2007).

5.3.2 The paleo Reno River fluvial sands

The sand samples from the paleo-Reno levee (unit A1-A2) and channel fill (A3) are quite homogeneous in composition (Fig. 10 a, b), slightly impoverished in lithic fragments compared to the modern Reno River sands. The amount of quartz ranges from 29.7 to 37.7%. Feldspars (both plagioclase and K-feldspar) vary from 18.1 to 23.7%. Fine-grained lithics are mainly sedimentary, made up of micritic and sparitic limestones (from 9.4 to 17.0%) and siltstones and shale (14.4 to 20.4%). Metamorphic lithics and cherts are minor components.

The composition of older channel sands (Unit A4), shows quartz content ranging from 28,8 to 39.6%, feldspars from 20.1 to 26.6%, siltstones and shale vary from 14.5 to 23%, carbonates from 21.3 to 23.7%.

5.3.3 The sand dikes

The sands filling the dikes show relatively homogeneous composition (Fig. 10d) with one exception. Total quartz range from 31.2 to 42.2%, feldspars from 16.3 to 24.9%. Carbonate lithics vary from 22.3 to 30.2%; siltstones and shales range from 11.8 to 18.4%. Only one sample (no. 23) from the deepest portion of dike 3, shows higher quartz and feldspar content and is very low in siliciclastic lithics. Sands from single dikes at different depths show minor, non-systematic, compositional variations, mainly due to quartz and lithic fragments variations (see Fig. 9).

5.3.4 The older sands: Holocene (unit B) to Pleistocene (unit C)

The core fluvial sands in the subsurface at depths from 7 to 10 m (Holocene) and from 22 to 24 m (Pleistocene in age) are rich in quartz and feldspar and metamorphic rock fragments (Fig.10c). Quartz range from 36.7 to 54.0%; feldspars vary from 19.7 to 28.6%; siltstones and shales are less than 11% and carbonate lithics range from 16 to 29.1%. Coarse-grained metamorphic rock fragments are also present.

5.3.5 Compositional fields

Data from modal analyses are reported in the classification diagram Q+F (quartz+feldspars), L (siliciciclastic fine-grained lithics), C (carbonate lithics) of Fig. 11, in which compositional fields of others fluvial sands in the Po plain are also reported (Lugli et al 2007).

The examined sands are characterized by well defined fields and show a clear trend from lithoarenitic to quartz-feldspar-rich compositions. In detail the sands from the modern Reno

River are the most lithoarenitic, with shales as the dominant lithic type. Sands are well distinguishable from the other rivers of the Po plain, as defined by Lugli et al. (2007). The sand from the paleo-Reno channel fill show composition slightly enriched in quartz and feldspars and impoverished in lithic fragments compared to the modern Reno River sands. A similar composition characterizes also sands at shallow depth (unit A4, 6.8-7.5 m depth). In the modern and paleo Reno river sands the lithic fragments derive mostly from the erosion of sedimentary carbonate and terrigenous successions.

Composition of dike sands clearly overlap that of the paleo-Reno river sands down to the depth of 7.5 m. Older Holocene sands coming from layers deeper than 8 m and the Pleistocenic sands (unit C) differ in composition and show an higher quartz-feldspar content. A similar enrichment in quartz and feldspars in the Pleistocene fluvial sands, compared with the present-day sands, was noted by Lugli et al. (2007) for the fluvial sediments of the Po alluvial plain. This shifting composition back in time was interpreted as a consequence of the different climatic weathering condition that occurred during the last glacial stage. The strong denudation, erosion and accelerated transport were probably responsible of promoting the survival of feldspar grains.

5.3.6 Grain-size influence on sand composition

As the counting technique here adopted (Zuffa, 1985) is especially designed to minimize the dependence of the analysis from the grain-size, we plotted the mean diameter and the percentage of significant types of grains (quartz and feldpars, shales, carbonates) in order to verify the reliability of the point counting analyses. Plot of Fig. 12 shows no correlation between composition and grain-size of sands. These results suggest that disintegration, microfracturing or erosion of most erodible grains, such as shales, due to the abrasive flow of sand grains was not responsible of significant compositional variation.

6. Discussion

In our study, texture and composition characteristics provide important constrains for source layer indentification in liquefaction processes and flow regime.

Although there is currently no unequivocal evidence that texture in sand dikes (i.e. lamination, clay content, alignment of platy and elongate grains) may be indicative of a particular flow regime (Hurst et al., 2011), the diverse sedimentary features coexisting within the same dike, are probably related to the multiple rythmic opening and closing of the fracture borders that may have lasted for several minutes. The sedimentary features suggest that the fractures were rhythmically injected and filled of slurry sand and mud during the compression pulses end emptied by the rushing of the slurry back down deep into the fractures during the extension peak. These alternate flows, together with the sequential opening of various fractures in different area, may account for the presence of both inverse and direct grading of the sand filling different portion of the same dike and for the concave stratification of the dikes.

Unfortunately this phenomenon was not observed directly in May 2012, but similar examples, although of much larger magnitude, were filmed during the M 9.0 Tohoku great earthquake in Japan (see Great Japan Earthquake, 2011, www.youtube.com/watch?v=TzlodnjPAuc).

The pulse mechanism of sand blows is also supported by the well stratified structure of the sand volcanoes that formed on the top of the fractures in many of the liquefaction sites around San Carlo (Fig. 6) and elsewhere, a feature described also by Rodríguez-Pascua et al. (2015).

These volcanoes are up to a few tens of centimeters high and show several centimetic to millimetric alternance of graded laminae consisting of sand and mud (Fig. 6).

The grain-size distribution of the sands filling dikes clearly overlaps that of sands at dephts of 6.8-7.5 meters, and in deeper layers. Grain-size distribution of examined dikes show a good agreement with the grain-size characteristic reported in the literature for sands ejected during earthquakes in

California or Japan (Kishida,1970; Figueroa et al.,1995). In particular, the amount of clay less than 10% fits with other case histories that show that only sand with a low natural clay content are susceptible to liquefaction. Tokimatsu and Yoshimi (1983) documented 70 cases in Japan resulting from 10 separate earthquakes that show a cut-off for liquefaction susceptibiliy at a clay content of about 15-10%.

The composition adds an important constraint in identifying the source layer. Composition of the sand filling the dikes show close similaritiy with the composition of the sand layer located at a depth from 6.8 to 7.5 metres (Unit A4), while clearly differ from deeper sands which are richer in quartz and feldspar and poorer in sedimentary lithic fragments.These data clearly indicate a relatively shallow source for the blowouts.

About the relatively shallow depth of the source layer, it is known that the liquefaction resistance of a soil deposit increases with depth as the effective overburden pressure increases. For this reason, sand deposits deeper than about 15 m are rarely observed to liquefy (Krinitzsky et al. 1993). Particle cementation, not observed in the examined dike sands, is also an important factors and layers older than the Holocene are usually not prone to liquefaction (Youd and Perkins 1978), perhaps due to a weak cementation at the grains.

Regarding the possibility that selective mechanism due to flux variation may have influenced the sand composition, our data seem to indicate that no major variation was induced by liquefaction phenomena. This is probably the result of the point counting technique which seems to successfully reduce the effect of grain size over composition.

Finally, an interesting point concerns the enrichment in quartz and feldspars in the relatively shallow sands of unit B deposited by the Reno River in the Holocene (pre 16th century C.E.), which are similar to the deeper Pleistocene sands (unit C). This could be due to partial recycling of sands deposited during the last glacial maximum at about 20 ka. Another possibility is that the drainage network was different from that of today, as suggested by Ravazzi et al. (2013), and those sand may have been deposited by another river, the Enza, which is today flowing much further to the west.

6. Conclusions

The study of the sands injected in the San Carlo area (Ferrara) during the Mw 6.1 earthquake, and the comparison of their texture and composition with those of buried fluvial sediments as deep as 20 m provided us with clues about the emplacement mechanisms and the source layers identification.

The sands from the dikes show a composition compatible with that of the recent shallow sands deposited by the Reno River. These sands clearly differ from deeper sands (at depth of more than 8 m), which are richer in quartz and feldspar and poorer in sedimentary lithic fragments as a consequence of their deposition during the last glacial maximum and later reworking.

