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Strong paleoearthquakes along the Talas-Fergana Fault, Kyrgyzstan

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Abstract: The Talas-Fergana Fault, the largest strike-slip structure in Central Asia, forms an obliquely oriented boundary between the northeastern and southwestern parts of the Tianshan mountain belt. The fault underwent active right-lateral strike-slip during the Paleozoic, with right-lateral movements being rejuvenated in the Late Cenozoic. Tectonic movements along the intracontinental strike-slip faults contribute to absorb part of the regional crustal shortening linked to the India-Eurasia collision; knowledge of strike-slip motions along the Talas-Fergana Fault are necessary for a complete assessment of the active deformation of the Tianshan orogen. To improve our understanding of the intracontinental deformation of the Tianshan mountain belt and the occurrence of strong earthquakes along the whole length of the Talas-Fergana Fault, we identify features of relief arising during strong paleoearthquakes along the Talas-Fergana Fault, fault segmentation, the length of seismogenic ruptures, and the energy and age of ancient catastrophes. We show that during neotectonic time the fault developed as a dextral strike-slip fault, with possible dextral displacements spreading to secondary fault planes north of the main fault trace. We determine rates of Holocene and Late Pleistocene dextral movements, and our radiocarbon dating indicates tens of strong earthquakes occurring along the fault zone during and interval of 15800 years. The reoccurrence of strong earthquakes along the Talas-Fergana Fault zone during the second half of the Holocene is about 300 years. The next strong earthquake along the fault will most probably occur along its southeastern chain during the next several decades. Seismotectonic deformation parameters indicate that $M>7$ earthquakes with oscillation intensity $I>$IX have occurred.

Key words: Tianshan region; Talas-Fergana fault; ancient earthquake; palaeoseismology; earthquake reoccurrence

1 Geological-tectonic structure and evolution of the Talas-Fergana Fault in the Cenozoic

The Talas-Fergana Fault is the largest strike-slip structure in Central Asia. It forms an obliquely oriented boundary between the northeastern and southwestern parts of the Tianshan mountain belt (Fig.1). The last portion includes the Fergana Depression, the Chatkal-Kurama mountain system, and the Alay valley. A wide belt of latitudinal oriented ranges, which are located between the Kazakh platform and the Tarim Basin, represents the northeastern Tianshan.

Most researchers interpret the Talas-Fergana Fault as a right-lateral strike-slip fault active in the Paleozoic, with right-lateral movements being rejuvenated in the Late Cenozoic because of crustal shortening linked to the India-Eurasia collision. Tectonic movements along

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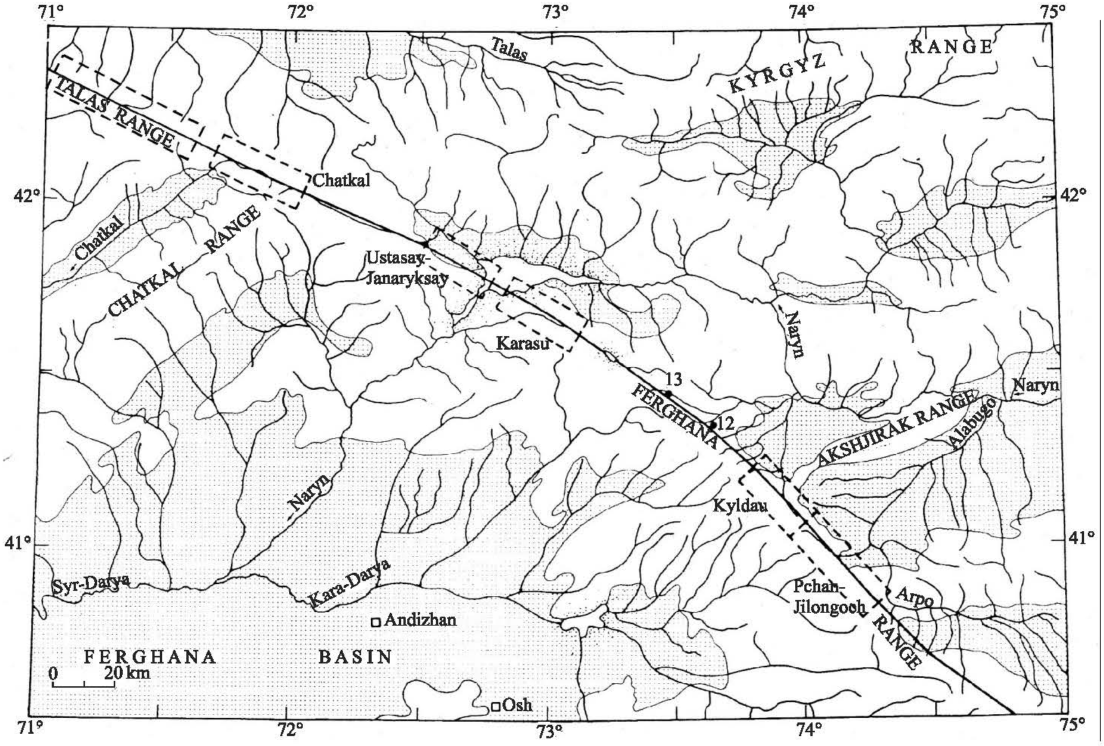

