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Late-Pleistocene seismites from Lake Issyk-Kul, the Tien Shan range, Kyrghyzstan

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Abstract

The aim of the study is to record the occurrence of sediment deformation structures in one of the tectonically most active areas on the globe, the Tien Shan range in Central Asia and to examine the significance of the deformations as indicators of palaeoseismicity.

Soft-sediment deformation structures in form of balls and pseudo-nodules are exposed in the Issyk-Kul basin, within interfingering beds of shallow lacustrine, beach and fluviatile origin. Additional deformation structures that were encountered are: a complex and chaotic folded structure, giant balls and a "pillar" structure which has not been previously reported, where marl intrudes down into coarse pebbley sand and forms pillar morphology. Liquefaction features and bedforms related to storm and breaking waves were not encountered. Neither was there evidence of turbidites. Seven field criteria for relating soft-sediment deformation to palaeoseismic triggering provide strong evidence for a seismic origin of the deformation structures. Empirical relationships between magnitude and the maximum distance from an epicenter to liquefaction sites make the active epicentral zone north of Lake Issyk-Kul, with its frequent high magnitude events, the most favorable source for the deformation structures. Luminescence dating of the sediments gives a time window of 26 ± 2.1 to 10.5 ± 0.7 ka BP, indicating latest Pleistocene seismic activity.

Keywords: Neotectonics; Seismites; Palaeoseismicity; Soft-sediment deformation; Tien Shan; Kyrghyzstan

1. Introduction

Soft-sediment deformation structures are common in unconsolidated, loosely packed and saturated sands interbedded with silt and some clay. They have been recorded in many studies from all sedimentary environments, in particular, from lacustrine beds (Hempton and Dewey, 1983; Tinsley et al., 1985; Anand and Jain,1987; Scott and Price, 1988; Calgue et al., 1992; Rodriguez-Pascua et al., 2000; Galli, 2000). The soft sediments were described as having lost strength through becoming semiliquid (Lowe, 1975). Deformation of liquidized sediments without application of much external force has been associated, by Dzulynski (1966), with inverse density gradients acquired at deposition, or during resedimentation into

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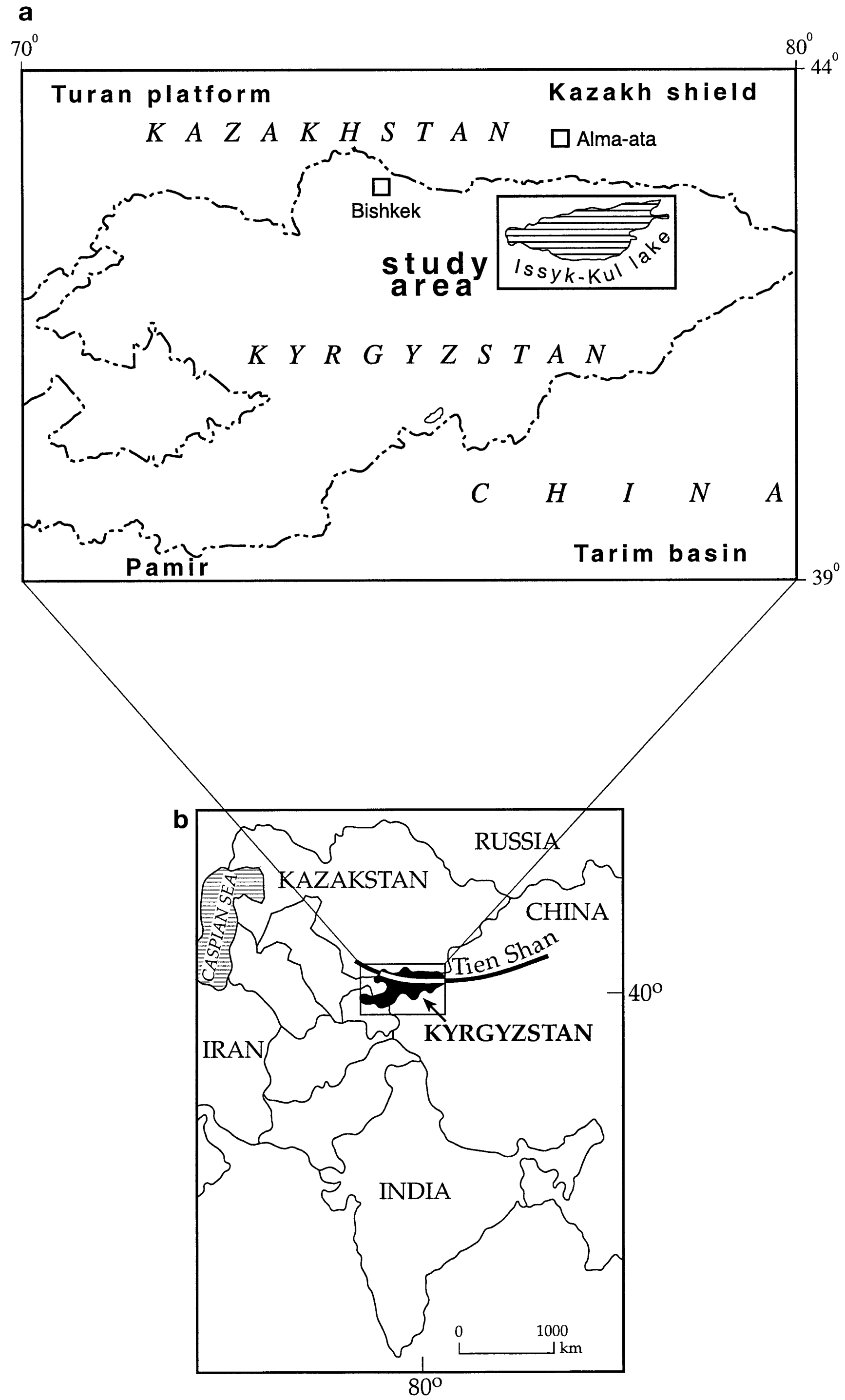

Fig. 1. Location (a, b) and structural setting (c) of the northern Tien Shan belt, the Issyk-Kul lake and the basin.

