ACTIVE TECTONICS AND SEISMIC HAZARD OF THE ISSYK-KUL BASIN IN THE KYRGYZ TIAN-SHAN

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1. Introduction

The Issyk-Kul basin is a large intramountain depression located in the northeastern part of the Kyrgyz Tian-Shan (Fig. 1). It is bordered on both northern and southern sides by E-W trending mountain ranges rising up to 5000 meters in altitude (Fig. 2). During last 100 years, these two ranges were subjected to an unusual series of major earthquakes, some of them raking among the strongest ever felt in continental areas (Table 1; Fig. 3).

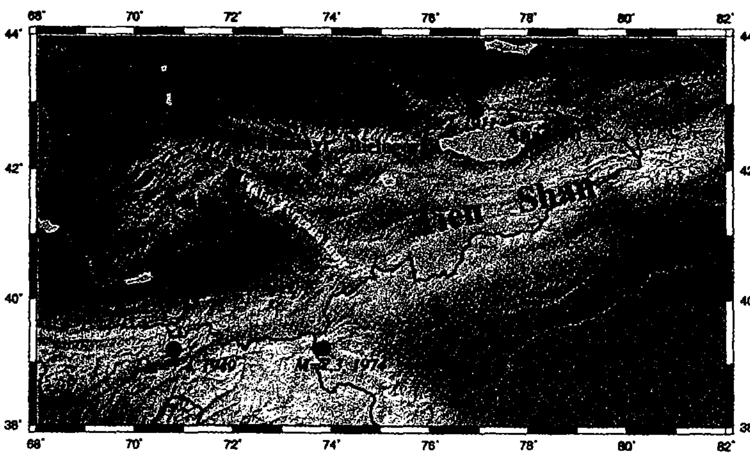

Figure 1. The Kyrgyz Tian-Shan in Central Asia, with shaded relief and location of recent strong earthquakes.

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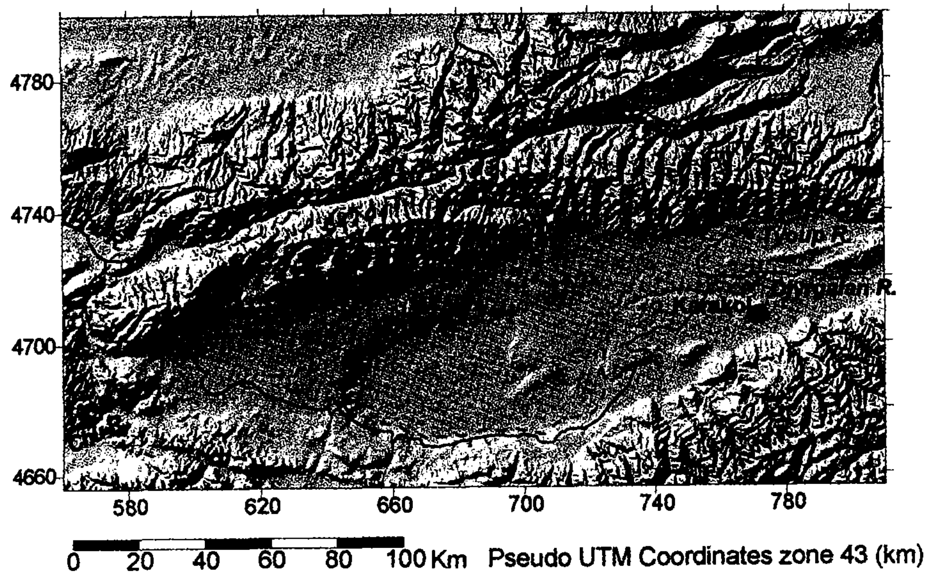


Figure 2. Digital elevation model of the Issyk-kul depression and surrounding areas. Constructed from digitised 1/200.000 topographic maps and 1/100.000 bathymetric chart of Lake Issyk-Kul. The dotted line shows the altitude of the lowest underwater terrace, highlighting a past low lake level (112 m under the present lake level).