Figure 1 The Talas-Fergana Fault line and adjacent territories (modified after the reference [1]); dashed rectangular boxes show the studied portions of the fault; sedimentary basins are indicated by uniformly dotted filling; irregularly dotted areas indicate lakes and reservoirs; numbers along the fault line are observation points Nos. 12 and 13 from the reference [1].

the intracontinental strike-slip faults contribute to absorb part of the regional crustal shortening. Strike-slip motions along the Talas-Fergana Fault are necessary for a complete assessment of the active deformation of the Tianshan orogen.

Our focus is to improve the understanding of the intracontinental deformation of the Tianshan mountain belt and the occurrence of strong earthquakes along the whole length of the Talas-Fergana Fault. The aim of this work is to identify features of relief arising from strong paleoearthquakes along the Talas-Fergana Fault, fault segmentation, the length of the seismogenic ruptures, and the energy and age of ancient catastrophes. These data are critical for complete seismic hazard assessment for a territory with an absence of historical seismicity records.

Many researchers[1-11] have performed detailed paleoseismological studies of the Talas-Fergana Fault zone. Some of them[1,3,7-8,10-11] collected samples for radiocarbon dating. Because the organic material was deposited later than the formation of the upslope-facing scarp, displacing channels of gullies, and the watershed, the radiocarbon dates point to minimum ages of the events that led to displacement of relief forms along the fault zone.

The features developed along the fault zone that indicate seismic rupturing of the upslope-facing scarp affirm that the Talas-Fergana Fault has been active until present. Because of the fault's morphologic and kinematic characteristics, most researchers believe that it is a right-lateral strike-slip fault, with displacement amplitudes along it ranging from hundreds of meters to 12-14 km during the Cenozoic[10,12]. The most recent summary of previous investigations of the Talas-Fergana Fault is cited in a book and several papers[6-9,13].

This study is not only of pure scientific interest-the Talas-Fergana Fault passes in close proximity to the largest hydroelectric plant in Central Asia, the Toktogul hydropower station, behind which sits an artificial dam containing 19.5 km^3 of water. A strong earthquake occurring along the Talas-Fergana Fault could cause deformation or destruction of the dam. Such an event would bring untold harm and create numerous victims downstream along the Naryn River valley, as well as in the Fergana Depression, which has population of >10 million people.

2 Methodology

In addition to performing traditional field investigations, interpreting aerial and satellite images, and studying existing archive and published literature, we have conducted detailed mapping of selected key test sites: the Kara-Bura site in a region of the Kara-Bura Pass across the Talas Range, the Sary-Bulak test site at the head of the Sary-Bulak River (the left tributary of the Uzun-Akhmat River), and the Kok-Bel test site in a region of the Kok-Bel Pass on the "Bishkek-Osh" highway.

At the studied test sites, the Talas-Fergana Fault line usually goes across the slope of one of river valleys or a ridge slope. Along the line, there is usually a fault scarp in the form of a swell. The height of this scarp usually ranges from several tens of centimeters to a few meters. At the studied test sites, numerous broken forms of modern relief were found, including valleys of temporary waterways and watersheds between them, the upper parts of which are shifted horizontally to the right, a distance from several tens of meters to several hundred meters.