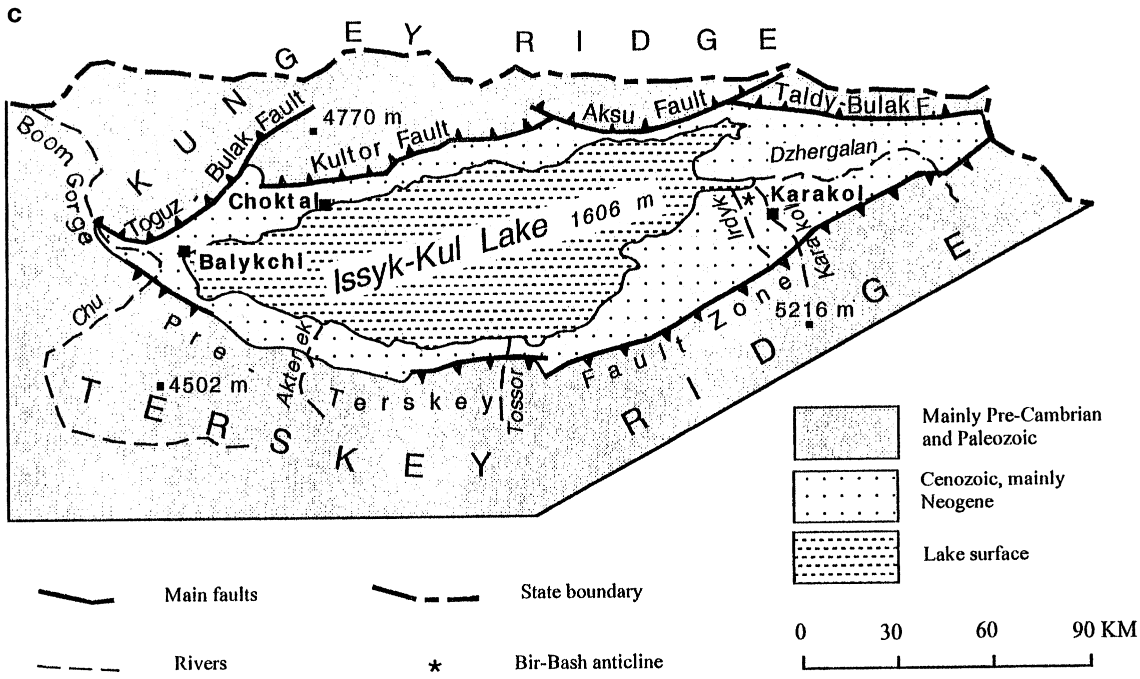

Fig. 1 (*continued*).

a tighter packing. In many cases, the deformations were attributed to shaking by earthquakes. Soft-sediment deformations of a plastic nature may, however, also be triggered aseismically by rapid deposition and unequal loading, by cyclic oscillation of storm surges, by the force of downslope-driven density currents or following a significant change in artesian pressure.

The Tien Shan range (Fig. 1) is one of the most seismically active regions of the world and is known for major earthquakes (Dzhanuzakov et al., 1980; Kondorskaya and Shebalin, 1982). Several lakes occupy depressions within this active range. The Middle to Upper Pleistocene and Holocene lacustrine deposits were susceptible to intense earthquake activity but no previous attempts have examined their sediment deformation structures as indicators of palaeoseismicity so as to extend backwards the record of active seismicity.

The aim of the study is to locate, characterize and date sediment deformation structures in the Issyk-Kul Lake area, northern Tien Shan, and assess their significance as indicators of palaeoseismicity, bearing in mind the difficulties in distinguishing between seismic and nonseismic triggering.

2. Study area

The Issyk-Kul lake area (Fig. 1) is a tectonic ramp depression bordered by convergent thrust faults, dipping in opposite directions (Chedia, 1993). In the north, the Issyk-Kul depression is bounded by the Kungey ridge and by a set of en-echelon thrust faults, i.e., the west Toguz-Bulak, the Kultor and the northern Aksu and Taldy-Bulak faults. The Terskey ridge bounds the depression in the south along with the southern pre-Terskey fault zone. The Miocene and Pliocene mark an era of intensive orogenic uplift shown by the coarsening upward of the 4000-m thick, sandy gravelly Issyk-Kul formation (Fortuna, 1993). The Quaternary deposits include lacustrine clays to giant glacier boulders (Korjenkov, 2000). Maximum thickness of the Cenozoic deposits in the Issyk-Kul depression is 5000 m.

The Issyk-Kul intermontane basin has been occupied by lakes since Early Neogene (Voskresenskaya, 1983). The present lake has existed since Mid-Pleistocene, about 700,000 years ago. Its maximum level was 1675–80 m (Trofimov, 1990). The highest possible lake level, before spilling over through the Boom Gorge to the northwest, towards the Chu valley, is today 1620 m (Fig. 1). During the Holocene, the water level of Lake Issyk-Kul dropped to 110 m below the present level (Fig. 2), as indicated by underwater shore terraces, submerged canyons, a network of river channels and submerged human settlements (Bondarev, 1983). Subsequently, in the first half of the 19th century, the lake level rose to 1622 m. Since then the lake level has gradually dropped towards its current 1606-m level. The fluctuations of the lake level are related to climatic changes superimposed upon tectonic movements (Grigina and Fortuna, 1981).

The maximum length and width of Lake Issyk-Kul are 179 and 60 km, respectively. The total shoreline length is 662 km and maximum depth is 668 m. A strong gradient of precipitation exists from the east with 720 mm/year to the west with 120 mm/year. Evaporation amounts to 836 mm per annum (Krivoshey and Gronskaya, 1986). The water is brackish: salinity is 5.9 g/l (Romanovsky, 1990).

The receding lake level has cut a beach cliff at an altitudinal range of 1620–1640 m. The cliff is composed of interfingering alluvial and lacustrine sediments. An array of gravelly sandy beach bars extends from the base of the cliff down to the recent shoreline, reflecting the last stage of lake-level fall.

3. Methods

3.1. Field work

Extensive surveys were carried out along the shores of the lake and the beach cliffs in order to locate deformation structures. Detailed mapping was undertaken at five locations (Fig. 3): along sections by the Akterek outlet (stations 11, 15); by the outlet of the Irdyk (station 18); at the Karakol river outlet (station 17) and by the Choktal beach (station 10).

The altitudes of all the sections were tied by leveling to the current lake level. At each station, a systematic description of the stratigraphic column was done. The following sedimentary characteristics were recorded in detail: texture, including grain size; roundness and sorting; thickness and regularity of the bedding; lenticular features; cyclic bedding; cross-bedding; microstructures and micro-cross-lamination. The deformation structures were measured in terms of their size and geometric characteristics including thickness and length, symmetry, shape, degree of penetration and isolation, top and bottom contacts, structural gradient, composition of the host unit and lateral continuity.

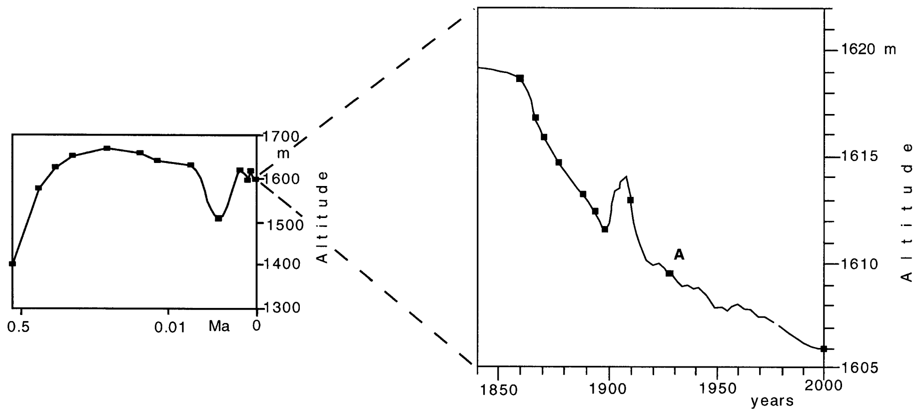

Fig. 2. The Issyk-Kul lake level fluctuations from Mid-Pleistocene on and for the period 1860–2000 in detail, following Trofimov (1975). The period 1860–1910 is based on reports of various researches and on cartographic sources. From A onward, there was regular monitoring. The period 1975–2000 had been lineary reconstructed to the recent 1606-m lake level.

