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Srpenica seismites - indicators of paleoseismicity in the Upper Soča valley, NW Slovenia

Seizmiti v Srpenici - pokazatelji paleoseizmičnosti v Zgornjem Posočju

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Ključne besede: Kvartar, seizmičnost, potres, seizmiti, deformacije v mehkem sedimentu, jezerski sedimenti, Srpenica, Zgornje Posočje, Slovenija

Abstract

Varve-like lacustrine sediments of Pleistocene to Holocene age were studied in the abandoned clay pit near Srpenica in the Upper Soča valley. Within a sequence of laminated to thin bedded lacustrine deposits, two intervals of soft-sediment deformations were studied and interpreted herein in terms of seismites. The age of deformation is estimated by a radiocarbon date of wood (at the top of the lower deformed layer) at 12790±85 14C years BP, and the genesis is attributed to strong past earthquakes, which is very much in accordance with the present seismicity of the studied area.

Povzetek

V opuščenem glinokopu pri Srpenici so bili preiskani varvam podobni jezerski sedimenti pleistocenske do holocenske starosti. V vodoravno laminiranih jezerskih sedimentih sta bili prepoznani dve plasti deformacij v nekonsolidiranem sedimentu, ki ju interpretiramo kot seizmite. Starost deformacij je na podlagi ^{14}C datacije lesa iz spodnje deformirane plasti ocenjena na 12790±85 ^{14}C let pred sedanjostjo. Nastanek seizmitov pripisujemo močnim potresom v geološki preteklosti, kar se ujema tudi s sedanjo seizmičnostjo območja Zgornjega Posočja.

Introduction

The area of the Upper Soča Valley was well investigated after the earthquake that occurred there on April 12, 1998 (Ribičič, ed., 1998). Investigations consisted of detailed geological mapping, geophysical investigations, as well as seismological and geomechanical research. An effort has also been made to recognize possible paleoseismicity indicators in the area, i.e. to identify traces of past earthquakes in the geological environment. Imprints of such earthquakes, described as seismites, have indeed been found in laminated lake sediments of Quaternary age exposed in an abandoned clay pit near Srpenica. This was for the first time that seismites were recognized here, which should induce paleoseismic investigation over similar environments in the other regions of Slovenia.

Seismites are deformational structures of sediments attributed to seismic shocks. The term was first introduced by Seilacher (1969) describing a sequence of structures spanning from undisturbed to faulted and finally to liquefied sediments exposed in the Monterey Shales (Miocene) in California. He attributed differences in intensity of deformation to varying degree of compaction and mechanical properties of the sediment. Seilacher was fully aware that the structures described represent only one type of 'earthquake beds', or *seismites*. He also speculated (p. 158) that *»the scale of deformation will to a certain extent express the strength of the shock as a sort of paleo-seismogram«*. The term was later redefined by Vittori and coworkers (Vittori et al. 1991) who broadened its definition as to *»include all geologic structures that are related to earthquakes.«* However, in order to relate structural deformation of given sediments to a certain seismic event, many other factors have to be eliminated as it has well been pointed out by Ricci Lucchi (1995) and Galli and Ferreli (1995).

We are describing herein the possible seismites that are akin to thin slumps, developed in presently seismically active area of the Julian Alps and their foreland, where rather strong earthquakes are relatively frequent. The last one (M = 5.6) occurred on April 12, 1998 having its epicentre at the Krn Mt., some 11 km east from Srpenica.

General geological setting

Geologic framework of the Soča Valley is thoroughly described by Zupančič et al. (2001), therefore only a brief tectonic outline is illustrated here (Fig. 1). Geotectonically the investigated area lies at the southern rim of the Southern Alps. The main tectonic feature in the area is the Southern Alps thrust front (Placer, 1998). The Southern Alps consist of several thrusts that are as a whole trusted onto the External Dinarides. The main structural features of the External Dinarides are NW-SE oriented faults. According to Placer (1998) the part of the External Dinarides that borders to the Southern Alps is the Idrija tectonic zone, named after one of the most prominent faults of the External Dinarides - the Idrija fault.