The identical width and morphology of the shifted parts of the dry valleys above and below the fault line indicate that the shift occurred quickly. This allows linking such shifts with earthquakes[3].

The majority of the shifted valleys of temporary waterways have remained below the fault line, where on the slope at earthquake a fault was formed in the shape of a swell. This scarp isolated the lower continuation of the broken valley, while seasonal waters found other drainage outlets, washing away the scarp in the lowest places. The isolated part of the valley could then further continue to be displaced along the fault.

For ascertaining the time of movements along the Talas-Fergana Fault, the indirect method of the reference [14] was used. As a scarp formed on the slope along the fault line, a depression was also formed. This scarp impounded the waters flowing down the slope and filtering along the fault plane, which created conditions for swamping of the depressions in the vicinity of the fault. The beginning of the formation of a peat swamp and a thick soil layer indicate the occurrence of a fault scarp that accompanied horizontal displacement along the fault.

For determining the age of these formations, we took samples of organic material prospected in impounded parts of the valleys from bore pits for radiocarbon analysis. Radiocarbon dates based on the sum of organic substance accumulated during some period of time are always earlier compared to the time when accumulation began. Determination of the residual activity of carbon was carried out on a Quantulus-1220 liquid scintillation counter (PerkinElmer, USA) at the Institute of Geology and Mineralogy of the Siberian Branch of the Russian Academy of Science, Novosibirsk. For age calculations, the half-life of ^{14}C was used (5570 years). The age was calculated from 1950. Age determination was made based on fraction of humic acids.

3 Parameters of paleoearthquakes occurring along the Talas-Fergana Fault

We have collected all absolute dates of paleoearthquakes occurring along the Talas-Fergana Fault obtained by us and combined them in figure 2 with data obtained earlier[1, 3, 10-11]. A total of 55 dates in 14 localities were collected from the Late Pleistocene to the Holocene.

An analysis of figure 2 has led us to conclude that the Talas-Fergana Fault zone can be generally divided into three chains according to peculiarities of the lateral distribution of earthquakes: 1) a northwestern chain starting from the Kurkureusu River valley in westernwest Kyrgyzstan and stretching to about the Sary-Bulak River valley in the Ketmen'-Tyube Depression; 2) a central chain stretching toward the southeast from the Sary-Bulak River valley to the Urumbash River (Kazarman Depression) inclusively; and 3) a southwestern chain starting from the Kyldau River valley and ending in the southern border region of the Kyrgyz Republic. We recognize the somewhat artificialness of our division, especially since no account is taken of records on the Talas-Fergana Fault from Kazakhstan and China.

Because of uneven investigations and the sparseness

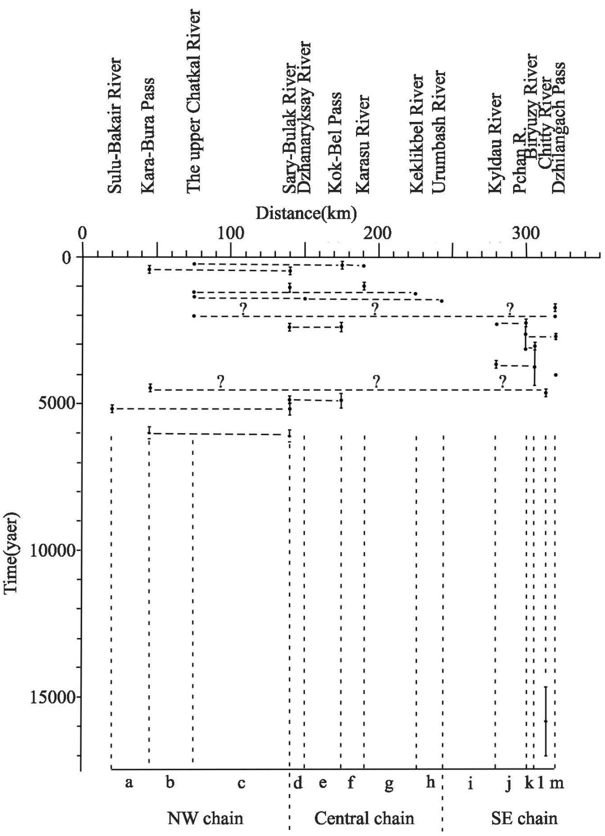

Figure 2 Distribution of earthquakes and segmentation along the zone of the Talas-Fergana Fault within the Kyrgyz Republic

of existing records, one has to discuss segmentation of the Talas-Fergana Fault zone with great care. According to existing data, we selected 13 segments: 3 in the northwestern chain of the fault, 5 or 6 in the central chain, and 4 or 5 in the southeastern chain (Fig.2).