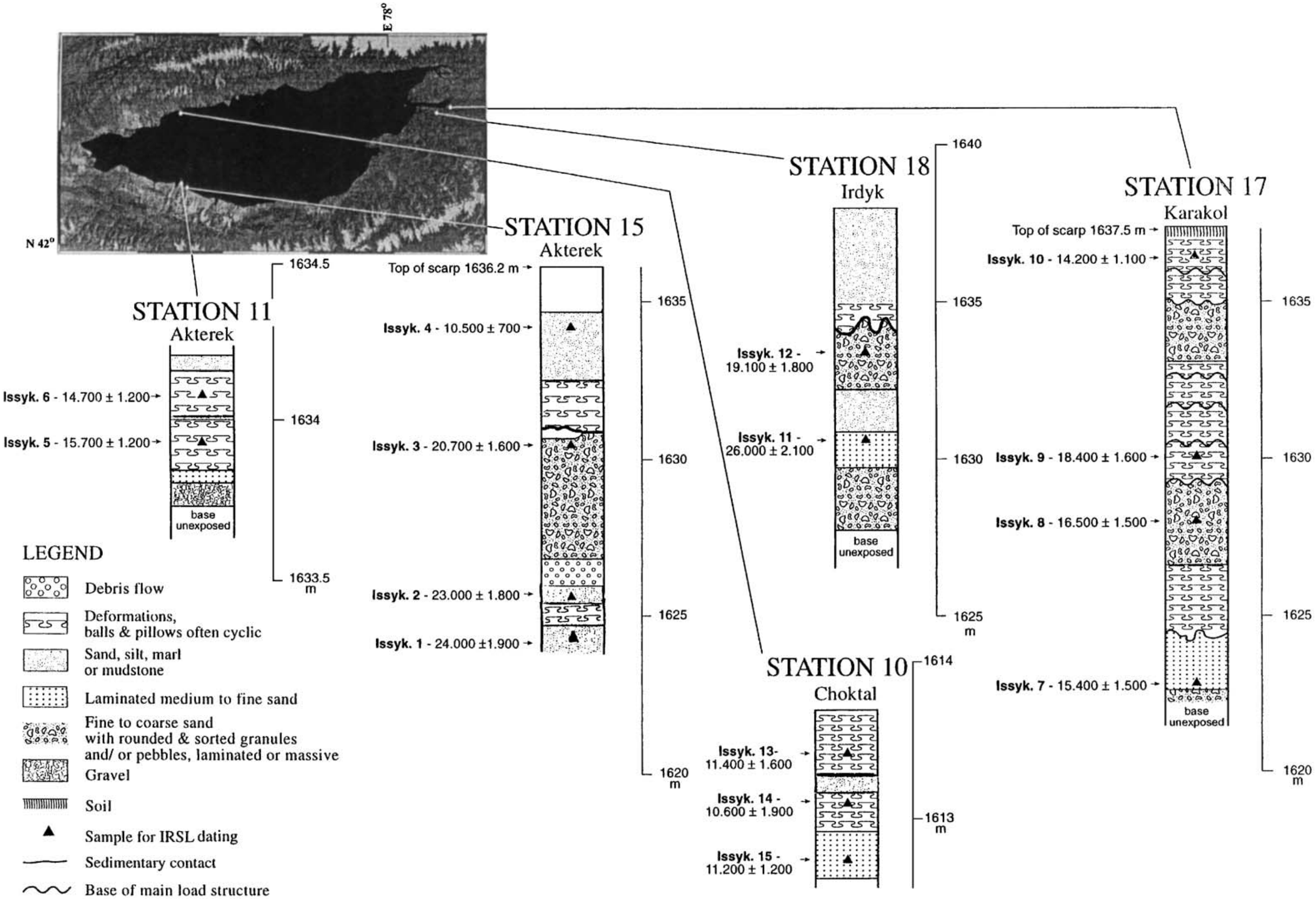

Fig. 3. The main sections studied along the Issyk-Kul shoreline. Soft sediment deformation, dates and the bases of the largest deformation units are indicated. Only sections 15, 17 and 18 are located altimetrically. Only well-developed load casts are shown.

Table 1
Luminescence dating – Field and laboratory results from the Issyk-Kul samples

Sample	Depth (m)	De (Gy)	K KF (%)	K (%)	U (ppm)	Th (ppm)	Internal β (μGy/a)	External α (μGy/a)	External β (μGy/a)	Cosmic (μGy/a)	External $\gamma+\cos^{a}$ (μGy/a)	External $\gamma+\cos^{b}$ (μGy/a)	Total dose[a] (μGy/a)	Total dose[b] (μGy/a)	Age[a] (ka)	Age[b] (ka)
1	10.5	115 ± 2.5	11.3	2.4	2.6	11.9	518	374	1990	35	1272	1894	4154 ± 268	4776 ± 358	27.6 ± 1.9	24.0 ± 1.9
2	9	106 ± 2.5	11.6	2.6	1.7	7.9	532	247	1962	45	1070	1848	3811 ± 234	4589 ± 335	27.7 ± 1.8	23.0 ± 1.8
3	4	96 ± 2.3	10.3	2.7	2.3	9.2	472	306	2107	90	1246	1748	4132 ± 260	4633 ± 335	23.2 ± 1.6	20.7 ± 1.6
4	0.45	55 ± 0.4	11.8	3.5	2.1	9.5	541	300	2627	210	1532	1771	5000 ± 305	5237 ± 356	11.0 ± 0.7	10.5 ± 0.7
5	0.7	70 ± 2.0	11.7	2.2	2.6	8.5	536	312	1811	190	1244	1826	3902 ± 236	4485 ± 360	18.1 ± 1.2	15.7 ± 1.2
6	0.55	68 ± 1.8	9.6	2.1	4.2	12.5	440	481	2013	200	1565	1748	4498 ± 296	4682 ± 344	15.3 ± 1.1	14.7 ± 1.2
7	14	84 ± 5.1	11.3	2.9	3.1	16.0	518	479	2475	35	1610	2022	5082 ± 338	5494 ± 414	16.6 ± 1.5	15.4 ± 1.5
8	9	74 ± 2.2	11.8	2.7	2.1	12.0	541	382	1776	45	1224	1796	3922 ± 354	4494 ± 385	18.9 ± 1.8	16.5 ± 1.5
9	6	87 ± 4.4	11.5	2.5	2.9	14.0	527	431	2144	65	1448	1636	4550 ± 297	4738 ± 345	19.1 ± 1.6	18.4 ± 1.6
10	0.5	71 ± 1.7	10.5	3.0	2.0	10.5	481	312	2302	210	1459	1921	4555 ± 281	5017 ± 354	15.6 ± 1.0	14.2 ± 1.1
11	5.5	149 ± 5.1	10.9	3.3	2.2	15.2	500	411	2616	85	1621	2197	5147 ± 334	5724 ± 426	29.0 ± 2.1	26.0 ± 2.1
12	3.5	102 ± 5.6	10.3	3.1	2.0	16.0	472	414	2453	105	1606	1995	4949 ± 321	5334 ± 394	20.6 ± 1.8	19.1 ± 1.8
13	0.35	66.3 ± 7.7	10.9	3.3	2.8	13.0	498	406	2624	220	1713	2297	5242 ± 332	5826 ± 423	12.7 ± 1.7	11.4 ± 1.6
14	0.65	59.1 ± 9.6	10.4	3.3	2.4	12.4	476	371	2570	190	1619	2144	5037 ± 319	5562 ± 402	11.7 ± 2.0	10.6 ± 1.9
15	1.1	68.1 ± 5.0	8.8	3.2	3.4	22.0	403	608	2799	180	2100	2296	6910 ± 402	6106 ± 465	11.5 ± 1.2	11.2 ± 1.2