Composition and fabric characteristics, such as grain-size distribution and clay content, indicate that liquefaction processes affected mainly sand layers at depth of 6.8-7.5 m, a relatively shallow source for the blowouts. Pulsations in the flow during shaking appear to be responsible for the concave and vertical layering within the dikes, normal and inverse gradation along the dikes and only modest petrographic compositional variations within individual dikes.

Our results show that selective mechanisms due to flux variation have not influenced the sand composition and thus petrographic point-counting methodology may be successfully applied to trace back the source sand layers of ancient blowouts.

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Figure captions

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 18° century diversion. Arrows indicate the river channel shift trends during the Holocene (Modified from Burrato et al., 2012).

Fig. 2. a) Stratigraphic section of the old Reno river channel ridge at San Carlo. Depositional facies and stratigraphic units (modified after Caputo et al. 2012 and Papathanassiou et al., 2012). b) Stratigraphy and depositional units in the trench exposure along two walls (upper section flipped) showing the sand dikes cutting the fluvial sequence. Sample location is also reported. Modified after Caputo et al., 2012

Fig. 3. Dike D7 filled by laminated sand cutting through stratified proximal levee sand and silt facies. The left side of the wall collapsed as a result of lateral spreading. Laminae within the dike are highlighted by concave silt veneers suggesting multiple phases of sediment settling by collapse of the sand column along the fracture. The fracture is locally filled by silty clast originated by the mechanical crushing of the fracture borders (upper right). Location of dike in the trench is shown in Fig. 2.

Fig. 4. Dike D5 cutting across bioturbated massive clayey silt. Note the cross cutting relationships between the larger and smaller fracture which are also marked by a few oblique fine-grained laminae (upper left). Sand in the larger dike is normally graded. Location of dike in the trench is shown in Fig. 2.

Fig. 5. Distinct vertical lamination within dike D3. Single sand layers are graded and are separated by thin fine-grained laminae. Layering is accentuated by differential weathering. Location of dike in the trench is shown in Fig. 2.

Fig. 6. Ejected sand at San Carlo forming a volcano structure consisting of various laminated sand layers. At least 6 sand/mud couplets are visible indicating multiple opening and closing phases of the mother fracture.

Fig. 7. Cumulative grain size distributions of sands from the paleo Reno River levee and channels, units B and C, and the dikes.

Fig. 8. Triangular plot showing the relative proportions of sand, silt and clay for the examined samples.

Fig. 9. Variations in grain size (mean diameter), quartz+feldspars and shale contents in a vertical profile along dikes 3 and 5.

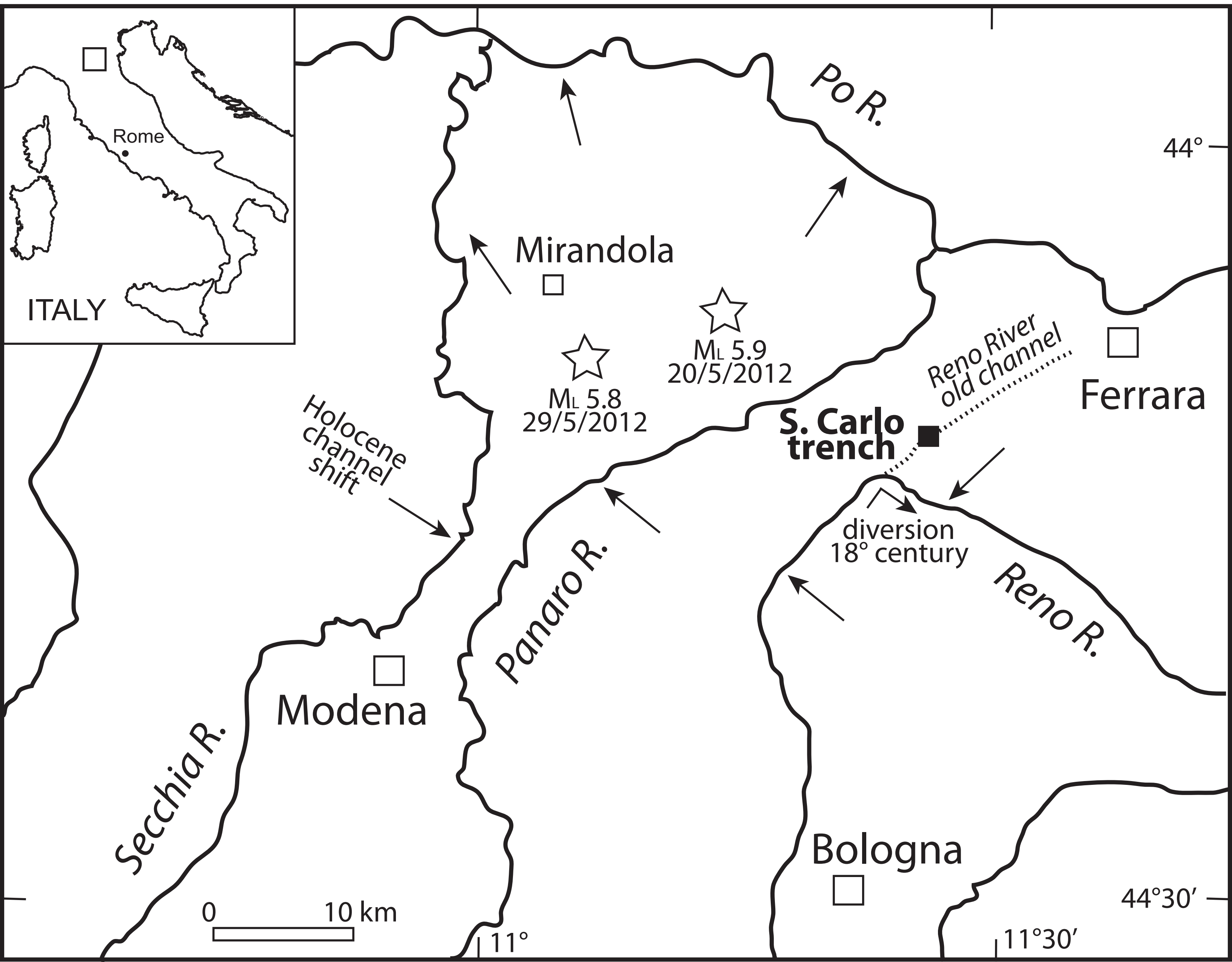
Fig. 10. Photomicrographs of sands from the old Reno River channel (a), levee (b), Pleistocene sands from unit C (c) and dike D3 (d). Transmitted light, crossed polars.

Fig. 11. Q+F, L, C diagram showing the composition of sands from dikes, recent and paleo Reno River and from older units B and C. Composition of sands from the Modena plain streams is also reported (Lugli et al., 2007). Q: quartz; F: feldspars; L: siliciclastic rock fragments; C: carbonate rock fragments.

Fig. 12 Plot showing the content of quartz+ feldspar vs the mean diameter for all the examined samples. Note the lack of correlation between grain-size and composition. This result is confirmed for the other compositional classes (not reported here).