An analysis and comparison of materials of figure 2 have allowed us to identify 18 paleoseismic events, 17 of which occurred in the second half of the Holocene (Fig.3). We also assessed distances between localities (Tab.1) where there were determined absolute ages of seismogenic displacements that occurred (supposedly) during one seismic event. We conditionally accepted these distances as minimum lengths of the seismogenic ruptures.

Some of the extreme values of rupture lengths, such as 270 and 220 km for earthquakes occurring 4530 and 1980 years ago, arouse some doubt as to their accuracy. Although such lengthy seismogenic ruptures are possible, the known strong historical earthquakes in the northern Tianshan exhibit maximum rupture lengths barely reaching 200 km (for example, the Kebin (Kemin) earthquake of 1911[15]). It is possible that in such (and probably in some other) cases, an artificial unification of different earthquakes occurring in different parts of the fault but in close temporal proximity took place. Nevertheless, one cannot exclude the possibility of propagation of many segments along almost the whole plane of the Talas-Fergana Fault (e.g., during the two earthquakes discussed there were 11 segments united in 3 chains of the fault). An example of such propagation in the Tianshan is the Kebin earthquake of 1911 ($M > 8$), during which there was a propagation of 6 fault segments of the fault zone closely related in time[16].

The temporal distribution of paleoearthquakes along the Talas-Fergana Fault (for exclusion of individual "jumps") provides clear evidence (Fig. 3). From 6000–4500 years ago, strong earthquakes occurred in the northwestern chain of the fault. Then, 4500–2500 years ago, seismic activity extended to the southeastern

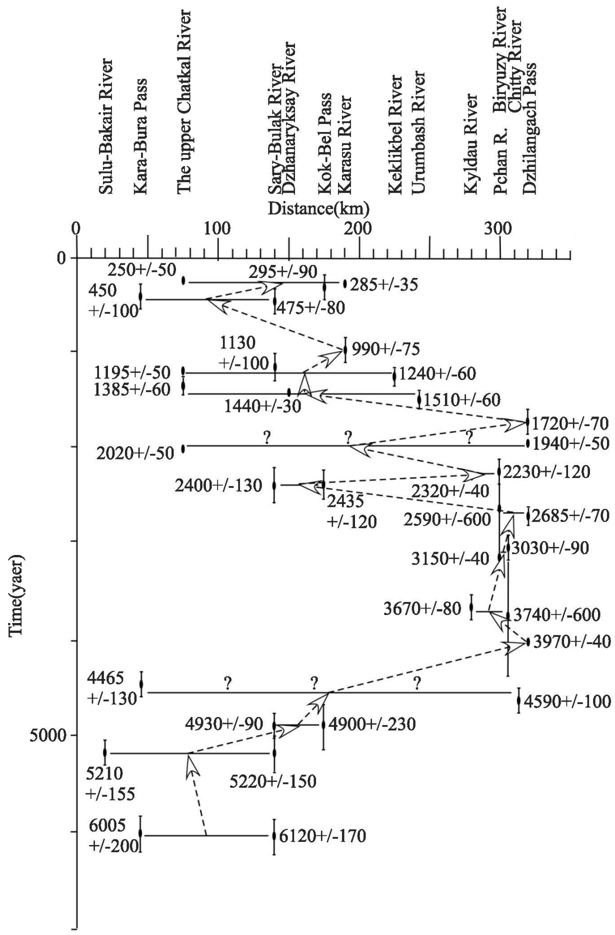

Figure 3 Migration of earthquakes along the Talas-Fergana Fault zone in the Holocene

Table 1 Average (calculated) ages of strong earthquakes occurring in the Talas-Fergana Fault zone in the Holocene, the interval between them, and the minimum length of the seismogenic rupture