Depth measured from present-day surface. De measured using infrared stimulated luminescence on alkali feldspars and the Single Aliquot Added Dose protocol. Grain size for all samples: 149 – 177 μm. Cosmic dose estimated from burial depth. Time-averaged water contents estimated at 15 ± 5%.

[a] Calculated from radioisotope contents measured in the lab.

[b] Calculated from field measurements, attenuated for 15% water contents. These ages are used in the paper.

3.2. Luminescence dating

The luminescence method dates the last exposure of mineral grains to sunlight (Aitken, 1998), that is to say, the age indicates the burial time of the sediment. In case of deformed sediments, deformation occurred when the sediment was saturated near the water–sediment interface and the luminescence ages give the maximum age of deformation.

This dating method uses signals that accumulate in minerals as a result of natural ionizing radiation and which are zeroed by exposure to sunlight. After a resetting event the signals grow as a function of time and environmental radiation, and therefore can be used to estimate the time elapsed since the mineral underwent an event of transport and burial (Aitken, 1998).

Fifteen samples for luminescence dating were collected from the five sections, four along the southern shores and one on the northern shores of Lake Issyk-Kul (Fig. 3). In all cases, the dated beds consist of very fine to fine sands. The samples usually bracket deformed units in order to optimize coverage of the deformation events. The samples were collected from holes dug into the sections under a black tarp and were immediately placed in black light-tight bags. All further laboratory sample processing was carried out under subdued orange light.

The laboratory procedures roughly follow those described by Porat et al. (1999). Sand-size (150–177 μm) alkali feldspars (KF) with densities less than 2.58 g/cm^3 were extracted from the sand by heavy liquid separation, following sieving and dissolution of carbonates with 10% HCl. Aliquots of ~ 5 mg of extracted KF were deposited on 10-mm aluminum discs using silicon spray as an adhesive. All measurements were carried out on a Risø DA-12 reader, equipped with an array of infrared diodes and a ^{90}Sr β irradiator (Bøtter-Jensen et al., 1991). Equivalent doses were determined by the Single Aliquot Added Dose technique (Duller, 1994), whereby the infrared emission at 880 nm was used for stimulation.

External γ dose rates were measured in the field in the holes dug into the sections for sample collection. A portable Rotem P-11 γ scintillator with a 2-in. sodium iodide crystal was used, calibrated to measure cosmic rays (Porat and Halicz, 1996). The concentrations of U and Th in the sediments were measured using inductively coupled plasma mass spectroscopy (ICP-MS) and the K content was measured by ICP-emission spectroscopy. External a and β dose rates were calculated from the concentrations of the radioelements in the sediments. Internal β dose rate was determined from the K contents of the extracted KF. An a-value of 0.2 ± 0.05 was used for α-efficiency corrections (Mejdahl, 1987; Rendell et al., 1993).

Today, the studied sediments are dry, however, at the time of deposition and until lake levels receded, the sediments were water-logged. Therefore, a time-averaged estimated water content of $15 \pm 5\%$ was used in the age calculations. The ages were calculated using the software Age developed by R. Grün. Table 1 gives all field and laboratory measurements and dose rate calculations. Errors on individual dates were calculated from errors on all laboratory and field measurements, and they include uncertainties in field data, analytical and random errors.

Gamma dose rates were obtained by two means, (a) measurements in the field and (b) calculations from the concentrations of the radioelements. All values were attenuated for 15% moisture contents. On average, the γ dose rates measured in the field are 25% higher than the values calculated from the radioelements. Consequently, the ages calculated from the field measurements are on average younger by ~ 10% (Table 1). We chose to use the younger ages calculated from the field measurements, as in situ γ measurements take into account local inhomogeneities in the sediment.

4. Results

4.1. Main sedimentary characteristics and facies association of the deformation-bearing beds

The studied sections (Fig. 3) expose alternations of well-stratified or laminated sand, mud and sandy–pebbly beds, often showing wavy bedding, some cross-lamination, foreset bedding and some massive layering. The sorting is good. Mollusks and inclusions of hydrous ferric oxides of lagoonal-lacustrine origin have previously been reported (Markov, 1971). Such cyclic patterns of mud and sand, often with pebbles,

Fig. 4. Washed-out circular depressions formerly occupied by isolated balls at the top of the coastal cliff by station 15, Akterek.

Fig. 6. A giant sandstone ball with a flat upper truncation surface. The underlying strata are undisturbed. Papers indicate sampling sites (station 10—Choktal).

indicate dynamic facies fluctuations between the shallow lacustrine—beach—and fluviatile environments. The following main characteristics were observed in the studied sections (Fig. 3).

4.1.1. Akterek section (station 11)

A gravelly unit is overlain by fine laminated sand with micro-ripple cross lamination, alternating with laminated clay (samples Issyk. 5, 1633.9 m; and Issyk. 6, 1634.1 m). The section suggests transformation from a beach/ fluviatile facies to shallow lacustrine conditions. Two deformed beds are present at different elevations.