The recent dynamics of the area is attrib-

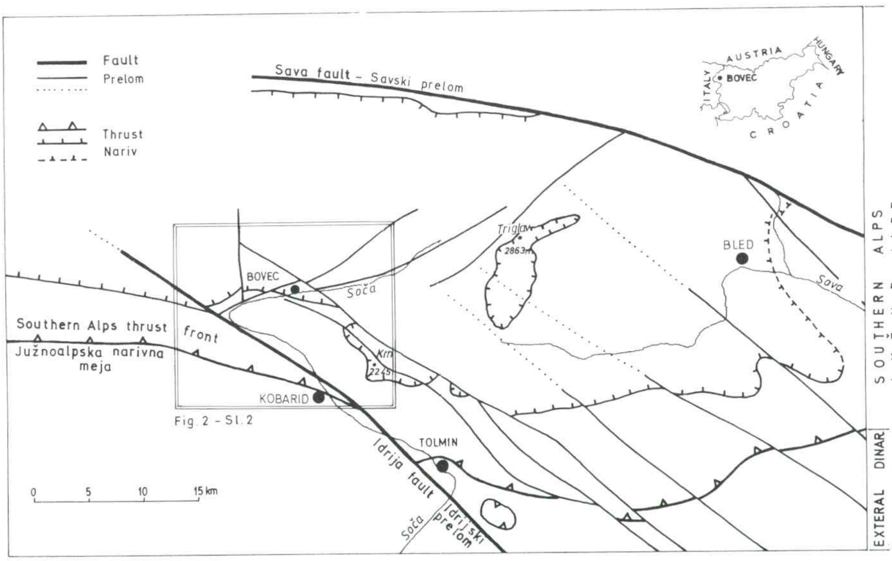

Fig. 1. Geotectonic position of the investigated area (modified after Placer et al., 1999).

Sl. 1. Geotektonska lega raziskanega ozemlja (prirejeno po Placer et al., 1999).

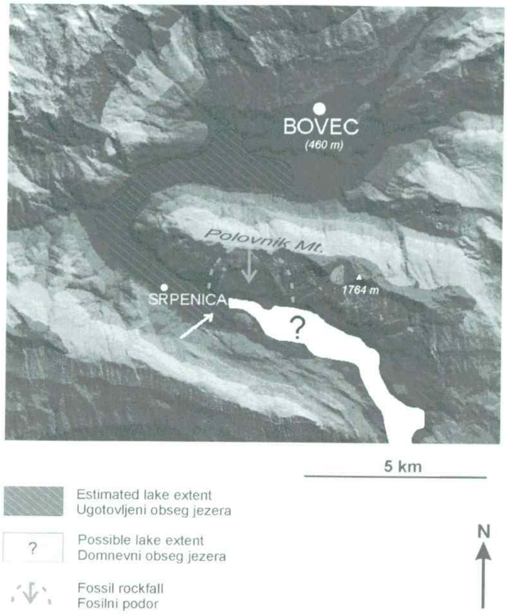

Fig. 2. Position of the Quaternary lake in the Upper Soča valley. Digital Elevation Model is represented by graduated gray scale where each shade of gray represents an elevation range of 250 m (modified after Bavec, 2001).

Sl. 2. Lega kvartarnega jezera v Zgornjem Posočju. Posamezen sivi odtenek na digitalnem modelu reliefa predstavlja višinsko razliko 250 m (povzeto po Bavec, 2001).

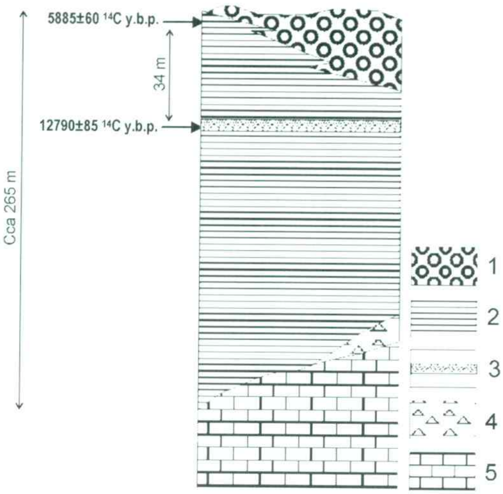

Fig. 3. Schematic stratigraphic column of Quaternary sediments near Srpenica; 1. fluvial gravel, 2. laminated lacustrine sediments, 3. horizon with seismites, 4. diamicton, 5. bedrock.