No	River valley or name of the segment where an earthquake has occurred	Minimum length of the rupture (km)	Average (calculated) age of the earthquake (years ago)	Interval between given and previous earthquakes
1	Region of the Kara-Bura Pass to the Sary-Bulak River valley	100	6065	
2	The Sulu-Bakair River valley to the Sary-Bulak River valley	120	5215	850
3	The Sary-Bulak River valley to the Kok-Bel Pass	40	4915	300
4	Region of the Kara-Bura Pass to the Chitty-Western River valley	270?	4530	385
5	A region of the Dzhilangach Pass	?	3970	560
6	The Kyldau River valley to the Burguzy River valley	30	3705	265
7	The Pchan River valley to the Birguzy River valley	10	3090	615
8	The Pchan River valley to the Dzhilangach Pass	20	2640	450
9	The Sary-Bulak River valley to the Kok-Bel Pass	40	2420	220
10	The Pchan River valley	?	2275	145
11	Head of the Chatkal River valley to a region of the Dzhilangach Pass	220?	1980	295
12	A region of the Dzhilangach Pass	?	1720	260
13	Head of the Chatkal River valley to the Urumbash River valley	170	1445	275
14	Head of the Chatkal River valley to the Keklikbel River valley	150	1190	255
15	The Karasu River valley	?	990	200
16	A region of the Kara-Bura Pass to the Sary-Bulak river valley	100	465	525
17	Head of the Chatkal River valley to the Karasu River Valley	120	275	190

chain. From 2500−1500 years ago, strong earthquakes occurred in the central and southeastern chains of the fault. Then, 1500−250 years ago, seismic activity became concentrated in the northwestern and central chains. How the fault will behave in the future is not clear. Two variants can be proposed: Seismic activity will either continue in the northwestern and central chains of the fault or most probably extend to its southeastern chain, where there is currently a so-called aseismic gap (with the last earthquake there having occurred 1720 year ago!).

An important question for long-term forecasting of strong earthquakes is their reoccurrence interval. We have calculated intervals between strong earthquakes along the Talas-Fergana Fault during the second half of the Holocene (Tab.1) where representation of earthquakes is more complete. The intervals range from 145 to 850 years. Thus, the average calculated reoccurrence interval of earthquakes along the whole zone of the Talas-Fergana Fault is 375 years. However, taking an arithmetic mean value is not the best way to characterize natural phenomena. A comparison of the number of strong earthquakes along the fault with the interval of their occurrence (Fig. 4) has allowed us to discern three clear peaks of earthquake occurrence in the second half of the Holocene divided by intervals of 300 years.

Based on these findings, we can suppose that the next strong earthquake ($M > 7$) most probably will occur in about 25 years: 300−275 years (the age of the last strong paleoearthquake in the southeastern chain of the Talas-Fergana Fault).

Our segmentation of the Talas-Fergana Fault zone using existing data (Fig. 2) yielded 13 segments (from