This series started in 1887 by the (Ms=7.3) Verny earthquake near Alma-Ata. It was rapidly followed by the 1889 (Ms=8.3) Chilik, the 1911 (Ms=8.2) Kemin and the 1938 (Ms=6.9) Kemino-Chu earthquakes, in an east-to-west propagation. In reaction to this series of unusually strong earthquakes, the eastern part of the Issyk-Kul basin was later affected by the 1970 (Ms=6.8) Sarykamysh then 1978 (Ms=6.7) Djalanash-Tioup and the 1990 (Ms=6.4) Baisoorun earthquakes. Earlier seismic events in the same area are also known from historical data (1): the –250±100 Grigorevka, the 500±500 Toru-Aigir and the 1475±100 Balasogun earthquakes.

According to data of the Institute of seismology of the National Academy of Sciences Kyrgyz Republic, the level of seismic activity in the southern part of the basin is quite high but the intensity of earthquakes remained moderate, no more then 7 balls (intensity force) according to the MSK-64 scale (equivalent to Ms=6.0). A large number of small earthquakes occurred near the source of the Sarykamysh earthquake (Fig. 4). Near Kadji-Say (location on Fig. 4), earthquakes with intensity equivalent to 5-6 balls periodically took place in a cluster. The area occupied by the lake itself is surprisingly almost aseismic, with only a small number of weak events.

As a consequence of the high seismic activity in the mountain ranges bordering the lake, all the Issyk-Kul area is particularly exposed to direct and indirect effects of strong earthquakes.

TABLE 1: Strong earthquakes of Issyk-Kul basin and surrounding areas

Date Year Month Day	lat dec.deg	long dec. deg.	Ms	Shaking intensity (Balls)	Energy class K (log E)	Usual name of event	UTM X	UTM Y
-250 +/- 100	42,80	77,50	6,7	8-9	16,7	Grigorevka	704	4730
500 +/-500	42,80	76,40	6,7	8-9	15,7	Toru-Aigir	623	4730
1475 +/- 100	42,60	75,20	6,4	8-9	15,6	Balasogun	520	4716
1807 +/- 10	43,10	76,90	6,7	8-9	16,0		657	4774
1869 08 29	42,70	75,90	6,4	8	15,3		578	4730
1874 10 18	42,90	77,40	5,9	7	14,6	Aksu-Chilik	695	4751
1880 12 01	43,10	76,90	5,7	7-7	14,3		657	4774
1884 03 13	42,70	78,20	5,8	7	14,4	Tioup	762	4731
1887 06 08	43,10	76,80	7,3	9-10	16,6	Verny	646	4774
1889 07 11	43,20	78,70	8,3	10	18,0	Chilik	800	4790
1893 11 04	42,70	75,80	6	8	15,0	Chu	565	4730
1911 01 03	42,90	76,90	8,2	10-11	17,8	Kemin	659	4756
1938 06 20	42,70	75,80	6,9	8-9	16,0	Kemino-Chu	566	4728
1970 06 05	42,52	78,73	6,8	8-9	15,6	Sarykamysh	807	4712
1978 03 24	42,87	78,58	6,7	8-9	15,6	Djalanash-Tioup	794	4748
1990 11 12	42,98	77,92	6,4	8	15,0	Baisoorun	739	4775