Sl. 3. Pregledni stratigrafski stolpec kvartarnih sedimentov pri Srpenici; 1. rečni prod, 2. laminirani jezerski sedimenti, 3. plast s seizmiti, 4. diamikton, 5. predkvartarna podlaga.

uted to anti clock-wise rotation of the Adriatic plate towards the Eurasian plate and the resulting stress and strain field. The principal stress axis (δ_1) is oriented N-S (Poljak et al., 2000). Resulting structural deformations therefore manifest as southward thrusting along the Southern Alps thrusts, as well as right-lateral strike-slip shearing along the External Dinarides faults. The mechanism described was also recognized by analyses of earthquakes between the Southern Alps and the External Dinarides in northern Italy and NW Slovenia (Placer et al., 1999; Zupančič et al., 2001), and is characterized by thrusting and shearing mechanisms.

Investigated lacustrine deposits are developed in the Upper Soča valley between Bovec and Srpenica. It is possible that the same lake sediments formation extends towards Kobarid (Fig. 2), yet evidences for such a conclusion are vague. Lake sediments overly Mesozoic bedrock and Pleistocene diamictons (Kuščer et al., 1974; Bavec, 2001), and they are overlain by fluvial gravel and sand of the Bovec terrace (Fig. 3). Lacustrine sediments are best exposed at Srpenica in an abandoned clay pit, where some 30 m of section makes a good cliff exposure.

Seismicity of the studied area

The regions of Friuli in the northeastern Italy and the region of the northwestern Slovenia are among the seismically most active in this part of Europe. Strong earthquakes in this region have been documented for almost a thousand years. It should be noted, however, that for most historical earthquakes the exact location and size are highly uncertain. Two strongest events being the so-called »Villach« earthquake of 1348 and »Idrija« earthquake of 1511 have caused significant damage in northwestern Slovenia. Recent studies have concluded that the likely location of the »Villach« event is in Friuli (Gutdeutsch & Len-

Date Datum	Imax	M	Epicentral region Območje epicentra	Distance to Srpenica [km] Oddaljenost od Srpenice [km]
1348 01 25	IX	6.9	Friuli/Slovenia Furlanija/Slovenija	10
1511 03 26	X	6.9	Slovenia/Friuli Slovenija/Furlanija	12
1511 08 08	IX	6.0	Slovenia/Friuli Slovenija/Furlanija	31
1700 07 28	IX	5.6	Carnia Koroška	50
1928 03 27	IX	5.8	Friuli Furlanija	42
1976 05 06	X	6.4	Friuli Furlanija	36
1998 04 12	VII-VIII	5.6	NW Slovenia SZ Slovenija	10

Table 1. Earthquakes that, following the criteria of Galli (2000) and Keefer (1984), have been of size and within distance that could have caused liquefaction in the studied area. The date, maximum intensity and estimated magnitude of the earthquake are given as well as epicentral region and the distance from the Srpenica clay pit.

Tabela 1. Preglednica potresov, ki bi sodeč po kriterijih Gallija (2000) in Keeferja (1984) lahko povzročili likvifakcijo na obravnavanem ozemlju. Predstavljeni so datum potresa, največja intenziteta, ocenjena magnituda, območje epicentra in razdalja do glinokopa v Srpnici.

hardt, 1996), Italy, whereas Boschi et al. (2000) put its epicentre in the vicinity of Bovec (Slovenia). Equally uncertain is the location of the »Idrija« earthquake of 1511 as well as its relation to possible shock of approximately same strength and at approximately same time in northeastern Italy. While Ribarič (1979) specifies two earthquakes with epicentres near Idrija and Cividale, Boschi et al. (2000) list only single event of magnitude 6.9 with epicentre in the vicinity of Robidišče. The strongest earthquake in the recent times happened in 1976 in Friuli (M=6.4) and caused numerous cases of liquefaction in the area close to the epicentre (Galli, 2000). An earthquake of magnitude 5.6 with epicentre in Krn Mountains happened on 12. April 1998, and it caused extensive coseismic and postseismic rockfalls and landslides (Vidrih & Ribičič, 1999) up to the distances of 16 km. It is therefore very likely that earthquakes of the size of »Villach« and »Idrija« events could have caused similar and perhaps larger effects in the geological history too regardless of their exact locations. There is several other earthquakes that, following the criteria of Galli (2000) and Keefer (1984), have been of size and within distance that could have caused liquefaction in the studied area (Table 1):