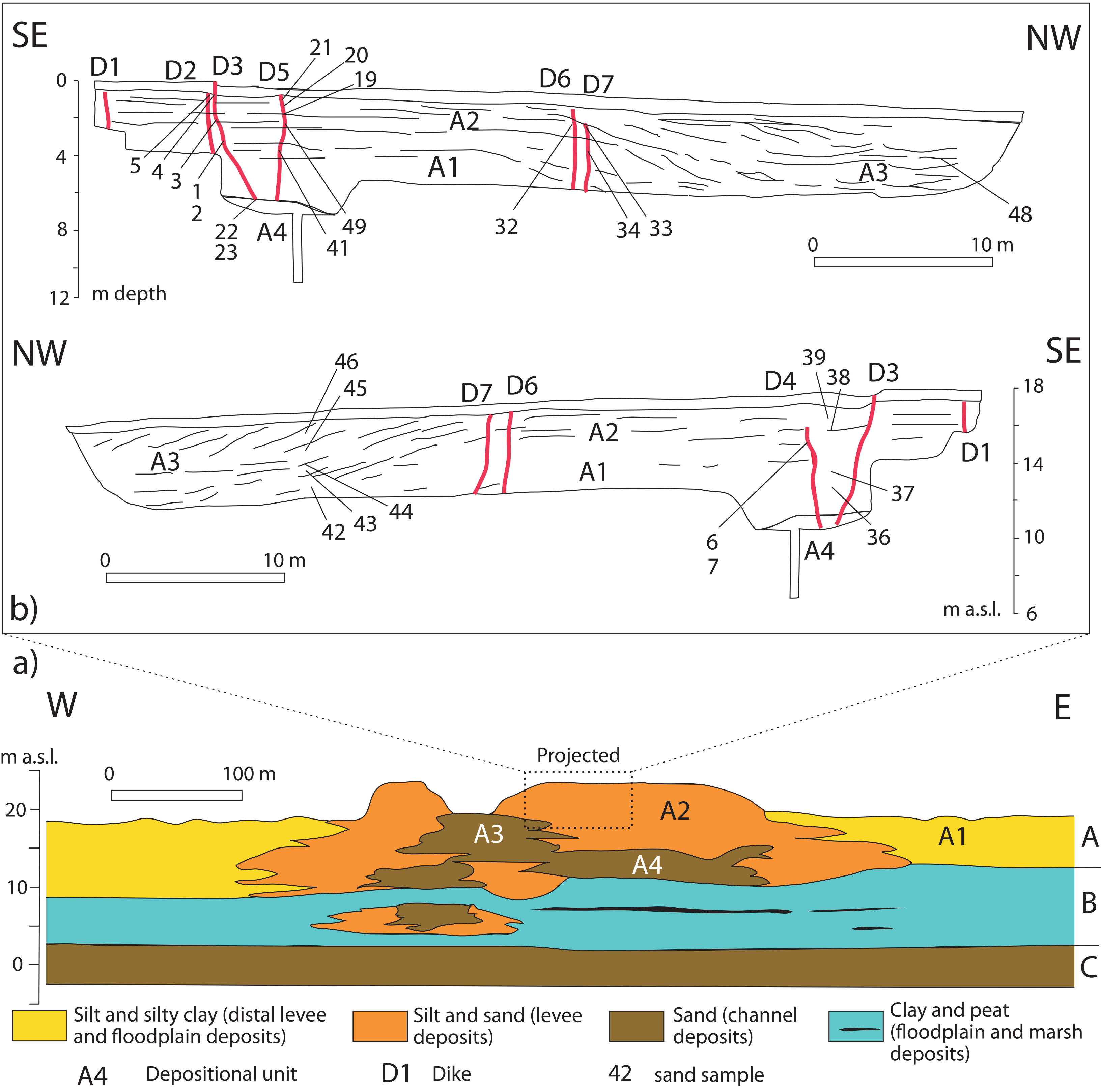
Table 1. Results of petrographic modal analyses.

Figure 1



Rome
ITALY
Po R.
44°
Mirandola
M_L 5.9
20/5/2012
M_L 5.8
29/5/2012
Reno River
old channel
Ferrara
S. Carlo
trench
Holocene
channel
shift
diversion
18° century
Panaro R.
Reno R.
Modena
Secchia R.
Bologna
44°30′
0
10 km
11°
11°30′

Figure 2



SE
NW
D1
D2
D3
D5
D6
D7
21
20
19
A2
A1
A3
A4
5
4
3
1
2
22
23
49
41
32
34
33
48
0
4
8
12
m depth
0
10 m
NW
SE
46
45
D7
D6
D4
39
38
D3
D1
A3
A2
A1
A4
42
43
44
37
36
6
7
0
10 m
18
14
10
6
m a.s.l.
b)
a)
W
E
m a.s.l.
0
100 m
Projected
20
10
0
A3
A2
A4
A1
A
B
C
Silt and silty clay (distal levee and floodplain deposits)
Silt and sand (levee deposits)
Sand (channel deposits)
Clay and peat (floodplain and marsh deposits)
A4 Depositional unit
D1 Dike
42 sand sample

Figure 3

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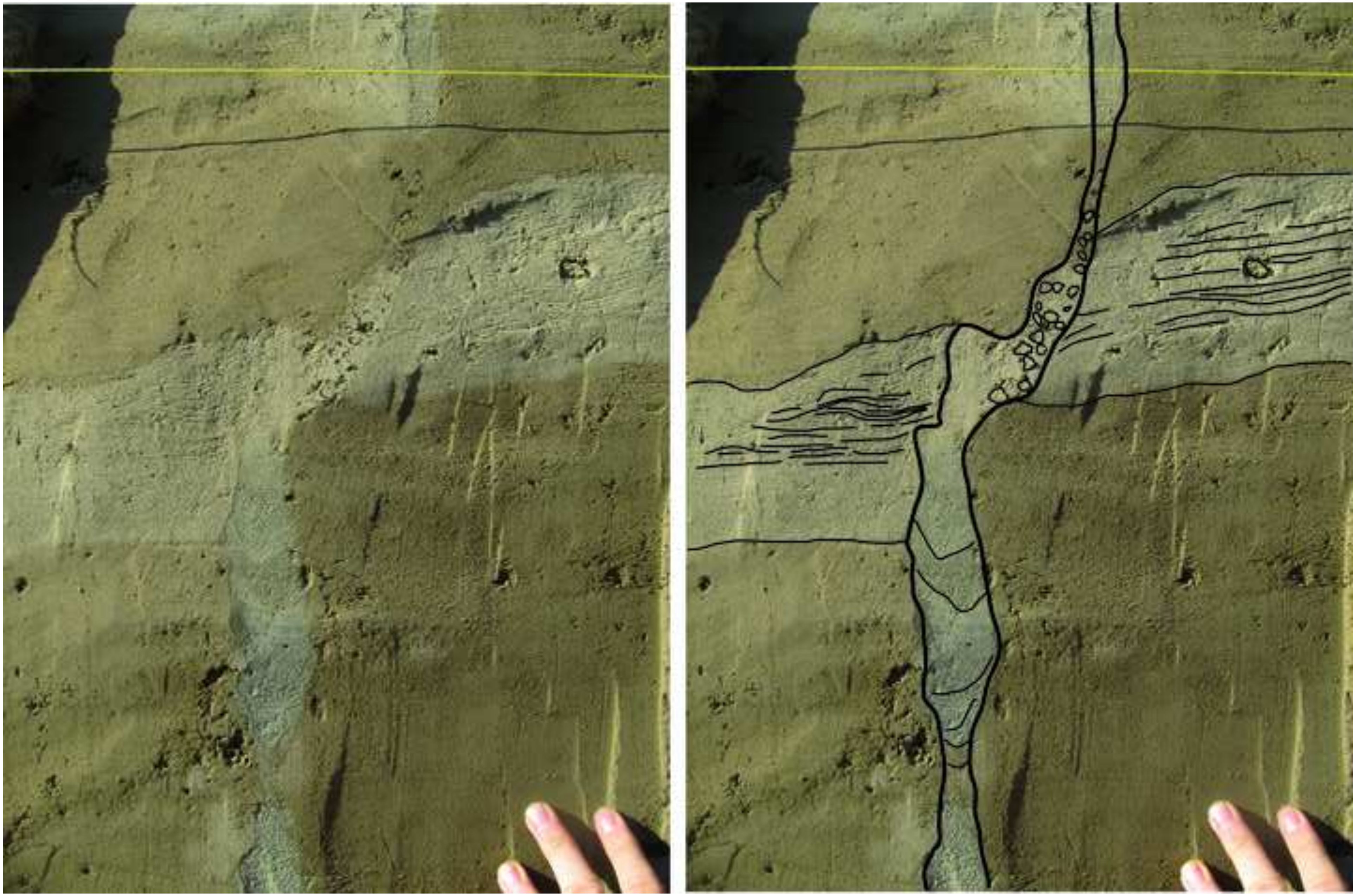

