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Morphotectonics and Paleoseismology of the eastern end of the Bolnay fault (*Mongolia*)

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Abstract

The Bolnay (Hangayn) fault is an active shear system which generated the $M = 8.2–8.5$ Bolnay earthquake of 23 July 1905, one of world's largest recorded intracontinental event. The fault follows the Mesozoic suture formed during closure of the Mongolia–Okhotsk ocean. Late Cenozoic faulting in the region was induced by propagation of strain from the India–Eurasia collision that had reached Mongolia about 5 ± 3 Ma ago. The left-lateral strike slip almost all over the fault length is compensated in its western end by Late Quaternary reverse motion. We estimated coseismic slip associated with the event of 1905 and the previous earthquakes in the eastern fault end and checked whether vertical offset compensates the strike slip in this part as well. The 1905 coseismic slip measured from a displaced dry stream bed and pebble bars in the Hasan-Gol river valley was 6.5–7.5 m. The 13 ± 1 m left-lateral displacement of pebble bars in the same valley represents a cumulative slip of two events. Paleoseismological studies across the strike of surface ruptures reveal at least two generations of rupture in two events that postdated the deposition of sediments with a ^{14}C age of 4689 ± 94 yr. Hypsometry of the alluvial surface in the zone of deformation shows gradual elevation increase toward the mountains, but without abrupt change across the fault. This means the absence of vertical offset and reactivation of the fault as a left-lateral strike slip. The horizontal slip in the eastern extension of the Bolnay fault is compensated rather by parallel fault-bounded pull-apart basins trending northeastward oblique to the principal fault strike. The age of their sedimentary fill suggests no older than middle Pleistocene normal faulting that compensated the Bolnay strike slip.

Keywords: strike-slip fault; morphotectonics; paleoseismology

Introduction

The Bolnay (Hangayn) fault is an active shear system which generated the $M = 8.2–8.5$ Bolnay earthquake of 23 July 1905, one of world's largest recorded intracontinental event (Baljinnyam et al., 1993; Khilko et al., 1985; Schlupp and Cisternas, 2007). The W–E Bolnay fault extends from the northern Hangayn mountains in the east to the Great Lakes Basin in the west (Fig. 1). The 375 km long surface rupture first described by Voznesensky (1962) and resurveyed later (Khilko et al., 1985; etc.) corresponds to a left-lateral strike slip. The fault follows the Mesozoic suture associated with closure of the Mongolia–Okhotsk ocean; Late Cenozoic faulting in the region was induced by propagation of strain from the India–Eurasia collision that had reached Mongolia about 5 ± 3 Ma ago (Jolivet et al., 2007). Motions for the past ~1.5 Ma produced a total left-lateral displacement of ~4 km inferred from studies in the western and central parts of the fault (Rizza et al., 2015). This study focuses on the eastern end, which lies at the transition from compression predominant in northern Mongolia to extension southeast of Lake Baikal (in Transbaikalia).

According to previous morphotectonic studies in the central Bolnay fault (Rizza et al., 2010), slip rates in its two segments range from 2.6 ± 0.7 to 3.15 ± 0.9 mm/yr, and the mean horizontal slip rate for the Late Pleistocene–Holocene period is 2.7 ± 0.3 mm/yr (Rizza et al., 2015). These estimates are consistent with GPS measurements indicating strain accumulation rates about 2.6 ± 1.0 mm/yr (Calais et al., 2003).

The 1905 event produced coseismic slip which was estimated to vary from 8 ± 2 m to 11 ± 2 m, with only 5 ± 2 m in the western fault flank (Baljinnyam et al., 1993; Khilko et al., 1985; Schwartz et al., 2009), or to be a constant horizontal slip, with a mean value of 8.9 ± 0.6 m, according to Trimble