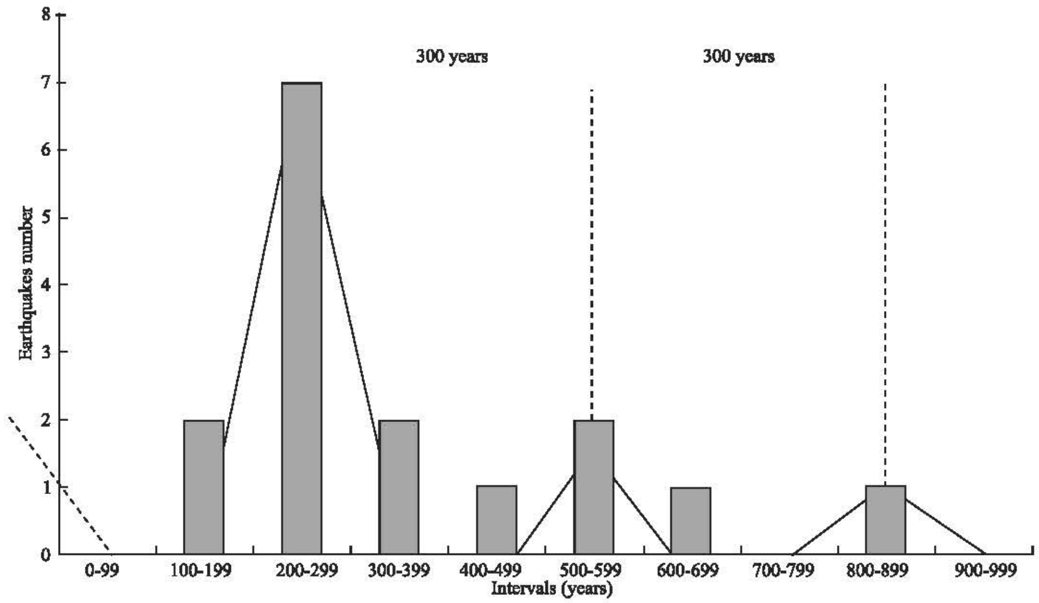

Figure 4 Comparison of the number of strong earthquakes along the Talas-Fergana Fault with intervals of their occurrence

"a" to "m"). We also mentioned that previous studies[16] revealed that during strong Tianshan earthquakes, a unification of several segments of the fault zone can take place. We pointed out above that during the Kemin earthquake of 1911 ($M=8.2$), a unification of 6 segments of the Chilik-Kemin seismogenic zone (of total length = 200 km) took place[16]. The same unification of segments could take place also during strong earthquakes that occurred along the Talas-Fergana Fault zone (Tab.2).

We have analyzed a number of formulas for determining the magnitudes of paleoseismic catastrophes according to parameters of seismic rupture published by different investigators[17-19]. Let us investigate their formulas for magnitude assessment by using the length of the seismogenic rupture expressed at the surface and checking these results on measured parameters of the fault scarps and the instrumental magnitude of the Tianshan's Suusamyr earthquake of 1992 occurring in the depression of the same name.

During the earthquake, at the surface only two short seismogenic ruptures occurred; they had a total length of 4 km and were separated by a distance of 26 km[20]. The magnitude assessed instrumentally was $Ms = 7.3$. As was discussed above, in this case we have to deal with a so-called blind seismogenic rupture, only the larger part of which reached the surface.

Let us assume that the total length of the rupture (L) was 4 + 26 km = 30 km. From the formula of the reference [18] (for earthquakes of the Lake Baikal and Caucasus regions), we get

$$M=0.6 \log L+6=6.89 \quad (1)$$

From the reference [17] (from data on Central Asian earthquakes), we get

$$M=6.61+0.55 \log L=7.42 \quad (2)$$

From the formula of the reference [19] (from worldwide data), we get

$$M=5.08+1.16 \log L=6.79 \quad (3)$$

These calculations show that the data on earthquake parameters of the Lake Baikal and Caucasus regions[18], as well as world data[19], underestimate the magnitude of the Suusamyr earthquake compared with the instrumental value. In contrast, the formula from the reference [17], calculated for earthquakes of Central Asia, gives a value that is only on 0.1 higher than the instrumental value. This is a very good result, especially given that the accuracy of magnitude determination by using such a method is ±0.5 magnitude units. This is why we based our magnitude assessments on the formula from the reference [17], which was deduced for Central Asia.

Table 2 Lengths of the seismogenic ruptures along the Talas-Fergana Fault zone and possible magnitudes of earthquakes

No	River valley or fault segment where the earthquake has occurred	Minimum length of the rupture (km)	Number of united or propagated segments (see Fig.2)	Possible maximum magnitude of the paleoearthquakes
1	A region of the Kara-Bura Pass to the Sary-Bulak River valley	100	2 (b, c)	7.71
2	The Sulu-Barair River valley to the Sary-Bulak River valley	120	3 (a-c)	7.75
3	The Sary-Bulak River valley to the Kok-Bel Pass	40	2 (d, e)	7.49
4	A region of the Kara-Bura Pass to the Chitty-Western River valley	270	11 (b-l)	7.95
5	A region of the Dzhilangach Pass	?	?	?
6	The Kyldau River valley to the Birguzy River valley	30	2 (j, k)	7.42
7	The Pchan River valley to the Birguzy River valley	10	1 (k)	7.16
8	The Pchan River valley to a region of the Dzhilangach Pass	20	3 (k-m)	7.33
9	The Sary-Bulak River valley to a region of the Kok-Bel Pass	40	2 (j, k)	7.49
10	The Pchan River valley	?	?	?
11	Upper part of the Chatkal River valley to a region of the Dzhilangach pass	220	11 (c-m)	7.90
12	A region of the Dzhilangach Pass	?	?	?
13	An upper part of the Chatkal River valley to the Urumbash River valley	170	6 (c-h)	7.84
14	An upper part of the Chatkal River valley to the Keklikbel River valley	150	5 (b-g)	7.81
15	Karasu River valley	?	?	?
16	A region of the Kara-Bura Pass to the Sary-Bulak River valley	100	2 (b, c)	7.71
17	An upper part of the Chatkal River valley to the Karasu River valley	120	4 (c-f)	7.75