4.1.2. Akterek section (station 15)

Alternations of sandy–muddy laminae (sample Issyk. 1, 1624.5 m) coarsen upwards to sandy granules and pebbles (Issyk. 2, 1625.5 m). Above, there is a hard muddy debris flow unit overlain by well-stratified and laminated loose sand with well-sorted and rounded pebbles, dipping 8° northwards (sample Issyk. 3, 1630.2 m) and tangentially cross-bedded to the underlying debris flow unit. The section is capped by marly–muddy sand (sample Issyk. 4, 1634.2 m). Two deformed beds are present at different elevations.

Fig. 5. Intrusive contacts between marly balls. Bedding is deformed and preserved. The injected sand forms flame structures. Flat bounding contacts at the top indicate postdefomational erosion prior to deposition of the overlying beds.

Fig. 7. Large-scale complex convolute bedding structure. The features incorporate ball and pillow structures. Note the truncated flat upper surface. Bedding is well preserved (station 15—Akterek).

Fig. 8. Detail of Fig. 7 left, by the hammer: complex convolute bedding with recumbent and overturned folds.

4.1.3. Irddyk section (station 18)

Sandy pebbles are overlain by alternating fine and coarse wavy laminated sand beds (sample Issyk. 11; 1630.8 m), followed by laminated and massive and pebbley granular sands (sample Issyk. 12; 1633.5 m). The Irddyk section is overlain by a whitish mudstone and includes a deformed horizon at its base.

4.1.4. Choktal section (station 10)

This comprises alternating fine-bedded sand and silty mud (sample Issyk 15, 1612.7 m; sample Issyk 14, 1613.1 m; sample Issyk.13, 1613.4 m), including two deformed beds.

4.1.5. Karakol section (station 17)

The base is a sandy–pebbly bed, abruptly overlain by laminated wavy sand (sample Issyk. 7, 1622.5 m). This is followed, across an irregular contact, by deformed whitish mudstone, overlain abruptly by well-bedded sand with granules and small pebbles (sample Issyk. 8, 1628 m). The overlying micro-rippled cross-laminated fine sand (sample Issyk. 9,

Fig. 9. Deep penetration of marly "pillars" intruding down into pebbley coarse sand, which was injected upwards. The internal stratigraphy of the sand beds was completely destroyed by its liquefaction. The curved " pillars" (above, at station 18 Irdyk; Fig. 10, by the Tossor river) and the isolated marly blocks (Fig. 10) may imply lateral flow of the sand.

1630 m) is deformed. So there are five overlying beds, including the topmost bed of mud and sandy pebbles (sample Issyk. 10, 1636.4 m). The Karakol section includes seven deformed beds.

4.2. Soft-sediment deformation features

The following main deformed features have been observed in the sites studied around Lake Issyk-Kul:

1. Pseudo-nodules or isolated balls. These balls, composed of sand or mud, vary from 14–18 cm long and 4–6 cm thick to 19–50 cm long and 13–29 cm thick. The deformations form a pear structure and are separated by crested diapiric flame structures composed of the coarse, loose and unstratified sandy host unit. Original layering is bent around the balls and is parallel to the basal surface. This interpenetrative type of deformation (Allen, 1977) at the top of the coastal cliff (Akterek station 11, Figs. 4 and 5) occurs in rather regular lateral intervals in beds of uniform thickness and often changes laterally from a ball form to wavy anticlinal and synclinal convolute bedding. The top of such deformed structures is commonly sharply truncated. Their lateral extent ranges from tens to hundreds of meters, implying little variation in loading. No indications of ripple morphology related to the deformation were observed.

2. Giant balls and pillows, 0.7–2.1 m long and 0.3–0.7 m thick with flame structures. These features are marly-muddy, bounded by subhorizontal sandy–muddy lamina and hosted in massive loose sand (Fig. 6). They differ in size from the previous category and were observed in the Choktal section, on the northern shore of the lake. Primary lamination remained in most cases undestroyed; however, torn lamination was also encountered.

3. Complex and irregular convoluted sand beds which comprise a tabular unit, 40–60 cm thick,

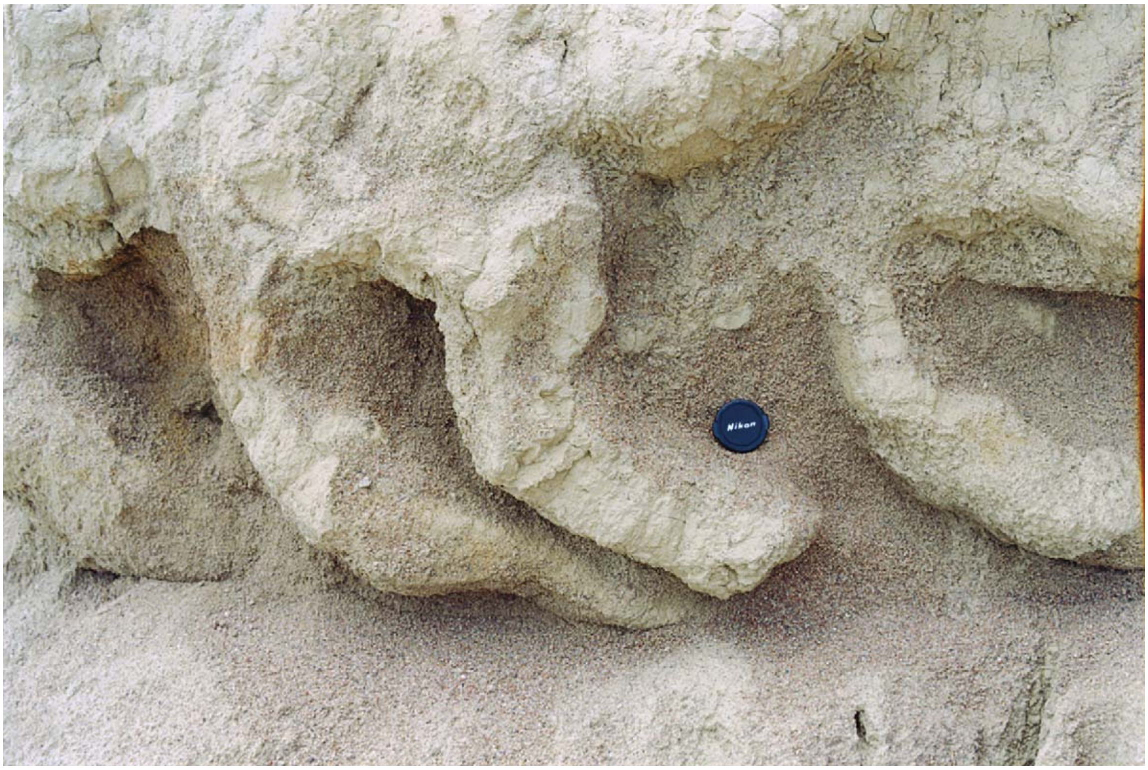

Fig. 10. Deep penetration of marly "pillars" intruding down into pebbley coarse sand, which was injected upwards. The internal stratigraphy of the sand beds was completely destroyed by its liquefaction. The curved " pillars" (Fig. 9, at station 18 Irdyk; above, by the Tossor river) and the isolated marly blocks (above) may imply lateral flow of the sand.

bounded by undisturbed and undeformed horizontal beds, were observed at the base of the section at section 15 (Fig. 3, altitude 1625 m). They include (Figs. 7 and 8) vertical intrusions and large-scale complex recumbent folds, partly in a highly disorganized, irregular and chaotic pattern that might imply some horizontal displacement. The internal lamination, although distorted, is well preserved. This unit is traceable laterally for tens of meters. It is very different from the regular-spaced folding of broad synclines and pinched anticlines described by Cojan and Thiry (1992).