Quaternary lake deposits

Investigated lacustrine and fluvial Quaternary sediments fill an elongated depression in the western part of the Bovec Basin and beyond its limits along the Soča River valley (Bavec, 2001). They consist mainly of carbonates (85 %) the rest are oxides, hydroxides and micas (Kuščer at al., 1974). Geophysical and borehole data (Kuščer et al., 1974) indicate that they overlie mostly the bedrock but locally they overlie Pleistocene diamictons as well. The maximum thickness of fine-grained sequence in the area is 200 m, whereas the total thickness of described Quaternary sediments (including the Bovec terrace and underlying diamictons) reaches 265 m (Kuščer et al., 1974). Schematic stratigraphic column of these is presented on Figure 3. The lacustrine sediments are almost entirely covered by the prograding fluvial infill consisting of bedded gravel, sand and weakly cemented conglomerates forming the Bovec Terrace.

It has been suggested that a large rockfall from the Polovnik Mt. (Fig. 2) dammed the valley just west of Srpenica and caused formation of the lake (e.g.: Kuščer et al., 1974; Kunaver, 1975). According to revised borehole data and appearance of lake sediments downstream of the rockfall, it seems likely that tectonic subsidence of the Bovec basin is contributed to the formation of the lake too. Moreover, there are indications that the rockfall may have crushed into an existing lake splitting it into two parts of which existence of the downstream one is still ambiguous.

The fine-grained sequence of lake deposits is varve-like, consisting of alternating dark gray and light gray laminae. Lamination is well developed in the central part of the sediment body with transition to non-laminated sands and gravels towards its marginal parts. Thicknesses of laminae vary from less than a millimetre up to over 10 mm forming thin layering where thickness exceeds 1 cm. Silt and clay size particles form 99 % of the sediment in the central (i.e. laminated) part (Iskra, 1963). Field observations indicate clearly that darker laminae are significantly finer grained than lighter ones but no quantitative grain-size analyses were done on separate laminae. Laminations were not investigated precisely, so we are unable to distinguish seasonal varves (*sensu* De Greer, 1912) from laminae produced by non-seasonal processes. These fine-grained deposits do not show current laminations, what indicates that the deposition took place in pelagic environment. The deposition was apparently slow and delicate, since no loading was found on bedding planes. The lack of wave-produced lamination indicates on deposition in a quiet pelagic environment bellow the wave base (even below the storm-wave base which is usually deeper). The lack of body fossils and bioturbations indicates disaerobic bottom conditions, probably below termocline. Generally flat, undeformed bedding suggests that the depositional environment around today's Srpenica was flat lake basin bottom (basin centre), far from lake shores. Coarser sediments (i.e. sand) found in the marginal parts of the unit were deposited in a higher-energy shoreline environment.

Locally, wood fragments can be found in the fine-grained sequence. Radiometric dating (Bavec, 2001) yielded two ^{14}C dates: 12790±85 ^{14}C years BP at depth of 34 m and 5885±60 ^{14}C years BP at the very top of the sequence (Fig. 3). The calculated average sedimentation rate is therefore between 4 - 5 mm per calendar year. Both, the age as well as the pollen content of approximately upper 30 m (Šercelj 1970; 1981) indicates the transition from colder Late Glacial to warmer Holocene.

Seismites

The near-vertical exposure, about 40 m high, of undisturbed varve-like lacustrine deposits in the abandoned Srpenica clay pit, comprises two interbeds characterized by soft-sediment deformation structures. The deformed layers were found 34 m below the top of the exposed sequence laying 30 cm above each other, and could be traced laterally for ca. 30 metres until they are covered by the quarry slope talus (Fig. 4 and 5).