Figure 4
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Figure 5
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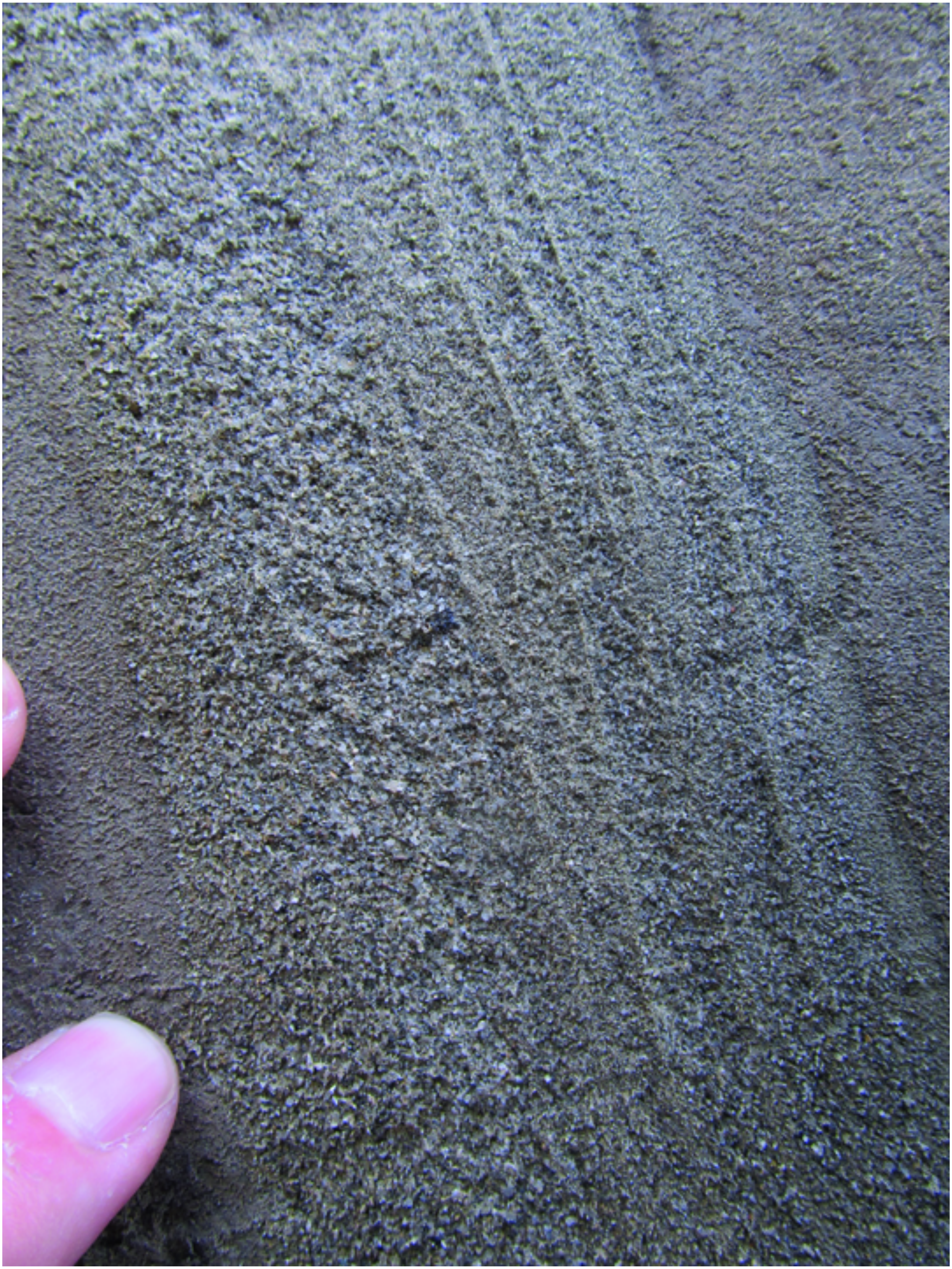

Figure 6
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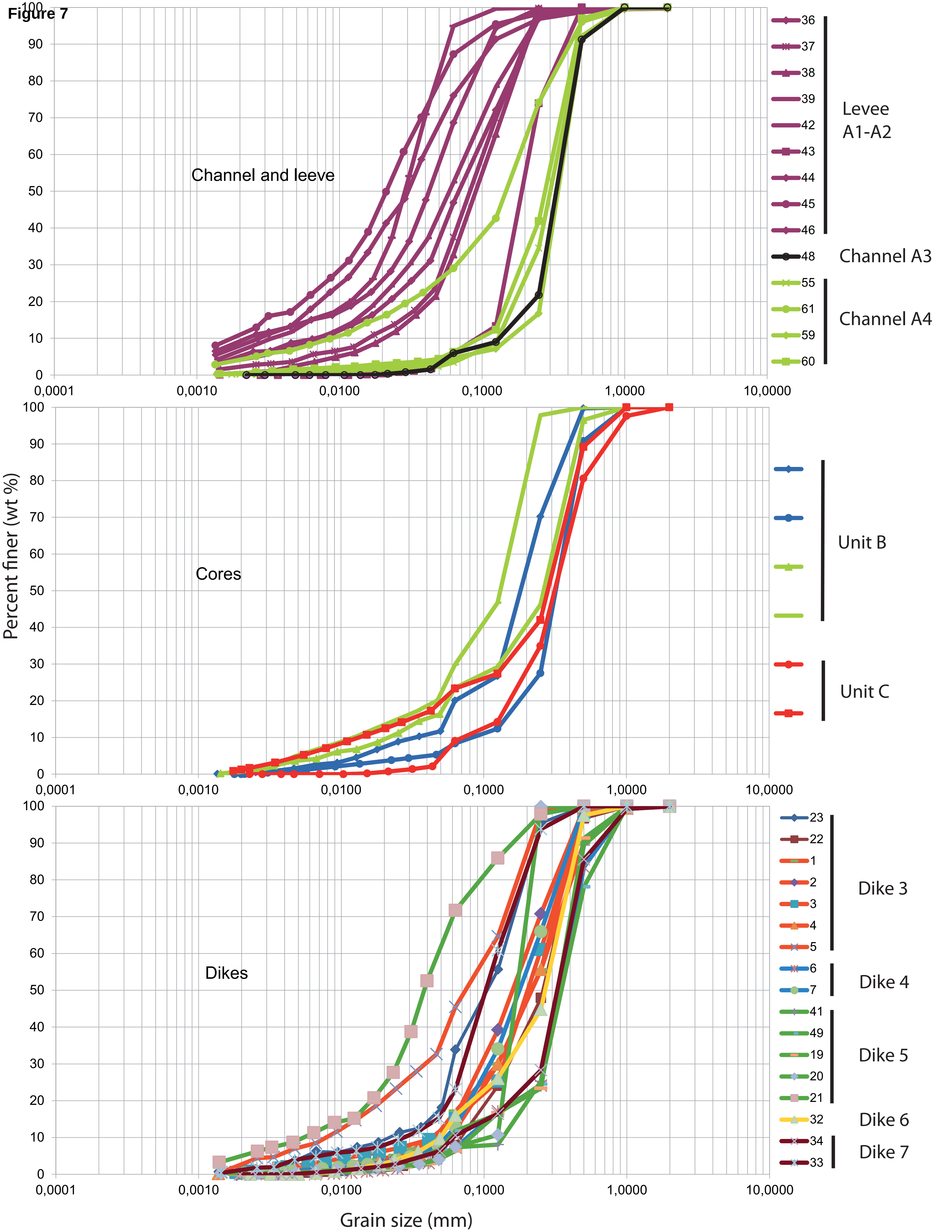
Figure 7



Channel and leeve
Cores
Dikes
Percent finer (wt %)
Grain size (mm)
0,0001
0,0010
0,0100
0,1000
1,0000
10,0000
0
10
20
30
40
50
60
70
80
90
100
36
37
38
39
42
43
44
45
46
Levee A1-A2
48
Channel A3
55
61
59
60
Channel A4
Unit B
Unit C
23
22
1
2
3
4
5
Dike 3
6
7
Dike 4
41
49
19
20
21
Dike 5
32
Dike 6
34
33
Dike 7