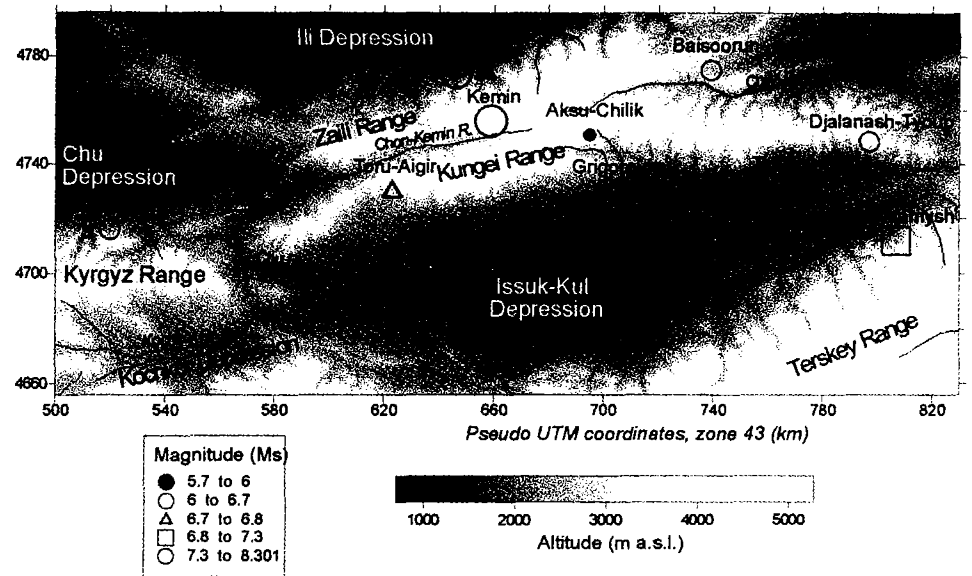


Figure 3. Issyk-Kul depression and location of strong earthquakes reported in Table 1.

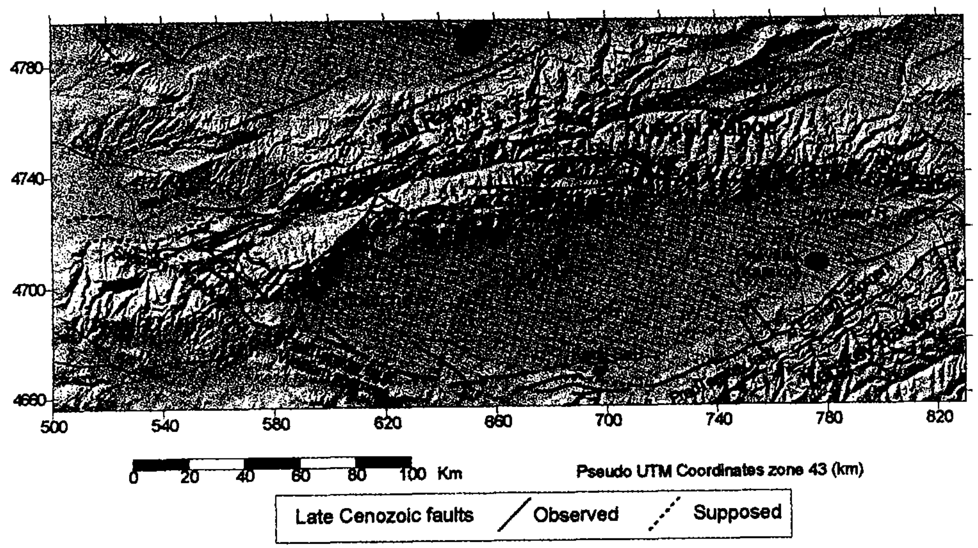


Figure 4. Undifferentiated late Cenozoic faults of the Issyk-Kul depression and surrounding area (faults active in the late Pliocene-Quaternary).

Most of this area is already characterized by critical slope stability due to the generally steep relief. Therefore strong seismic shaking can easily destabilize large rock masses and cause numerous gravity mass movements like landslides, rockfalls and rock avalanches. This aspect was the topic of an Inco-Copernicus project funded by the European Community: "Landslide Risk Triggered by Earthquakes in Kyrgyzstan, Tian-Shan".

In this article, we will first revise the recent structure of the Issyk-Kul depression, map the major faults of Late Tertiary-Quaternary age (Fig. 4) and identify those who present late Quaternary activity (Fig. 5). These late Quaternary faults are determined on the basis of morphological features (they displace Late Pleistocene or Holocene river terraces or glacial deposits). These faults are therefore considered to be seismogenic, even if no seismic activity was recorded along them during the last century.

An important part is devoted to the effects of the 1911 Kemin earthquake that affected the whole range between Lake Issyk-Kul and Alma-Ata and caused large landslides and rockslides (Fig. 6A-D). The investigation of these effects was undertaken to illustrate the potential destructive effects of such strong earthquake in mountainous areas.

Finally we briefly introduce the major approaches for estimating and mapping the seismic hazard and landslide risk of this area.