4. Whitish, muddy–marly "pillars", 50–60 cm high, which intrude down into sand, were observed in the Irdyk and Akterek sections and near the Tossor river (Figs. 9 and 10). The unit that hosts the "pillars" is composed of very fine to medium sand, often with micro-ripple cross-lamination, alternating with silt and mud. Alternatively, it is composed of massive coarse sand with well-sorted and rounded granules or small pebbles. The deeply intruded sand is injected upward between the downwards-intruding "pillars" of marl, some of which are in a curved position. The upper sand–mud interface is completely destroyed. The unit containing the "pillars" is bound by planar upper and lower surfaces.

The "pillar" deformation is easily distinguishable from pillows and pseudo-nodules. It is a vertically, deeply displaced structure. It is unique being a soft muddy–marly load on top of a coarse granular sand which is of high initial porosity.

5. The field criteria for seismites

We use the term "seismites" following Seilacher (1969) for structures formed in soft sandy sediment by seismic shocks. Each typical field criterion (Sims, 1975; Hempton and Dewey, 1983; Anand and Jain, 1987; Obermeier, 1996a) suggested for relating deformation features to palaeoseismic events, though not as compelling evidence, is discussed and related to our observations in the Lake Issyk-Kul area.

(A) Suitable location in a seismically active area. Lake Issyk-Kul is situated in an area where many strong modern earthquakes have occurred (Dzhanuzakov and Sadykova, 1993; Abdrachmatov et al., 2002). The epicenters in the vicinity of the Issyk-Kul depression (Fig. 11) indicate a seismically very active zone, mainly north of the lake. During the 101 years 1889–1990, the following strong (M>6.2) earthquakes were reported in the basin, some of them ranking among the strongest ever felt in continental areas: the Chilik 1889, $M_S = 8.3$ earthquake (Mushketov, 1899); the Kebin, 1911, $M_S = 8.7$ (Bogdanovich et al., 1914); the Kemin-Chue, 1938, $M = 6.9$ (Vilgelmzon, 1947); the Sary-Kamysh, 1970, $M = 6.8$ (Grigorenko et al., 1973); the Zahalanash-Tyup, 1978, $M_b = 7.1$ (Aitaliev, 1981); and the Baysoorun, 1990, $M_S = 6.3$ (unpublished data of the Institute of Seismology, NAS, Kyrghyzstan).

(B) Suitable sediments—loosely consolidated, metastable sands and silts with low cohesion. Because of these properties (Dzulynski and Smith, 1965; Mills, 1983) and following an excess of pore pressure in water-saturated conditions and a reverse density state sufficient to cause gravity instabilities, the sediments may loose cohesion and liquefy. Clay-rich sediments are generally not susceptible to liquefaction because of their cohesiveness. Poorly sorted coarse sediments tend to be less permeable and of greater strength. The lacustrine sandy–muddy facies observed in the study sites are partly porous and loosely packed, thus meeting the basic textural requirements for plastic load deformation.

(C) Similarity to structures formed experimentally under conditions of earthquake-induced shaking (Kuenen,1958; Owen, 1996) or reported elsewhere as seismites (Seilacher, 1969; Scott and Price, 1988; Ringrose, 1989). The deformation features revealed in our work compare well with both soft-sediment deformation structures reported from the geological record and with those demonstrated experimentally. It is, however, noteworthy that the study area is typified by absence of liquefaction-induced fluidization and vented sediments (Obermeier, 1998a,b), in form of clastic dikes, sand-filled fissures, sills and intrusions that pinch together upwards.

(D) Preclusion of trigger by gravity flow. Seismites should relate to areas where slope instabilities induced by gravity control can be excluded in order to avoid deformation induced without shaking. The lateral continuity of the deformation structures within well-defined beds precludes a gravity flow origin. Laminated clay, silt and fine sand deposited in-between the deformed beds suggest still-water lacustrine condi-

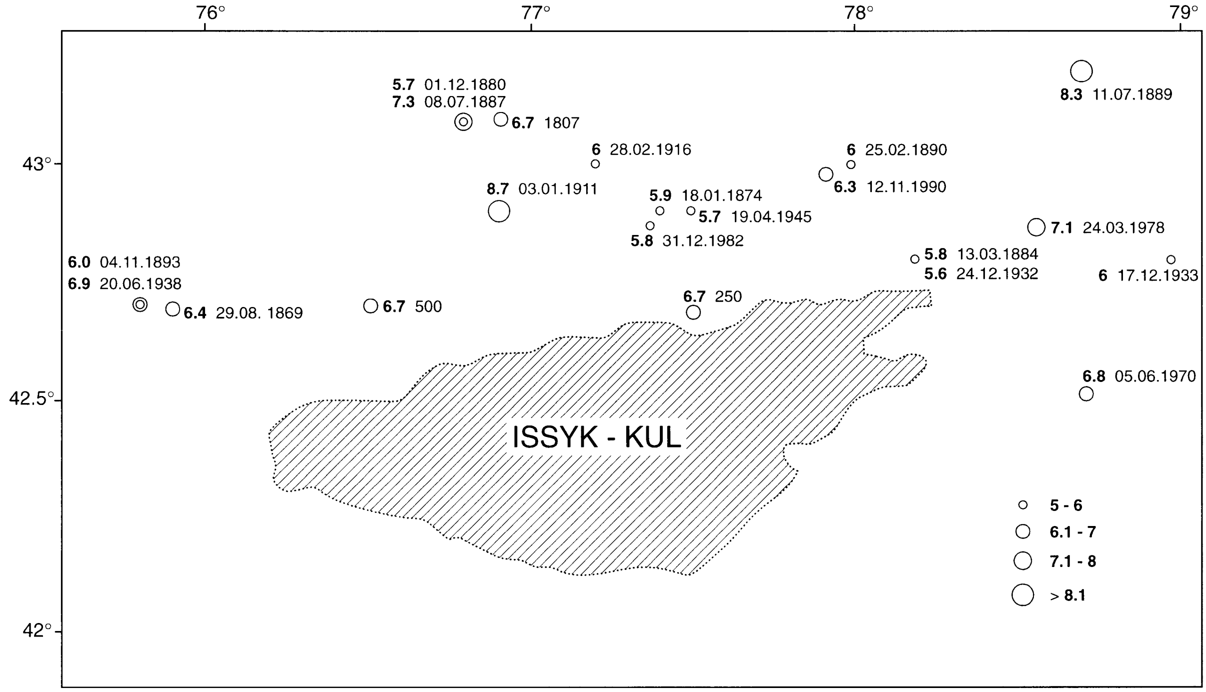

Fig. 11. The spatial distribution of epicenters for events M>5 recorded or known in the study area, focusing mainly on the period 1874–1990. Data sources: Dzhanuzakov and Sadykova, 1993; the Kyrgizian Seismological Institute (personal communication); U.S. Geological Survey Earthquake Data Base and Harvard CMT catalogue.

tions, diminishing the likelihood of occurrence of gravity-driven density currents producing shear (Jones and Omoto, 2000). Lack of evidence of rotational slips, pull aparts and forward displacement of material, which is typical of slumps (Mills, 1983), decreases the likelihood of slope control.