Figure 8

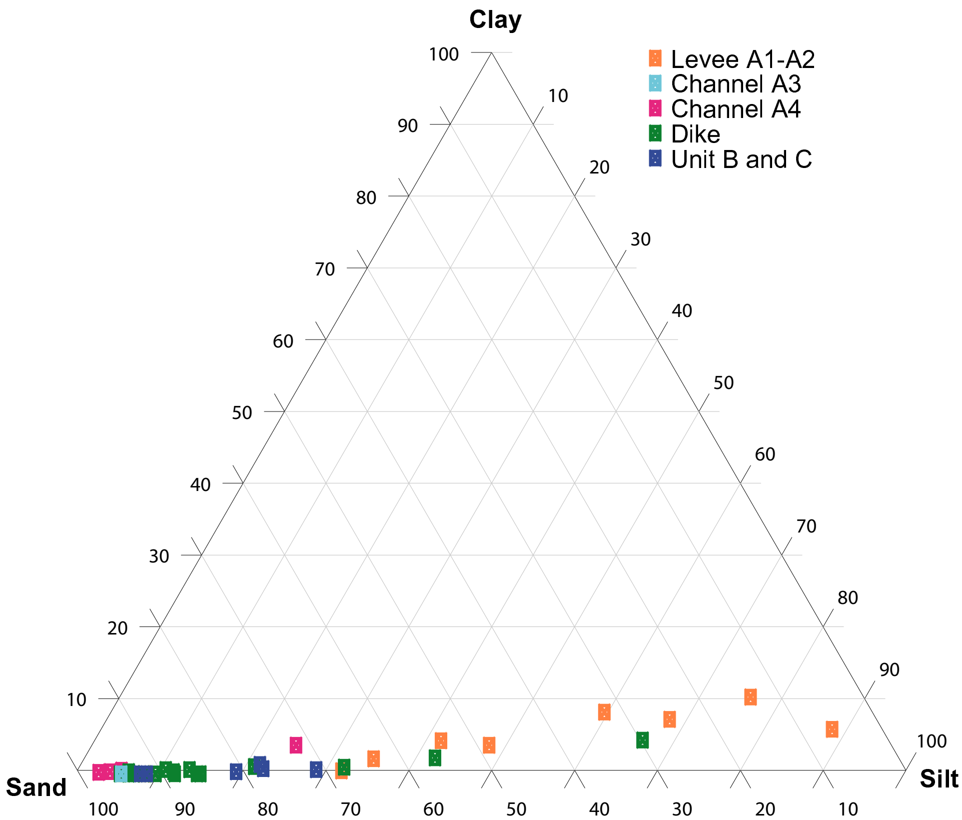

Clay
Sand
Silt
Levee A1-A2
Channel A3
Channel A4
Dike
Unit B and C
100
90
80
70
60
50
40
30
20
10

Figure 9

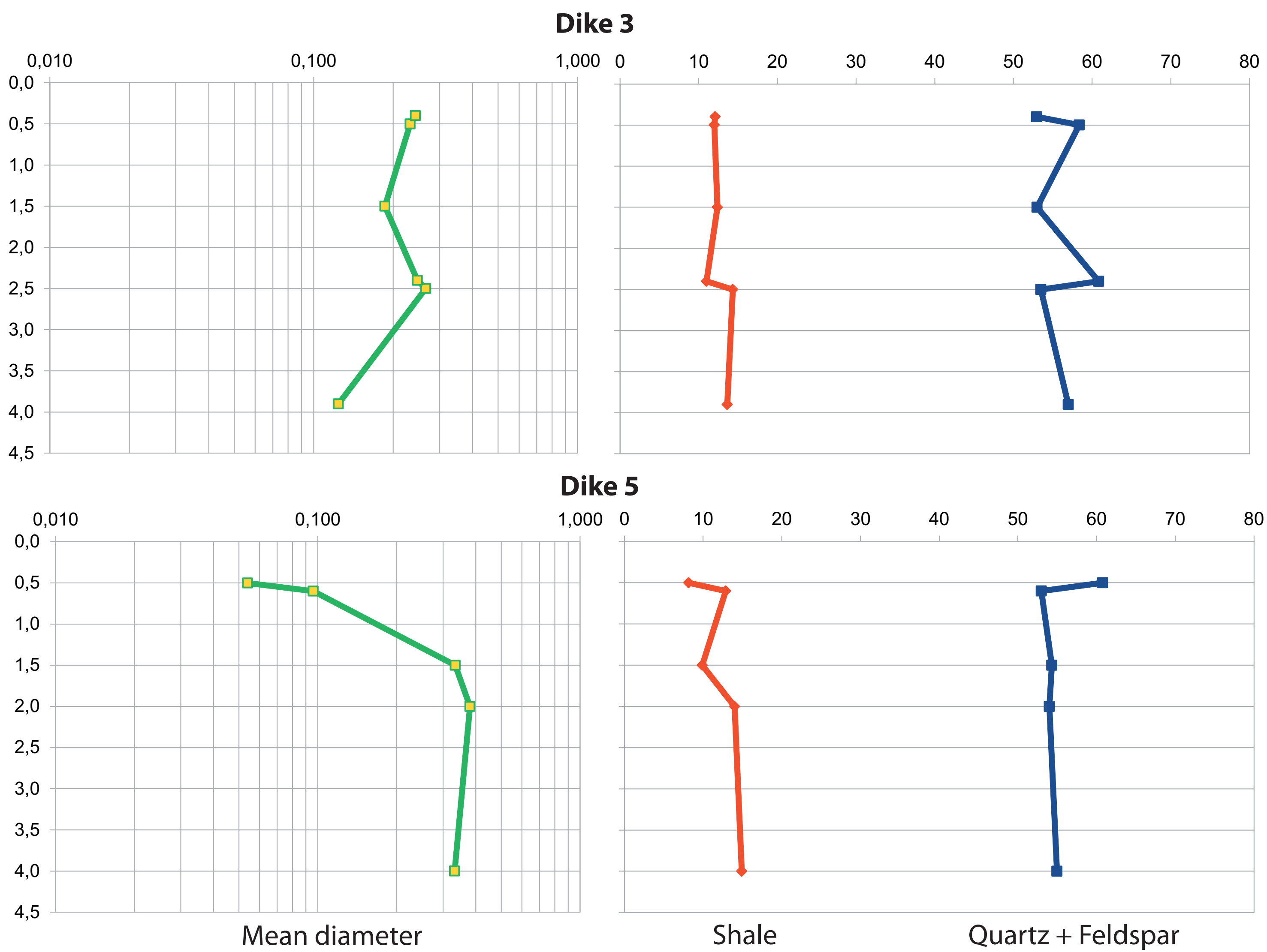

Dike 3
0,010
0,100
1,000
0
10
20
30
40
50
60
70
80
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
Dike 5
0,010
0,100
1,000
0
10
20
30
40
50
60
70
80
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
Mean diameter
Shale
Quartz + Feldspar