Deformed horizons are 5-6 cm thick and bound by flat, sharp and locally gently undulated lower boundary, and gently undulated but sharp upper boundary. Each horizon is composed of two strongly deformed dark grey laminae and one light grey. The internal structures of this deformed sediment are pseudo-nodules (Fig. 6) and various types of folds (Fig. 7), which range from normal to recumbent, with predominating random orientation of their axes (just locally they tend to show vergence). The intensity of deformation differs laterally, so at the distance of a few decimetres folded sediment turns into pseudonodular. The Srpenica deformed sediments are almost identical to *plastic glide* of Dzulynski and Walton (1965, fig. 128) which was interpreted in terms of a coherent slump, and *flame-like structure* of Blanc et al. (1998). At the top of deformed sediment scattered angular rock fragments (up to 10 cm across) occur, and one over 1m long wood fragment was found (Fig. 4). The radiocarbon date obtained from the later yielded the age of 12790 ±85 ^{14}C years b.p.

Deformed sediments can be produced by different processes, but slumping and loading are being most frequently reported. Kuenen (1958) described his experiments on formation of pseudo-nodules, with testing of a scaled earthquake-trigger. During his experiment, sand started load casting into underlying mud soon after the external shock was applied. The local loads sank quickly into the mud, forming ball- and kid-

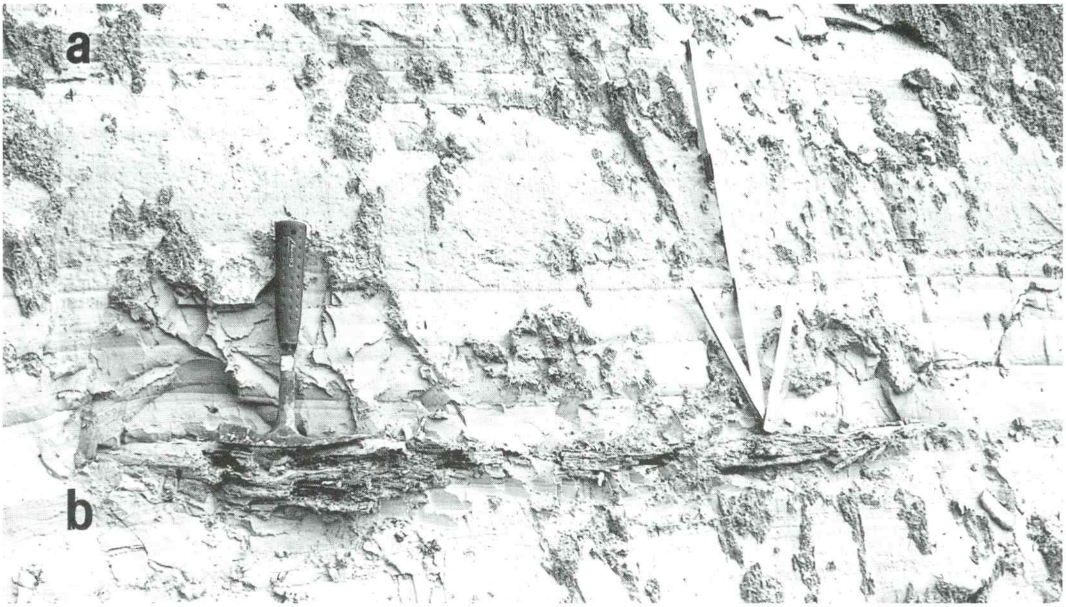

Fig. 4. Deformed layers interpreted as seismites within laminated lacustrine deposits in the abandoned clay pit near Srpenica; a. upper horizon, b. lower horizon. The hammer rests on a piece of wood that yielded the age of 12790±85 ^{14}C years b.p.

Sl. 4. Deformirani plasti, interpretirani kot seizmiti znotraj laminiranih jezerskih sedimentov v opuščenem glinokopu pri Srpenici; a. zgornja plast, b. spodnja plast. Radiokarbonska starost lesa, na katerem leži kladivo, je 12790±85 ^{14}C let b.p.

ney-like »nodules«. He was aware of close resemblance of structures produced experimentally with those formed by slumping, and he allowed the possibility that the earthquake may trigger both slumps, and induce load casting, so that there could exist all transitions between the two.