(E) A stratigraphically sandwiched position. The deformed layers should be stratigraphically sandwiched between undeformed stratigraphic intervals. This is shown in many cases by the undeformed, overlying and underlying bounding strata (Figs. 5 and 6). Clear rhythmic alternation of deformed beds with undisturbed strata may also indicate the instantaneous nature of seismic triggering (Rossetti, 1999), implying that deformation occurred very shortly after deposition (Jones and Omoto, 2000).

(F) Lateral continuity and regional abundance. A wide lateral extent of the deformation structures and their regional abundance are prerequisites for regarding them as seismically triggered (Allen, 1986; Obermeier, 1996b). They are widely distributed along the Issyk-Kul lake shorelines. Their abundance and extent fits the expected effect of earthquake-induced events, although no synchroneity could be established (Fig. 3). At each study site, the deformations are laterally continuous for only tens to hundreds of meters. These findings strongly corroborate Obermeier's (1996a,b) conclusion about the large variations in the abundance of liquefaction-induced features within a local area. Nonetheless, the spatial distribution of the soft-sediment deformations is very wide around Lake Issyk-Kul. The specific zones showing soft-sediment deformations alternate, as elsewhere, also according to the textural interfingering, along the margins of the basin. Textural interfingering causes regions of non-liquefiable deposits within the potential area of liquefaction, complicating the spatial distribution pattern.

(G) Cyclic repetitions of structures. Cyclic repetitions of structures are expected in seismic zones following recurrent seismogenic triggering. Two to seven vertical repetitions of discrete horizons bearing these deformation structures were exposed in the studied sections (Fig. 3). Such cyclicity is, however, by itself, not diagnostic of a seismogenic origin. It may also indicate repetition of depositional events or repeated wave-induced liquefaction.

6. The age of the seismites

All the samples analyzed in this study were taken from a height range of 25 m, at altitudes between 1612 and 1637 m (Fig. 3). The time window of the 15 dates is from 26.0 ± 2.1 to 10.5 ± 0.7 ka (Table 1), all within late Upper Pleistocene. There is some data in previous studies for the age control. Markov (1971) dated mollusks by radiocarbon, at an altitude of 1633 m, 7 m below the tread of the "Nikolaevka" lacustrine terrace, a well-known marker of the region at an altitude of 1640 m. His date, 26,340 ± 540 YBP, falls within our oldest ages.

During a considerable part of the Holocene, including the last 100 years, the lake level was lower than the study area (Fig. 2). Deformations related to that period, including the last century which was of very intense earthquake activity (Fig. 11), must be buried under the recent sand and beach gravel and below the recent lake level. This conclusion is strengthened by Ricketts et al. (2001) who collected piston cores in the lake from which 16 AMS radiocarbon dates were obtained up to a core depth of 40 m. The ages for the sediment ranged from 1480 ± 45 to 8940 ± 65 radiocarbon year BP.

From the point of view of the spatial correlation of the dates, when based on altimetry, section no. 18 Irdyk stands out with its relative high, though old, dates (Fig. 3, samples 11 and 12). Its location on the limb of the Bir-Bash anticline (Fig. 1) may indicate warping. Samples 13–15 from Choktal, on the north-

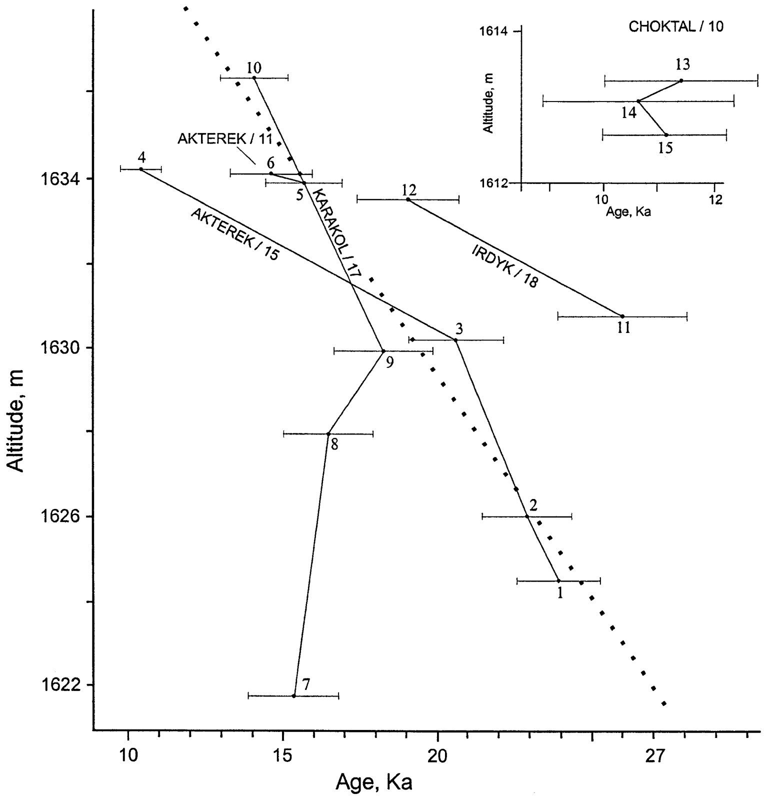

Fig. 12. Age vs. altitude of the 15 samples taken for luminescence dating. Age is attenuated for 15% water content. Note negative altitude–age correlation in the Akterek—15, Akterek—11 and Irdyk—18 sections. The number and error limits of each dating are indicated. Approximate line of best fit is shown excluding Irdyk and Choktal sections and samples 4, 7 and 8.

ern side of the lake, were taken from 6 to 8 m above the recent lake level and show the same age as sample no. 4, almost 20 m higher, from Akterek on the southern side of the lake. This may reflect a greater subsidence on the down-thrusted side of the Kultor fault compared to the down-thrusted side of the Pre-Terskey fault (Fig. 1c).