TABLE 2. Focal mechanisms of strong earthquakes for the Issyk-Kul region

Date					lat	long	H	Mag.	class	P axis		N axis		T axis		Shmax	Stress
Year	mm	dd	hr	min	deg	deg	km	Ms	K	Paz	Ppl	Naz	Npl	Taz	Tpl	azim.	regime
1970	06	05	04	52	42,50	78,90	15	6,4	15,5	013	14	106	11	231	72	13	TF
1975	02	12	13	34	43,30	78,80	15	5,0	13	337	05	240	52	072	37	337	SS
1978	03	24	08	29	42,00	79,80	30	5,6	14	067	12	331	27	178	60	67	TF
1978	03	24	08	29	41,92	79,97	15	5,1	CMT	180	17	314	66	085	16	180	SS
1979	04	06	18	30	42,00	77,40	10	5,0	13	005	46	209	41	108	12	198	NF
1979	04	06	18	30	41,92	77,74	19	4,9	CMT	008	28	272	12	160	60	8	TF
1980	07	05	20	25	41,90	77,50	15	5,6	14	116	10	212	32	010	56	116	TF
1980	07	05	20	25	41,94	77,40	15	5,2	CMT	344	01	075	29	252	61	344	TF
1983	12	21	19	30	42,07	77,45	15	5,0	13	337	09	067	01	165	81	337	TF
1982	12	31	19	46	42,75	77,01	15	5,1	CMT	159	22	063	14	303	63	159	TF
1988	06	17	13	30	43,00	77,42	20	5,0	13	330	68	149	22	59	00	149	NF
1988	06	17	13	30	43,01	77,51	15	5,3	CMT	354	39	093	11	196	49	354	TF
1990	11	12	12	28	42,98	77,91	5	6,1	15	136	15	326	75	225	03	315	SS
1990	11	12	12	28	43,18	78,24	15	6,3	CMT	162	03	257	57	070	33	162	SS
1996	01	18	09	33	41,92	77,45	5	5,0	13	005	04	274	11	115	78	5	TF
1996	01	18	09	33	42,10	77,98	20	4,6	CMT	309	14	216	11	090	72	309	TF

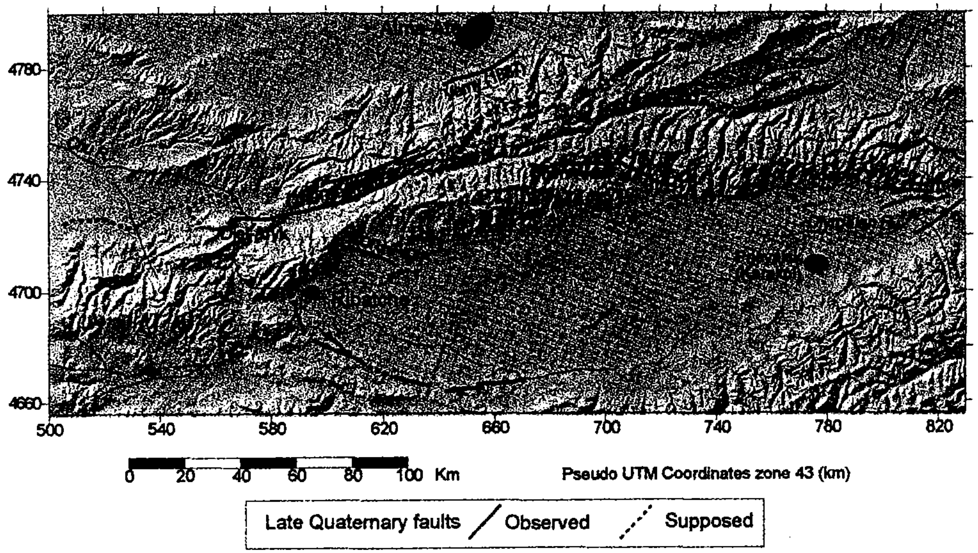
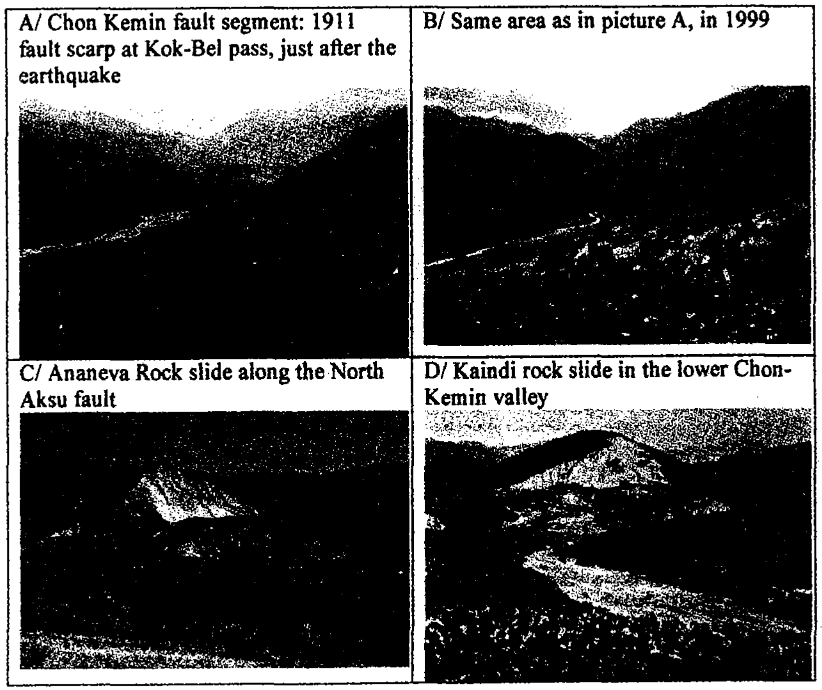