Kuenen's experiment allowed deep sinking of load casted sand, since creation of pseudo-nodules was his aim. In our case, the deformational structures are restricted to only two thin layers, what suggests that the space available was very limited, possibly due to compaction of the underlying fine-grained sediment, so deep sinking was not possible. The sediments affected by soft-sediment deformations must have still been uncompacted, unconsolidated, and water-saturated. This sediment was deformed by liquefaction most probably at the time when the top layer was actually the lake bottom layer in contact with water. The process of liquefaction involves increase in pore-water pressure, and its expulsion that initiates the overlying sediments to sink, or slide if placed on an even negligible slope.

The liquefaction events were unique during deposition of these sediments, since only two were recognized so far, and can therefore not be related to either possible seasonal causes, or slope overloading. In the latter case, high sediment supply would be required that would be indicated by many loaded bedding planes.

Described soft-sediment deformation structures were therefore most likely caused by a strong earthquake shock, which initiated liquefaction of unconsolidated sediment, and caused plastic deformation. Rodriguez-Pascua et al. (2000) discussed progradation of earthquake-induced deformation through the sediment, and suggested that the thickness of deformed sediment is a function of time, namely earthquake duration. Srpenica deformed sediment differs from *mixed layer structure* described by Rodriguez-Pascua et al. (*ibid*) in lack of upper horizon of completely disrupted structures, which was also recognized by Seilacher (1969) as the »*rubble zone*«. Jones and Omoto (2000) discussed that the thickness of deformed sediments

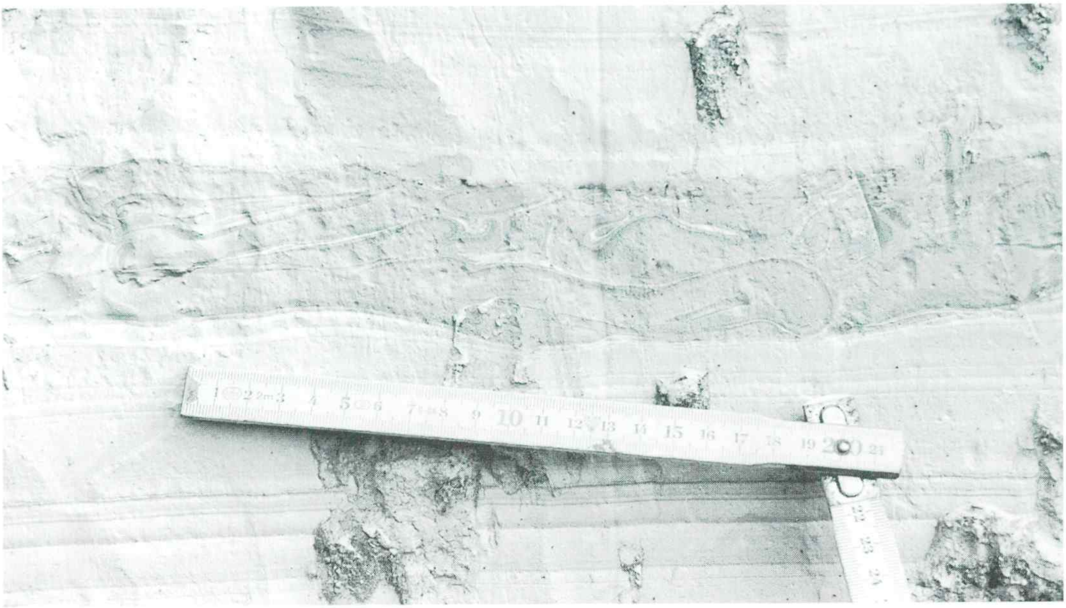

Fig. 5. A detail of the lower (b) deformed horizon.

Sl. 5. Detajl spodnje (b) deformirane plasti

may also be a consequence of magnitude, intensity and/or duration of a trigger and/or a combination of triggers. They also stated that the interpretation of triggering mechanism may require negative rather than a positive approach, meaning that interpretation of likely seismic trigger should be reached by elimination of, one by one, all other possible triggers.