Figure 10
Click here to download high resolution image

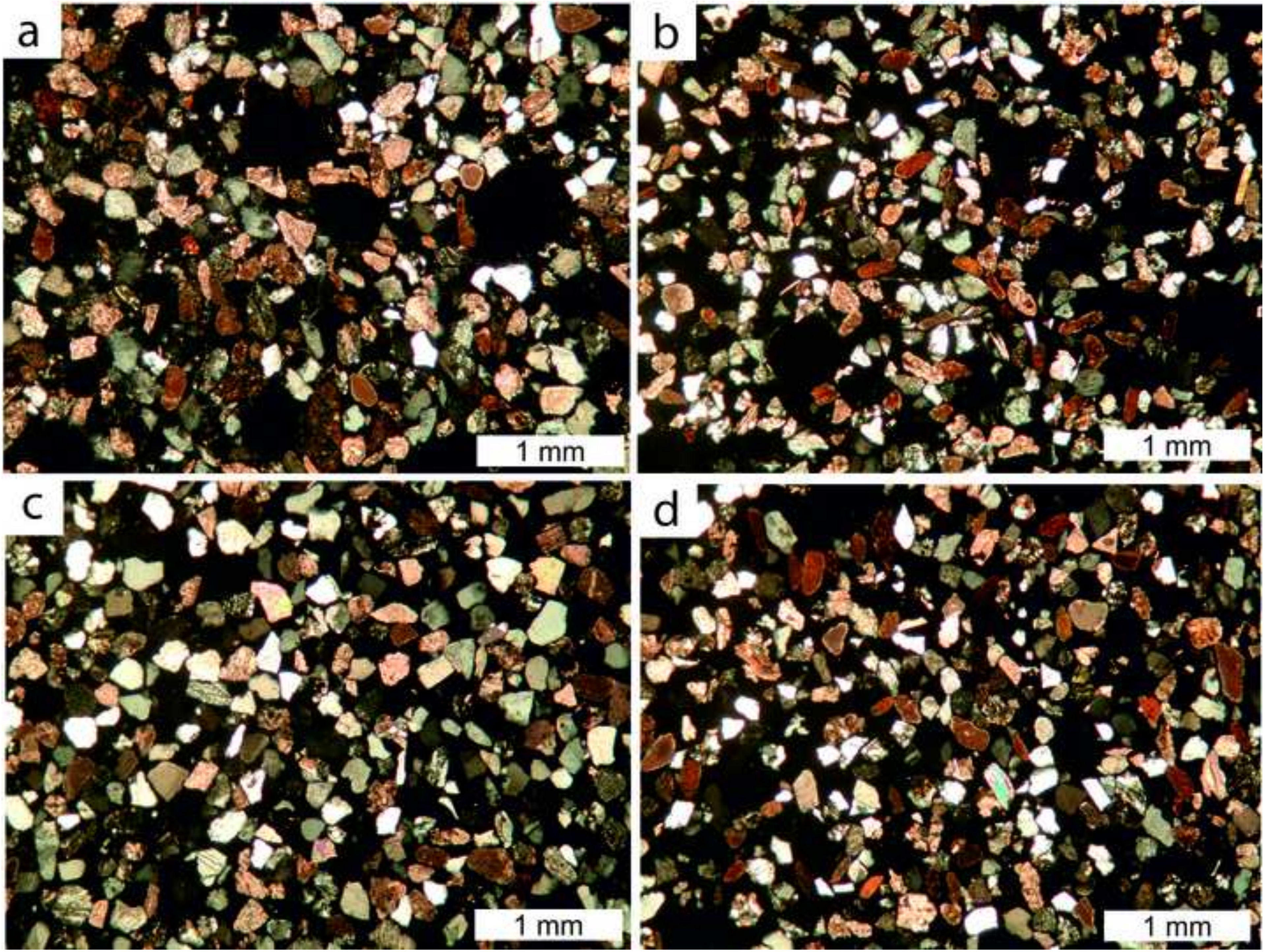
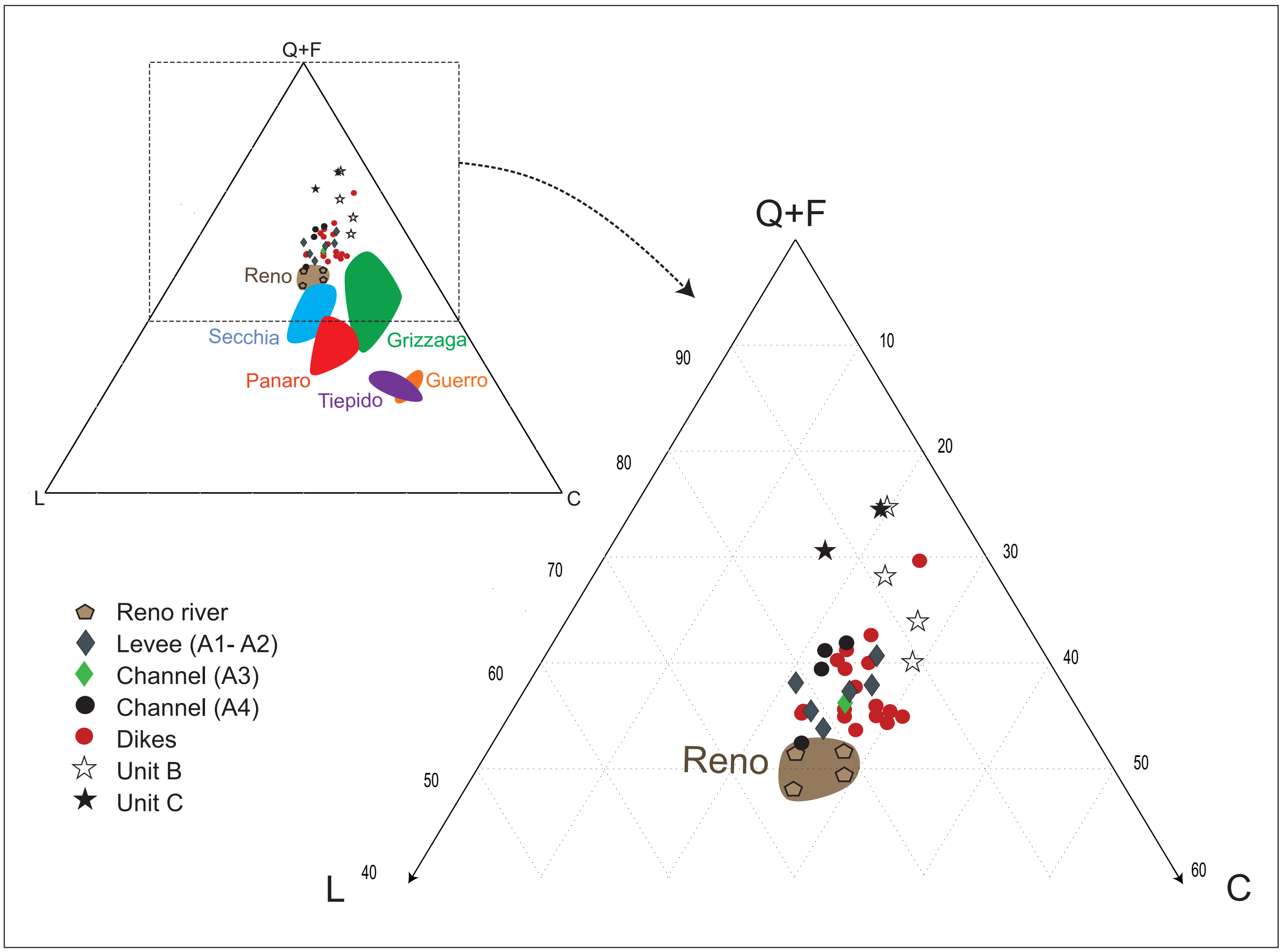


Figure 11



Q+F
L
C
Reno
Secchia
Grizzaga
Panaro
Guerro
Tiepido
Q+F
10
20
30
40
50
60
90
80
70
60
50
40
L
C
Reno
Reno river
Levee (A1- A2)
Channel (A3)
Channel (A4)
Dikes
Unit B
Unit C