Figure 5. Late Quaternary faults of the Issyk-Kul depression and surrounding area (faults active in the Late Pleistocene - Holocene).



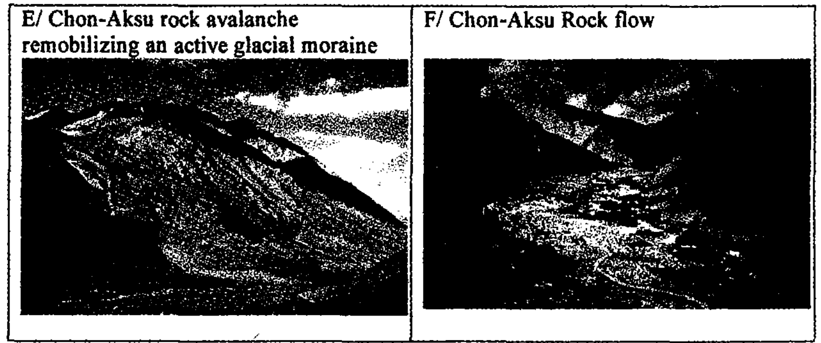


Figure 6. Photographs illustrating the effects of 1911 Kemin earthquakes (B, C, E & F: taken by D. Delvaux; A & D: reproduction of pictures published by Bogdanovitch et al. [10].

2. Recent structure of the Issyk-Kul depression and active faults

Earthquakes correspond to the sudden release of tectonic strain accumulated in rock masses by episodic movements along faults generating seismic waves. A direct implication is that the first step in the assessment of the seismic risk of an area is to identify the potential active faults. We generally consider that recent faults showing evidence for movement during late Pleistocene- Holocene (last 100-150 Ka) are active and will likely be reactivated in the nearest future. Several of such active faults are known in territory of the Issyk-Kul basin and surrounding mountain ranges (Fig. 5). They are described briefly hereafter on the background of the general Late Cenozoic structure (Fig. 4).

2.1. PREDTERSKEY SOUTH BOUNDARY FAULT ZONE

The PredTerskey boundary fault borders the Terskey Range at its foothills, along the southern margin of the Issyk-Kul basin. This fault zone is subdivided into three major segments showing different coupling between the mountain ranges and the sedimentary basin. They are referred to the Western, Central and Eastern segments.
The eastern PredTerskey fault segment is inclined 30-70 degrees to the SE, plunging under the Terskey Range. It is typically a reverse fault along which the Terskey range is transported over the Cenozoic sediments of the Issyk-Kul basin. The type section for this segment is exposed along the Dzhety-Ogyuz River and was studied recently by Cobbold et al. [2]. This segment shows no evidence for late Pleistocene and Holocene activities, but some secondary features that might be related to earthquake shaking are known. The epicenter of the Ms=6.8, 1970 Sarykamysh earthquake is located near Prjevalsk (now: Karakol) along this fault segment, at its intersection with a NW-trending transversal fault [3][4]. This earthquake caused a number of secondary