We prefer to attribute the Srpenica deformed sediments as seismites, because of the following: a) origin due to liquefaction, b) negative evidence of high deposition rate which would account for overloading, c) negative evidence of slumping and sliding within the studied sequence which would indicate a slope setting, d) rarity of deformed horizons in the Upper Soča valley Quaternary sedimentary record which negates seasonal-scale causes, e) depth of deposition which was sufficient to isolate the bottom sediments from shallow-water processes and possible wave- or current-induced loading, and f) depositional setting in seismically active zone, practically within seismogenic Idrija fault system.

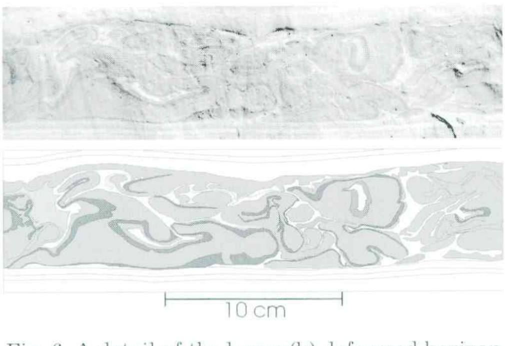

Fig. 6. A detail of the lower (b) deformed horizon showing pseudo-nodules.

Sl. 6. Detajl spodnje (b) deformirane plasti s psevdonodulami.

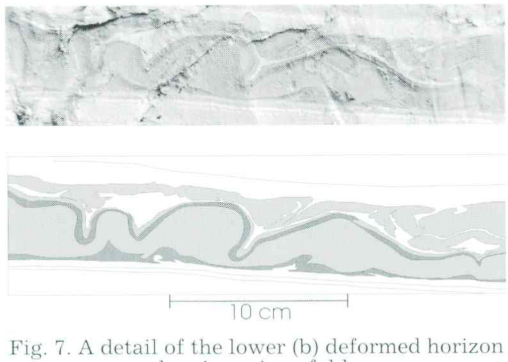

Fig. 7. A detail of the lower (b) deformed horizon showing micro-folds.

Sl. 7. Detajl spodnje (b) deformirane plasti z mikrogubami.

Discussion

It is known that strong earthquakes may affect sedimentation, although their geological record may be very different (see review in Vittori et al., 1991), and hard to attribute to seismic causes only (Ricci Lucchi, 1995). On one hand, recognition of paleo-seismic record is crucial for reconstruction of earthquake periodicity, but on the other, it is critical not to over-interpret the data because different processes may cause formation of similar sedimentary structures.

The earthquake affects the earth surface in different ways. It is commonly accepted that liquefaction represents a co-seismic process (Sims, 1975; Vittori et al., 1991; Galli, 2000) that affects the areas (usually composed of unconsolidated, uncompacted and non cemented sediments) where ground acceleration is high for longer time. This happens during strong earthquakes in regions relatively close to the epicentre. High acceleration (higher than 0.1 g) of long duration causes temporary conversion of unconsolidated soils into medium that behaves like a fluid. Liquefaction is caused by expulsion of interstitial water and surrounding sediments start to sink or slide. The latter leads to disruptions in otherwise uniform sediment pattern and can initiate deformation of the laminae, or of the beds in whole. On slopes, however, earthquake-inducted slope-failures are very common (e.g. Keefer, 1984), and will be recorded by mass-flow deposits, but these will be undistinguishable from identical aseismical deposits.

Many authors (eg. Seilacher, 1984; Davenport & Ringrose, 1987; Ringrose, 1989; Galli, 2000) accepted that the deformed sedimentary structures were created in uncompacted and unlithified sediments by seismically-induced liquefaction, which can be pervasive or just partial that probably depends on earthquake intensity, duration and physical properties of the sediment. Liquefaction affects only uncompacted and unlithified part of sediment, which was recently deposited, or it is still being deposited, and creates »boiling« of sediment, evidenced at the surface by sand, and mud volcanoes. The latter features were observed after several recent earthquakes (eg. Galli, 2000), but the deformational structures in sediments that were evidently formed co-seismically are seldom reported (eg. Sims, 1973; 1975; Greene et al., 1991). Galli (2000) reported in his review on all historical liquefaction features of Italy that although most liquefactions occurred during strong earthquakes (M>6.5) in areas located close to respective epicentres, a large number of moderate earthquakes (M>4.2) also induced liquefactions.