Figure 12

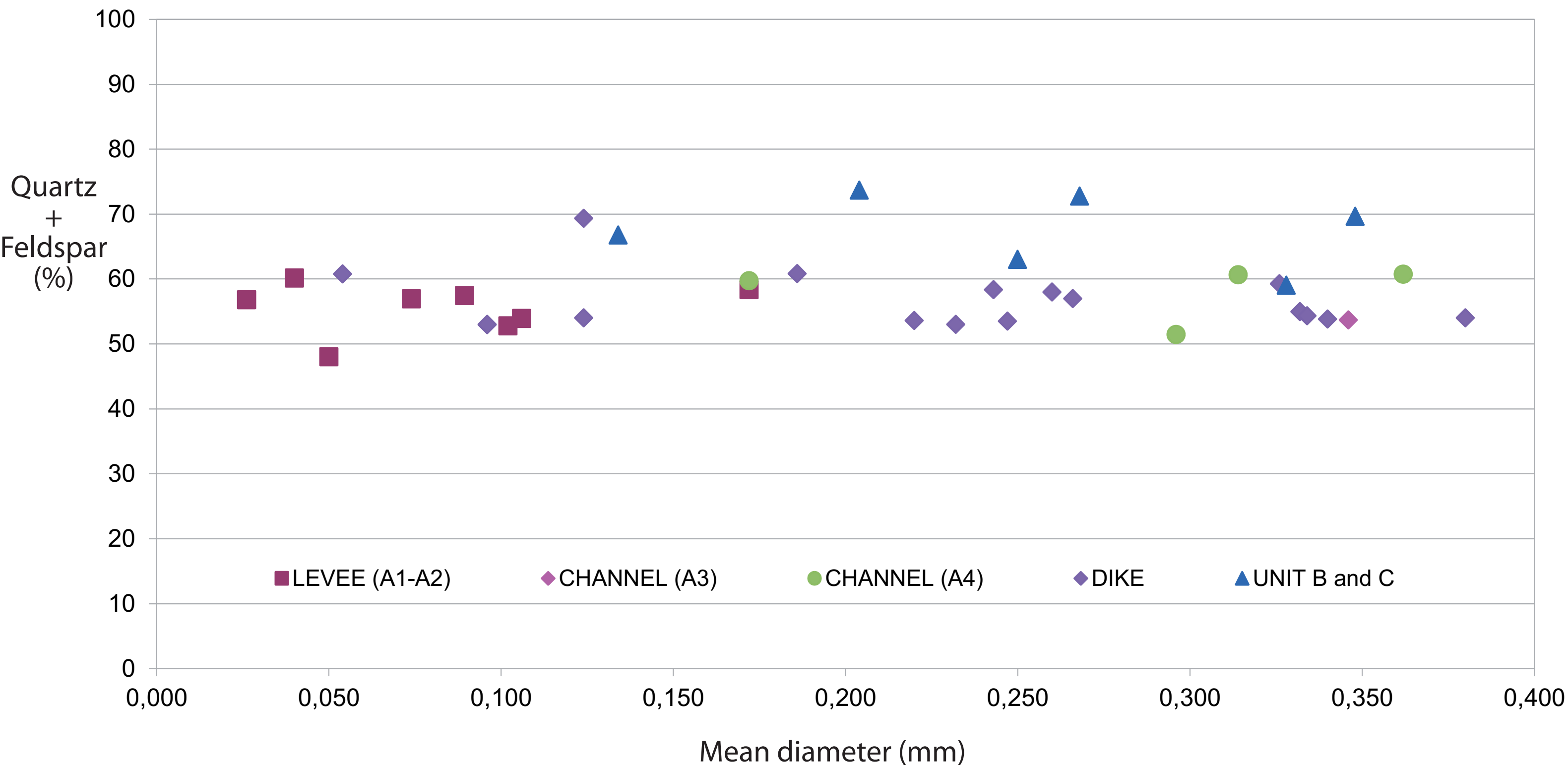

100
90
80
70
60
50
40
30
20
10
0
Quartz
+
Feldspar
(%)
LEVEE (A1-A2)
CHANNEL (A3)
CHANNEL (A4)
DIKE
UNIT B and C
0,000
0,050
0,100
0,150
0,200
0,250
0,300
0,350
0,400
Mean diameter (mm)

Table 1

Click here to download Table: Tab_MODALE_FINALEl.xls

			RENO RIVER				LEVEE (A1-A2)								PALEO CHANNEL (A3)	PALEOCHANNEL (A4)				DIKE 3						
		Sample	FR2	FR1	FR3	FR4	SC1 36B	SC1 37B	SC1 38B	SC1 39B	SC1 43B	SC1 44B	SC1 45	SC1 46B	SC1 48	SC1 55	SC1 61	SC1 59	SC1 60	SC1 23	SC1 22	SC1 1	SC1 2	SC1 3	SC1 4	SC1 5
NCE	Q	Quartz single crystal	23.4	27.1	20.6	22.1	28.9	25.9	28.5	31.1	22.3	26.3	30.4	25.3	26.3	26.1	28.9	25.2	22.7	28.0	27.3	25.5	30.7	27.3	21.1	24.2
NCE	Q	Quartz polycrystalline coarse texture	2.2	2.3	3.1	1.4	2.4	1.6	1.6	2.3	9.0	1.9	2.3	2.7	5.0	2.6	3.9	3.8	2.9	10.0	4.8	3.8	4.2	3.8	3.5	4.6
NCE	Q	Quartz polycrystalline fine texture	0.4	1.4	0.8	1.1	0.9	1.9	0.9	1.7	-	3.8	1.0	0.3	1.0	0.6	1.9	2.6	1.3	1.3	1.8	1.0	1.0	1.9	1.6	1.6
NCE	Q	Chert	0.1	0.9	-	0.3	0.3	-	-	0.3	-	0.9	0.3	-	-	-	0.3	0.3	0.3	-	0.3	0.6	-	-	0.6	-
NCE	Q	Quartz in plutonic-gneissic rock fragment	1.8	1.1	-	0.3	0.6	1.6	0.6	0.3	3.0	0.6	-	0.3	2.7	2.6	0.6	0.3	1.0	6.3	0.6	0.3	1.3	-	2.2	0.3
NCE	Q	Quartz in metamorphic rock fragment	0.1	-	-	-	-	0.3	-	0.7	-	0.3	0.7	0.7	-	0.6	1.0	0.2	0.3	-	0.3	-	-	-	0.3	1.0
NCE	Q	Quartz in volcanic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCE	Q	Quartz in clastic rock fragment	2.3	2.3	4.2	3.7	3.3	3.2	1.3	1.3	0.7	2.5	1.3	0.3	0.3	3.9	2.9	1.8	0.3	2.0	5.2	2.9	3.2	1.0	4.1	1.6
NCE	K	K-feldspar single crystal	9.1	9.4	11.3	9.5	8.5	8.1	7.2	10.6	8.7	10.1	10.2	9.0	6.7	11.3	10.7	15.1	7.1	10.3	9.4	12.4	13.3	7.9	12.6	10.5
NCE	K	K-feldspar in plutonic-gneissic rock fragment	0.6	0.9	1.1	0.9	0.3	-	-	-	0.3	-	1.0	-	0.3	0.3	-	0.2	0.6	0.7	-	0.6	0.3	-	0.9	0.3
NCE	K	K-feldspar in metamorphic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCE	K	K-feldspar in volcanic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCE	K	K-feldspar in clastic rock fragment	0.1	-	0.3	-	0.3	0.3	0.3	0.0	0.3	0.6	0.3	-	-	-	0.3	0.3	0.3	-	-	0.6	-	0.3	-	0.3
NCE	P	Plagioclase single crystal	7.9	4.0	7.9	7.5	9.7	9.7	12.5	7.3	13.3	11.7	9.2	-	10.3	-	8.8	10.1	13.9	9.3	6.4	5.1	6.5	9.5	10.4	5.9
NCE	P	Plagioclase in plutonic-gneissic rock fragment	-	0.3	0.3	-	0.6	-	0.6	0.3	0.7	0.6	-	8.7	1.0	11.9	0.3	0.5	0.6	1.3	0.6	0.3	0.3	0.6	0.3	1.0
NCE	P	Plagioclase in metamorphic rock fragment	-	-	-	-	-	-	-	-	-	-	-	0.7	-	0.6	-	-	-	-	-	-	-	0.3	-	-
NCE	P	Plagioclase in volcanic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.3	-	-
NCE	P	Plagioclase in clastic rock fragment	0.4	0.6	0.8	0.6	1.5	-	0.3	1.0	-	0.6	-	-	-	-	-	0.5	-	-	0.3	0.3	-	-	0.6	1.6
NCE	L	Metamorphic rock fragment	-	-	-	0.3	-	0.3	-	-	1.7	0.6	-	0.7	2.0	-	-	-	-	0.7	-	-	-	-	-	-
NCE	L	Volcanic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	0.7	-	-	-	-	1.7	-	-	-	-	-	-
NCE	L	Spilite	-	-	-	-	-	-	-	-	0.3	-	-	0.3	-	-	-	-	-	0.7	-	-	-	-	-	-
NCE	L	Serpentinite	0.4	-	-	0.3	0.3	0.3	-	0.3	-	0.3	0.3	0.3	0.3	-	0.6	-	-	-	0.3	-	0.6	-	-	-
NCE	L	Clastic lithic – Shale	18.3	14.3	18.6	12.4	13.7	16.2	16.3	12.6	10.7	7.3	9.9	10.3	10.7	13.2	14.6	9.9	17.2	1.0	13.6	14.3	11.0	12.4	12.0	12.1
NCE	L	Clastic lithic – Siltstone	6.4	5.7	5.4	7.5	6.1	3.2	4.1	3.6	3.0	4.4	4.6	4.0	3.7	3.9	2.9	4.6	5.8	1.0	2.4	4.1	3.9	2.9	4.1	5.9
NCE	M	Muscovite+Chlorite single crystal	0.1	0.6	1.1	0.6	0.6	1.6	1.9	1.0	0.3	1.3	1.7	4.0	1.7	0.6	-	0.5	0.3	-	0.6	-	0.6	-	1.3	1.6
NCE	M	Muscovite+Chlorite in rock fragment	0.3	-	-	0.6	0.6	-	-	-	0.3	-	-	0.3	0.7	-	-	0.3	-	0.3	-	-	-	-	0.3	-
NCE	M	Heavy mineral single crystal (unspecified)	0.3	-	-	1.1	-	-	-	-	-	-	-	-	-	-	-	0.3	0.3	-	-	-	-	-	0.6	-
NCE	M	Heavy mineral in rock fragment (unspecified)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCE	M	Fe-oxide	-	-	-	1.7	-	-	-	-	0.3	-	-	0.7	0.3	-	-	-	-	-	-	-	-	-	-	-
CE	C	Calcite single crystal	11.0	15.7	11.0	16.7	11.2	9.1	11.0	13.9	9.3	9.2	15.8	12.3	14.3	10.6	10.7	10.9	9.4	11.3	10.3	14.0	13.6	15.2	12.0	12.1
CE	C	Sparitic limestone	4.5	3.1	3.7	3.2	0.3	2.3	0.9	2.0	6.7	3.8	1.7	9.0	6.0	1.9	1.0	2.2	2.9	4.0	4.2	1.9	1.0	0.6	1.6	0.3
CE	C	Silty-arenitic limestone	-	-	-	-	-	0.6	-	-	2.3	-	5.9	0.3	0.3	-	0.3	0.6	0.6	1.3	0.3	1.3	-	-	0.3	0.3
CE	C	Mudstone-Wackestone	7.5	6.3	7.6	7.2	7.3	10.0	8.5	7.0	1.7	9.2	-	3.0	3.0	7.1	9.4	7.1	8.4	4.7	7.3	8.9	7.4	10.5	7.3	8.8
CE	C	Bioclast (terrigenous)	1.5	2.0	1.1	0.9	1.8	2.6	2.5	2.3	1.0	3.2	3.0	4.7	1.3	1.6	0.6	1.4	2.3	3.7	3.0	1.3	1.0	3.2	2.2	3.6
NCI		Brick and pottery fragments	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCI		Organic material	-	-	-	-	-	1.0	0.9	0.3	-	-	-	-	-	0.3	-	0.2	0.3	-	0.3	-	-	1.0	-	1.6
CI		Bioclast (penecontemporaneous)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.2	-	-	-	-	-	-	-	-
CI		Caliche	1.0	2.0	1.1	0.3	-	-	-	-	3.7	-	-	1.7	0.7	-	-	0.3	0.3	-	-	-	-	-	-	-
		Undetermined	-	-	-	-	0.6	-	-	-	0.3	0.6	0.3	0.3	0.7	-	-	0.6	0.6	0.3	0.6	0.6	-	1.3	-	0.7
		Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