gravitational dislocations as landslides, rock avalanches and rock falls. The source mechanism indicates that this event is related to a low-angle thrusting towards the NNE.
The central segment of the PredTerskey fault is composed of two parallel faults, well expressed in the region of Kadji-Say [5] (Fig. 4). The southern fault follows closely the outcropping line of the contact between the basement and Meso-Cenozoic deposits. It is a stratigraphic contact, dipping 40-60° north, where the Mesozoic and Tertiary sedimentary rocks overlie an erosion surface over weathered granites. The northern fault runs in the middle of the Tertiary deposits, and is associated to an asymmetrical anticline. Jurassic sediments and even pieces of basement granite are injected along the fault zone. The observed microstructures show that this fault zone is dipping steeply to the south and has a transpressional character, with both reverse and right-lateral components of movement.
This deformation affected the Tertiary deposits, but did not affected the late Pleistocene terraces. The main activity of this fault zone probably occurred at the Pliocene-Pleistocene transition and in the early stages of the Quaternary.
The western segment of the PredTerskey fault zone seems to be composed of several secondary faults (Fig. 4). As opposed to the other segments of the PredTerskey fault, the fault planes are dipping north. They are generally associated to fault-propagation-folds, with brittle ruptures in the basement and monoclinal folding in the overlying Tertiary sediments. At the subsurface, such faults cut the hinge zone of the monoclines, separating the long and weakly inclined backlimb from the steeply inclined short forelimb. This deformation also occurred during the Pliocene-Pleistocene transition. However, several faults of this segment (Fig. 5) were clearly reactivated during the Late Quaternary, as indicated by the dislocation of Quaternary terraces.
According to Iudahin [7], the boundary between the central and the eastern segments of the PredTerskey fault zone corresponds to an hypothetical NW-trending Trans Issyk-Kul fault, deduced from geophysical interpretation. On a structural basis, Chedia [8] and Trofimov [24] suggested that the two segments are separated by a NE-trending transversal fault, active in late Pleistocene.

2.2. PREDKUNGEY NORTH BOUNDARY FAULT ZONE

The PredKungey fault zone delimits the Issyk-Kul basin on its northern side, separating it from the Kungey Range. It is also composed of several individual faults; from East to West: the Taldysu, North-Aksu, Kultor and Toguzbulak faults (Fig. 4).
At the extreme East, the Taldysu fault is almost vertical. It runs at the foot of the Kungey range, then it follows the Tioup valley. Along this valley, systematic morphological displacements of small streams illustrate a significant left-lateral component of movement for this fault. The 1978, Ms=6,7 Djalanash-Tioup earthquake is probably associated with this fault system. A number of gravitational dislocations were reported as a result of ground shaking during this event. Other secondary surface deformations reported by Abdrakhmatov et al. [9] evidence the high seismicity of this area during the Late Pleistocene - Holocene. Two focal mechanism solutions are available for this event: one from the Kyrgyz Institute of Seismology (KIS) and one from the Harvard CMTS catalogue. Both are compatible with NW-SE trending fault, steeply SE-dipping (KIS solution) to subvertical (CMTS).
Further to the west, the North-Aksu fault was reactivated during Ms=8.2, 1911 Kemin earthquake, described in detail in Bogdanovich et al. [10]. Several large rockslides and rock falls with millions of cubic meters in volume were triggered by this event. One of them is situated along the Aksu fault segment, near Ananeva (Fig. 6A). This fault is dipping to the north, and the Kungey range was thrusted over the basin sediments. No lateral movements could be observed along this fault segment. To the west, the Aksu fault is relayed by the Chon-Aksu fault (Fig. 6C-D). It looks similar as the Aksu fault and runs trough the Kungey range itself, in the direction of the Chon-Kemin valley. It was also activated by the same 1911 Kemin earthquake and had also a reverse faulting mechanism. Several large rock avalanches and a debris flow (Fig. 6B) occurred in the upper reaches of the Chon-Aksu valley as the result of this earthquake.
Near Cholpon-Ata, the Kultor fault has a complicated structure. At its eastern extremity, it is reverse fault dipping under the Kungei range. To the west it changed into an en-échelon south-dipping thrust, uplifting the lower part of the range relatively to the upper one. As evidence for late Pleistocene activity, it is offsetting glacial moraines from the last glaciations.
In the Toru-Aigir area, the Toguz Bulak fault has a complex structure. It evolved in several stages during the late Tertiary and the Quaternary. The most recent activity occurred along a WNW-trending fault with a clear geomorphic expression (Figs. 4, 5).