Blanc et al. (1998) linked co-seismic stratigraphic disturbances to five parameters: »*a) the original petrotexture of sediment, b) the induration of the sediment during the event, c) the thickness of the layer and the nature of the beds under the layer, d) the water saturation of the `ground` during each event, and e) the magnitude of the earthquake and the distance from epicentre*«. There is a direct relationship between earthquake magnitude (and intensity) and the maximum distance from an epicentre where liquefaction may occur; it starts with M=5 earthquakes which are just strong enough to initiate liquefaction, and increases with stronger magnitudes, at M = 7 liquefaction can occur at a distance of 20 km (*ibid*). Galli (2000) provided new relationship between epicentral intensity (MCS) and epicentral distance, as well as magnitude and epicentral distance for liquefaction for earthquakes in Italy. They both show exponential increase of liquefaction distance with the increase of earthquake intensity/magnitude, starting with MCS=5.5/M=4.2.

There are just a few accounts on experimental work on deformational features related to shaking, which could represent scaled earthquake vibrations (e.g. Kuenen, 1958). Early experimental work on generation of sedimentary structures including convolutions and slumps by Dzulynski and Walton (1965) showed that loading can account for their creation, but also that the process would start sooner if experimenter applied external mechanical shock. Thus, the vibration triggered sinking of the overlying sediment into wet clay. If there was only a slight slope, this mobilized sediment would start to slide creating asymmetrical folds such as in figure 7.

Srpenica laminated Quaternary lake sediments meet all the criteria put by Ricci

Lucchi (1995) for a favourable sequence for paleo-seismites study, i.e.: a) the sediments were deposited in a relatively deep lake bellow the wave base (to prevent sediment disturbance by subaerial processes, extreme meteorological events, and waves, etc.), b) location near the lake basin centre (far enough from lake margins, so that slope instabilities do not occur), c) in low oxygenated waters (so that environment was inhospitable to organisms which could disturb bedding), d) sediments were formed by very slow suspension deposition and dilute underflows, and e) the lake was located in seismically active area (where we expect sufficiently strong earthquakes to disturb the bottom sediments).

If the deposition continued after seismically-induced liquefaction event, the deformed sediment was soon buried under a cover of new sediment, and loading flattened the upper surface of once liquefied sediment. Gently undulating upper boundary of deformed sediment in Srpenica was very likely formed by flattening under the load of overlying deposits.

Occurrence of large wood fragments, in addition to lithic fragments, which both mark seismite upper boundary indicate slope failures somewhere on vegetated mountain slopes. Since the most numerous wood fragments are found associated with the seismite interval, it is very likely that the wood was rafted from relatively distant source, whereas lithic fragments might have fallen on the lake bed from that rafted woods, or ballistically from a co-seismic rock-avalanche (a process described already by Hsü, 1975). Whether the nearby extensive rock fall from Polovnik marked on figure 2 could be attributed to the same earthquake event is not evident.

Conclusions

Described deformation structures dated at app. 12790±85 occur in Srpenica clay-pit interbedded with undisturbed parallel-bedded and laminated fine grained deposits. These sinsedimentary structures do not seem to be induced by compaction, slumping, or any other gravitational process. The studied area is situated in the region of the active tectonic contact between the Southern Alps and the External Dinarides where earthquakes up to M=6.9 have been recorded in the past. Described horizons with soft-sediment deformation structures produced by liquefaction are interpreted as seismites, i.e. the earthquake induced deformational structures caused by seismic shocks. The lacustrine depositional environment was very favourable for preservation of such deformational structures and the paleo-Soča valley lake is located in presently the most seismically active area of Slovenia. The later, together with the other indicators described in the paper supports the idea of seismic origin of liquefaction features in Srpenica clay pit. Thus, we were able to extend the knowledge on paleoseismicity of the area back to geological history, and to date at least one of supposed seismic events at 12790±85 ^{14}C years b.p.

It should also be pointed out that this is the first location in Slovenia where the soft sediment deformation structures have been interpreted as seismites. Following these investigations and obtained results, one can apply paeloseismic research to the other regions of Slovenia where suitable Quaternary structures exist. Indications of paleoseismic activity in a certain region with no or poor recent seismic activity, due to long recurrence intervals of strong earthquakes, may significantly change seismic hazard estimates for that region.

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