Our calculations (Tab.2) have shown that, according to paleoseismological data along the Talas-Fergana Fault zone, earthquakes with magnitude $M>7$ can occur and, during unification of many segments (up to 11), the maximum magnitude can reach $M=8$. One cannot exclude however the possibility that, along the fault zone, two or more independent earthquakes divided by short time intervals can occur. Such short intervals cannot be discerned because of the limitations of the radiocarbon dating method. It is possible that there was a clustering of earthquakes along the seismogenic zone. Such clustering of strong earthquakes in the Tianshan took place from the end of the 19th century to the beginning of the 20th century, when four strong earthquakes occurred along the so-called Northern Tianshan Seismic Zone during only 26 years: the Belovodsk earthquake of 1885 ($M_{LH}=6.9$), the Verny earthquake of 1887 ($M_{LH}=7.3$), the Chilik earthquake of 1889 ($M_{LH}=8.30$), and the Kebin earthquake of 1911 ($M_{LH}=8.2$[21]). If paleoseismologists study the consequences of those earthquakes in 1911 using radiocarbon dating, then, because of limitations of the method, they find that different segments of the Northern Tianshan seismogenic zone activated simultaneously in 1900±50 CE.

Thus we understand the conditional and approximate nature of the above-cited attempts to conduct a segmentation of the Talas-Fergana Fault zone and calculate the magnitudes of paleoearthquakes by using such scanty data along only the 350 km extent of the fault zone in Kyrgyzstan. However, one has to begin with at least an initial baseline. Future data on ages of displaced relief elements and full-fledged paleoseismological trenching that crosses the whole fault zone will help to more precisely refine these numbers.

4 Conclusions

1) Our study along the Talas-Fergana Fault zone, as well as analysis of published data, has shown that during neotectonic time, the structure developed as a dextral strike-slip fault. It is possible that dextral displacements are spread also on secondary fault planes north of the main fault trace.

2) Based on our absolute dating data, as well as those of previous researchers, the rates of Holocene and Late Pleistocene dextral movements were determined to be 0.4–1.9 cm/year.

3) The whole zone of the Talas-Fergana Fault is marked by well-developed paleoseismic deformations (upslope-facing scarps and fault scarps), as well as by horizontal displacements of the relief forms. In association with these features are numerous seismogravitation forms (rockslides and landslides).

4) Collected data on the absolute age of these deformations determined by radiocarbon dating indicate that > 18 strong earthquakes occurred along the fault zone during the interval of 275–15800 years ago.

5) The reoccurrence interval of strong earthquakes along the Talas-Fergana Fault zone during the second half of the Holocene is about 300 years.

6) From peculiarities of the lateral distribution of earthquakes, the zone of the Talas-Fergana Fault by can be divided into 3 chains and 13 segments: ① a northwestern chain starting from the Kurkureusu River valley in westernmost Kyrgyzstan and stretching up to about the Sary-Bulak River valley in the Ketmen'-Tyube Depression; ② a central chain stretching toward the southeast from the Sary-Bulak River valley up to the Urumbash River valley (Kazarman Depression) inclusively; and ③ a southeastern chain starting from the Kyldau River valley and ending in the southern border region of Kyrgyzstan.

7) The next strong earthquake along the fault will most probably occur along its southeastern chain during the next several decades.

8) Seismotectonic deformation parameters indicate that $M > 7$ earthquakes with oscillation intensity $I >$ IX have occurred. These data have to be taken into account when compiling a new map of the seismic zoning of the Kyrgyz Republic.

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