Negative altitude–age correlation were revealed in the Akterek-15, Akterek-11 and Irdyk-18 sections (Fig. 12). Such correlation suggests that the ages reflect the stratigraphical order without major interruptions by "cut and fill" events which often result in formation of insets. Ricketts et al. (2001) report the same trend for sediments below the lake level.

7. The relevance of historic seismicity

The epicentral map (Fig. 11) shows 19 earthquakes of M>5.5 during 183 years, 1807–1990, resulting in an average recurrence interval of 10 years with $1\sigma = 14$ years. The five strongest earthquakes (M> 6.2) during 101 years 1989–1990, which is the period with the best data, make an average recurrence interval of 25 years with $1\sigma = 23$ years. Based on the relation between the recurrence interval and earthquake magnitude (Slemmons and Depolo, 1986), the Issyk-Kul basin falls within the group of the "most active" seismic rate at major plate boundaries.

The empirical relationship between maximum distance of epicenter to liquefaction site R and the earthquake magnitude M is given by Kuribayashi and Tatsuoka (1975) and by Vittori et al. (1991): log $R = 0.87M - 4.5$. Thus, liquefaction may not occur further than 70 km from an epicenter of an earthquake with magnitude $M = 7.0$. For a distances exceeding 100 km, $M = 7.5$ seems to be a minimum threshold. Such relationships were also established empirically by Tinsley et al. (1985). Galli (2000), based on Italian data of the period 1117–1990, showed that following a 7 magnitude event, liquefaction may occur even in wider magnitude–distance combinations, even beyond 100 km. These distances make the active epicentral zone north of Lake Issyk-Kul (Fig. 11) with its high magnitude (> $M = 7$) events, the most favorable source for the soft-sediment deformations reported in our study. Although our study sites were far apart, their regional distribution was, however, not wide enough to indicate, through the magnitude of the deformations, the central core region.

8. Discussion

The ball-and-pillow and pseudo-nodules indicate loading of sand above water-saturated, soft and fine clay-rich sand and silt, and build up of pore-water pressure, which caused the loss of bearing capacity (Lowe, 1975; Allen, 1982). The upper sand intruded downward the weaker beds and became detached, kidney-shaped and often completely enclosed pseudo-nodules. Such deformations have been also produced experimentally by shaking (Kuenen,1958). However, as both the seismic trigger and nonseismic triggers, such as rapid deposition, gravity-induced mass movements or storm wave impact, can produce deformation (Moretti et al., 1999; Owen, 1996) these structures cannot serve as diagnostic criterion for supporting a seismogenic origin.

The deformation structures encountered in the study area are typified by a relative high symmetry and are not structureless internally. Their nearby surfaces lack, almost entirely, ripples or other bedform features and evidence of lateral movement and orientation, suggesting lack of current and drag. The structures are not accompanied by floating clasts or tool marks typical of turbidites and high flow deposits, although recumbent folds and cross stratification, which would be expected following current shear on liquefied sand (Brenchley and Newall, 1977), have been observed. The main observations suggest that the trigger was not via the water body and that the style of rheological behaviour of the sediment was hydroplastic, indicating limited local and mainly vertical particle movements (Elliott, 1965).

Storm and breaking waves provide an attractive alternative to seismicity as a trigger of soft-sediment deformation. Storm wave liquefaction features due to the cyclicity of the impact of storm waves or due to the breaking process (Owen, 1987) are, however, poorly documented in the literature. Dalrymple (1979) described isolated slump bodies on the upper stoss side of mega-ripples, separated by sharply peaked anticlinal structures, as indicators of wave activity. Molina et al. (1998) reported soft-sediment deformation structures in form of casts and isolated water escape structures due to storm waves in marine Miocene carbonates. Common criteria for strong oscillatory flows at the base of storm waves, which indicate the inner shelf and the lower shoreface, are bedforms such as hummocky cross-stratifications and symmetrical ripples (Walker, 1980; Brenchley, 1985; Duke,1985; Greenwood and Sherman, 1986; Eyles and Clark, 1986; Cheel and Leckie, 1993). These liquefaction features and bedforms have not been encountered in the study sites. Based on present knowledge, we have no evidence or reason to regard storm waves as triggers for the deformations in the Issyk-Kul basin.

The absence of liquefaction-induced venting features and water escape flow paths in the studied localities, and the dominance of plastic deformation, makes the study area fall in the worldwide category of areas with plenty of plastic deformation, in which vented liquefaction features could not develop (Obermeier, 1996b).

Lowe and LoPiccolo (1974) described pillars as circular columns, ranging in size from 1 mm to several meters and over 1 m across. Pillar structures related to overloading and mass sedimentation were reported by Ricci Lucchi (1980) and by Allen (1982). Moretti et al. (1999) showed that fluid escape structures, centimeters in heights and similar to pillars, can form following seismically induced liquefaction in normal-graded beds. Pillar structures formed by fluidization of fine material escaping upwards were also described by Wentworth (1966) and by Lowe (1975). All these features are, however, very different from the "pillars" we have described.

It is noteworthy that our "pillars" did not develop in a reversed density system. Soft-sediment deformations in the form of "pillars", where a marly unit intrudes down into coarse gravelly sand, have not previously been reported. As marl on top of sand acts as an impermeable layer, water must have been forced through the sand laterally from subjacent strata. Shaking could decrease drastically the strength of the sandy unit which finally allowed the sinking of the overlying marl into the sand to form the "pillars" observed by us. The form of " pillars" indicate detachment and sinking—and not foundering—of the overlying stratum into the sand, strengthening the inference for a seismic trigger (Obermeier, 1998b). As liquefaction of a sand bed requires prolonged cyclic stress (Seed, 1968), the magnitude of the "pillars" and their wide extent may be suggestive of a high-magnitude and/or long-duration seismic event. We have observed also oblique "pillars" (Fig. 10) which may have been tilted following the shaking.

The chaotic deformation structure we have encountered (Fig. 8) is a multilayered system which would also require a substantial trigger to initiate break up (Brenchley and Newall, 1977). The "giant" ball (Fig. 6) is an additional possible indicator of a large seismic trigger. The absence of additional "giant" balls, 6–8 m above the current lake level, seems to be related mainly to the lack of exposures.

9. Conclusions

We cannot provide compelling evidence of seismic triggering, such as fitting radiocarbon dates of two different and separated, but stratigraphically correlated, features to a specific historic earthquake of the same date (Bowman et al., 2001). Each of the single field criteria cannot be regarded, by itself, as diagnostic of a seismic origin. However, we suggest that the accumulated field data, observed from one of the most active seismic zones on our globe, lend credence to the diagnosis of a seismic trigger. Rossetti (1999) applied a similar approach regarding the seismic origin of deformation structures in the Sao Luis Basin, northern Brazil. We conclude that what we have observed and described are quite possibly seismites of late Upper Pleistocene age, 26–10 ka BP, over an altitudinal range of 25 m, starting from 7 m above the current lake level.

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