2.3. CENTRAL PART OF ISSUK-KUL BASIN

The tectonic position of the central part of the basin occupied by Lake Issyk-Kul is not clear. The digital elevation model combining topographic and bathymetric maps illustrates the underwater morphostructure of Lake Issyk-Kul (Fig. 2). In particular, a series of steps were mapped at differed water depth. The most prominent one is at 110 meters of water depth (1495 meters above sea level). They likely correspond to underwater abrasive terraces that whiteness past low lake levels. Some investigators [6] [24] relate the lowering of lake level to a rapid tectonic collapse of the central part of the basin in the Holocene (5-7 Ka). Others believe that these terraces reflect dryer climatic conditions during or at the end of the last glacial cycle, followed by progressive lake expansion in the late Pleistocene.
Independently to this controversy, the central part of the basin appears as a fault-controlled tectonic depression with a trapezoid structure [25]. It is apparently bounded by normal faults on both its northern and southern margins [4].

2.4. CHON-KEMIN - CHILIK FAULT ZONE

The Chon-Kemin - Chilik fault zone runs in the middle of the area comprised between Lake Issyk-Kul and the Kazakhstan platform (Fig. 4). It broadly corresponds to the Chon-Kemin and the Chilik river valleys, respectively in Kyrgyzstan and in

Kazakhstan. This fault zone separates the Kungey range from the Zaili range. It mainly reactivates an important late Paleozoic fault zone [11].
The Cenozoic structure of this zone is interpreted in several ways. Some investigators suggest that the narrow Chon-Kemin valley is bounded by thrust faults. Other consider that it is bounded by normal faults [12][13]. Only recently, detailed investigations in the frame of the Copernicus project by Delvaux et al. [14] evidenced that these faults present a significant left-lateral component of displacement and that the whole structure has to be regarded as a sinistral transpressional fault zone.
Besides recent landslides and dislocations caused by the 1911 Kemin earthquake (described hereafter), several impressive rock avalanches and long-term paleoseismic fault scarps testify for repeated paleoseismic activity during the late Pleistocene, with earthquakes at least as strong as the Kemin one.

3. The 1911, Ms 8.2 Kemin earthquake

The 3 January 1911 (22 December 1910 following the Orthodox calendar), at 23H25, the Zaili-Kungei mountain ranges between Lake Issyk-Kul and Alma-Ata was hit by one of the strongest earthquake ever felt in the center of a continent: the Kemin earthquake of surface magnitude Ms=8.2 on the Richter scale. The epicentre was located near the junction between the Chon-Kemin, Chilik and Chon-Aksu valleys (Fig. 3).
The number of casualties was relatively low for such a strong earthquake, because it affected mainly mountainous areas and people used to live in yurts. However landslides, rock avalanches and rock falls triggered by the earthquake caused a lot of destructions. The following destructions were reported by Bogdanovitch et al. [10]: 452 persons killed, 740 persons injured, 1094 houses destroyed, 4545 yurts destroyed and 12962 cattle head killed.
The surface effects of the 1911 Kemin earthquake have been investigated only a few months after the event by an expedition led by K.I. Bogdanovitch in spring 1911 [10]. Since then, no further detailed investigations were performed on the seismotectonic expression of the Kemin earthquake, except by Kuchai [26], who revisited briefly the area. In the frame of the European Community Inco-Copernicus project "Landslide Risk Triggered by Earthquakes in Kyrgyzstan, Tian-Shan)", the surface effects of the Kemin earthquake were re-investigated along the Chon-Kemin, Chon-Aksu and Aksu valleys in the Kyrgyz territory only.
Combining the observations of Bogdanovitch et al. [10] and the recent observations (Delvaux et al., 2001) it can be precised that the 1911 Kemin earthquake generated nearly 190 km of surface ruptures along six different fault segments totalling 260-300 km long. The surface rupture created new lakes by damming rivers and diverting the water flows.
Along the E-W trending Chon-Aksu fault segment, paleoseismic trenching across a 18 meter-high multi-event fault scarp allowed to recognise the effects of at least 4-5 past strong earthquakes. It confirmed the reverse faulting character of that segment.