			DIKE 4		DIKE 5					DIKE 6	DIKE 7		CORE S3		CORE S2		CORE S10	
		Sample	SC1 6	SC1 7	SC1 41	SC1 49	SC1 19	SC1 20	SC1 21	SC1 32	SC1 34	SC1 33	SC1 52	SC1 53	SC1 51	SC1 50	SC1 28	SC1 26
NCE	Q	Quartz single crystal	21.0	21.9	27.5	21.7	25.9	26.6	34.6	25.7	30.7	26.3	40.0	25.4	31.3	32.9	36.0	31.3
NCE	Q	Quartz polycrystalline coarse texture	4.5	4.6	2.0	3.7	5.2	2.5	1.0	5.3	3.4	4.0	6.0	3.7	6.3	4.3	8.0	6.0
NCE	Q	Quartz polycrystalline fine texture	2.2	2.0	3.6	1.0	0.9	1.6	2.0	0.7	2.8	2.0	1.3	2.1	2.0	2.0	3.3	2.3
NCE	Q	Chert	0.3	-	-	-	-	-	-	0.3	-	-	-	0.3	-	-	1.0	0.5
NCE	Q	Quartz in plutonic-gneissic rock fragment	0.6	0.3	2.3	3.3	1.2	0.6	1.6	2.3	0.3	2.7	3.3	2.1	3.3	2.3	0.3	1.4
NCE	Q	Quartz in metamorphic rock fragment	0.3	0.7	-	0.3	-	0.3	0.7	0.3	0.6	-	-	-	-	-	-	0.3
NCE	Q	Quartz in volcanic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	0.3	-	-	0.2
NCE	Q	Quartz in clastic rock fragment	2.2	4.2	3.0	2.7	3.1	1.3	2.3	4.0	2.5	2.7	3.3	3.1	-	0.7	0.3	2.3
NCE	K	K-feldspar single crystal	11.5	6.9	8.6	12.7	7.4	9.7	9.8	11.3	12.5	10.0	7.7	12.2	10.0	11.3	12.7	14.8
NCE	K	K-feldspar in plutonic-gneissic rock fragment	0.6	-	-	0.3	0.6	0.6	-	1.0	-	2.0	1.0	0.6	1.3	1.0	0.3	1.2
NCE	K	K-feldspar in metamorphic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCE	K	K-feldspar in volcanic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCE	K	K-feldspar in clastic rock fragment	0.3	0.7	-	0.3	-	-	-	-	-	-	-	-	-	-	-	-
NCE	P	Plagioclase single crystal	8.9	12.1	7.6	7.3	9.0	9.4	8.8	6.0	6.0	4.0	10.0	8.3	7.7	12.0	7.3	9.7
NCE	P	Plagioclase in plutonic-gneissic rock fragment	0.6	-	0.3	0.7	0.3	-	-	1.0	0.3	0.3	1.0	0.6	0.7	0.3	0.3	2.8
NCE	P	Plagioclase in metamorphic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCE	P	Plagioclase in volcanic rock fragment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NCE	P	Plagioclase in clastic rock fragment	0.6	0.3	-	-	0.6	0.3	-	-	-	-	-	0.6	-	-	-	0.2
NCE	L	Metamorphic rock fragment	0.3	-	-	2.0	-	-	-	1.0	-	3.7	1.7	-	2.3	1.7	1.3	1.2
NCE	L	Volcanic rock fragment	-	-	-	1.7	-	-	-	1.0	-	0.7	0.3	-	0.7	-	-	-
NCE	L	Spilite	-	-	-	0.3	-	-	-	0.3	-	-	0.3	-	-	-	0.3	0.2
NCE	L	Serpentinite	0.6	0.7	-	-	-	0.3	0.3	-	0.3	1.0	-	-	-	-	-	0.2
NCE	L	Clastic lithic – Shale	9.6	12.1	14.9	14.0	9.9	12.9	8.2	8.7	10.3	11.7	2.3	6.7	2.0	5.3	3.3	2.3
NCE	L	Clastic lithic – Siltstone	3.2	2.3	3.0	3.7	4.6	2.2	3.6	3.0	5.6	4.3	1.0	3.7	3.3	1.7	7.3	1.9
NCE	M	Muscovite+Chlorite single crystal	0.3	1.0	1.0	-	0.3	1.9	2.0	2.0	0.6	2.3	-	0.9	0.0	1.0	0.3	-
NCE	M	Muscovite+Chlorite in rock fragment	0.6	-	-	1.0	-	0.3	0.3	1.0	-	-	0.3	-	0.3	-	0.3	0.5
NCE	M	Heavy mineral single crystal (unspecified)	0.3	-	0.3	-	0.6	-	-	-	-	-	-	-	-	-	-	-
NCE	M	Heavy mineral in rock fragment (unspecified)	-	-	-	-	-	-	-	-	-	-	0.3	-	-	-	-	-
NCE	M	Fe-oxide	-	-	-	0.3	-	-	-	-	-	-	-	-	-	-	0.3	-
CE	C	Calcite single crystal	14.3	14.7	10.3	13.3	13.9	12.5	11.8	12.0	11.9	12.3	13.0	14.7	18.7	15.9	7.3	10.5
CE	C	Sparitic limestone	2.2	3.3	6.0	3.0	4.9	0.3	1.0	3.7	3.4	2.7	3.3	2.4	2.3	2.0	2.0	3.2
CE	C	Silty-arenitic limestone	0.3	-	-	-	0.3	-	0.3	2.0	0.3	-	-	0.6	2.0	-	-	0.7
CE	C	Mudstone-Wackestone	10.2	7.2	7.0	3.3	6.8	11.0	8.2	5.0	6.0	5.0	2.7	8.6	2.0	2.0	6.0	4.7
CE	C	Bioclast (terrigenous)	3.2	3.9	2.6	2.7	3.1	4.7	2.6	2.0	0.9	2.3	0.7	2.8	2.3	2.7	1.3	1.1
NCI		Brick and pottery fragments	-	0.0	-	-	-	-	-	-	0.3	-	-	-	-	-	-	-
NCI		Organic material	-	0.3	-	-	0.3	-	-	-	0.3	-	-	0.3	-	0.3	-	0.6
CI		Bioclast (penecontemporaneous)	-	-	-	-	0.3	0.3	0.7	-	-	-	-	-	-	-	-	-
CI		Caliche	-	-	-	-	-	-	-	-	-	-	0.3	-	0.3	-	-	-
		Undetermined	1.0	1.0	-	0.7	0.6	0.6	0.3	0.3	0.6	-	-	0.3	0.7	0.7	0.3	0.2