The maximum height of the fault scarp associated to the 1911 event along the Chon-Aksu and Aksu valleys ranges between 6 and 10 meter high (Fig. 6 C-D). A left-lateral component of movement between 5 and 8 meter was observed along the Chon-Kemin valley.
The earthquake caused also numerous landslides, rockslides, rock avalanches, debris flows and secondary soil dislocations over a total area of 10.000 square kilometres (200 km long, 70 km wide), elongated parallel to the fault zone. The largest rock avalanches reached 15 million of cubic meters in volume (the Ananeva rockslide, Fif. 6A). The Kaindi rockslide itself killed 38 persons in a yurt camp in the lower Chon-Kemin valley.
Several rock avalanches occurred in high-mountain areas, along the upper reaches of the Chon-Kemin and Chon-Aksu valleys. They were caused by the collapsing of steep walls of glacial valleys at high altitude. The huge mass of debris covered active glaciers and their moraines, destabilizing the whole system and moved rapidly down to the main valley, more than 1000 meter lower. They partly blocked the main valleys.
An impressive delayed effect of the Kemin earthquake is the Chon-Aksu debris-flow (Fig. 6B). It happened several months to several years after the earthquake, because it was not seen on a photograph taken by the team of Bogdanovitch and published in [10]. This was formed by a gigantic collapse of an old large glacial moraine accumulation and the debris flow submerged the Chon-Aksu valley along 2,5 km. It occurred right along the trace of the active fault. The following mechanism of formation is suggested. The earthquake destabilised the moraine accumulation and water infiltrated along open fractures. It saturated progressively the fluvio-glacial material. Suddenly the whole mass moved in a catastrophic way and rushed to the alluvial plain as a large mudflow supporting large boulders of granite. It washed out the bottom of the valley over 2,5 km long, stripped away all the trees along its way and partly dammed the valley. The mass of the debris flow is estimated at 20 million of cubic meters.

4. Seismic hazard of Issyk-Kul basin

Several approaches were tested for the evaluation of seismic hazard of the Kyrgyz territory (Abdrakhmatov et al. [9] and earlier works).
The traditional approach is an expert evaluation scheme. It takes into account the history of geological development of the territory and its block structure (Petrushevskiy, 1968), the boundary conditions [18] and the influence of Cenozoic activation expressed in a quantitative way [19]. In addition, characteristic data derived from the investigation of paleoseismic dislocations are also taken into account [20][21].
Seismogenic zones (zones prone to earthquake activity) are delimited on the basis of combined geological and geophysical approach. The data on active faults are considered with the highest attention, as they might concentrate future seismic activity. The maximum possible earthquake magnitude can be evaluated from the historical data and instrumental seismicity. Such approach was used by Djanuzakov et al. [22] to produce the seismic hazard map of Kyrgyzstan compiled in 1995. Seismic hazard zones are classified in terms of balls - intensities. This map shows that the Kungei and Zaili

ranges between Lake Issyk-Kul and Alma-Ata and the Terskey range south and east of Prjevalsk (Karakol) have the highest intensity, with expected magnitudes larger than 7.5. This is a direct consequence of the strong historical and instrumental seismicity recorded in these area.

A more modern approach for the seismic hazard assessment is to construct probabilistic seismic hazard and Arias Intensity maps. This was performed in the frame of the Copernicus project, and the results are being published (Havenith et al., 2000; Havenith et al., in preparation). On the basis of seismicity (from the Kyrgyz and world seismic catalogues) and active tectonics, seismic zones are defined for the whole Kyrgyz Tian-Shan. Gutenberg-Richter laws are defined mainly from instrumental data and empirical attenuation laws are used. The probabilistic maps obtained present results in terms peak ground acceleration (PGA, in g), for defined periods (50 or 100 years) and with 90% probability of non-exedence.

This approach shows that large earthquakes can be expected in the whole region comprised between Lake Issyk-Kul and Alma-Ata (Chilik-Kemin region), and that the town of Alma-Ata is particularly at risk. Similarly, the Arias Intensity approach shows that the Chilik-Kemin region has the highest hazard for landslides triggered by earthquakes, due to the combination of strong Arias Intensities and steepness of the topography.

5. Acknowledgements

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