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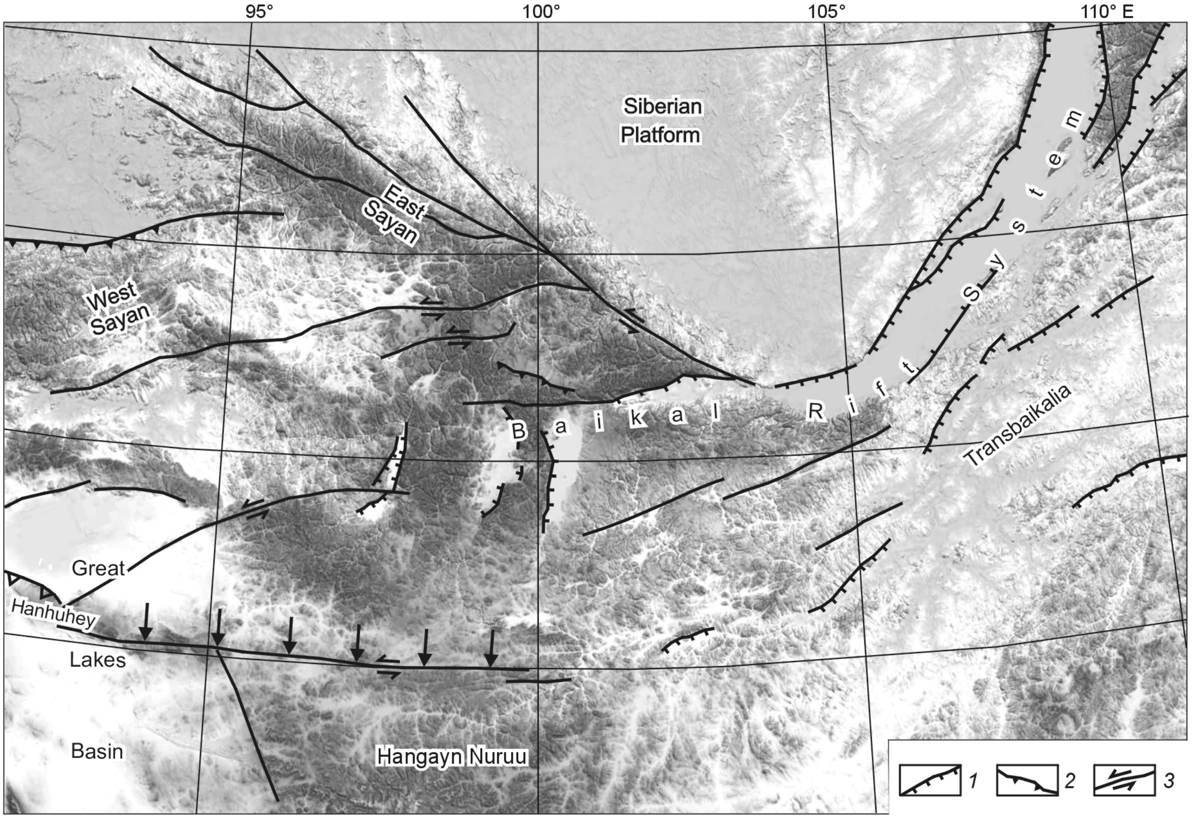

Fig. 1. Location map of Baikal-Mongolia region. Major active normal (*1*), reverse (*2*), and strike-slip (*3*) faults. Black arrows point to Bolnay fault.

kinematic GPS data from different sites in the fault central part (Rizza et al., 2015).

The area was repeatedly shocked by large earthquakes before the 1905 event. Judging by its extent and style, the surface rupture is a cumulative result of multiple shocks, such as two large earthquakes with a recurrence interval of 3000–4000 yr inferred by Rizza et al. (2015). Note that large events in the area were less frequent than in its surroundings. For instance, they recurred every 800 yr for the past 9000 years in the Chuya basin of Gorny Altai (Agatova et al., 2014).

The left-lateral strike slip almost all along the Bolnay fault (Fig. 1) is compensated by geomorphically expressed Late Quaternary reverse faulting in the western fault part, in the young Hanhukei mountains (Rizza et al., 2015). The objectives of the study in the eastern fault end included (i) estimating coseismic slip associated with the event of 1905 and previous earthquakes, (ii) checking the possibility for compensation of horizontal slip by vertical motion, and (iii) constraining the age of surface rupture. The obtained data will contribute to understanding of Late Quaternary crustal deformation in the transitional setting between compression in northern Mongolia and extension in Transbaikalia.

Morphotectonics

On its extension east of Lake Sangyin-Dalay-Nuur, the end of 1905 coseismic rupture, the Bolnay fault shows signature of reactivation as a surface rupture about 6 km long in the area of the Busyin-Gol River (Khilko et al., 1985). Then the fault turns southeastward where grades into a system of small parallel faults. Motion on these faults in the Bolnay mountains, where several old fault scarps (e.g., the Dzunnuur scarp) were found (Fig. 2), compensates the left-lateral displacement of the southern block. The Dzunnuur scarp is a 53 km long reverse fault with a sinistral horizontal component that generated an $M = 7.8$ earthquake (Khilko et al., 1985).

Further eastward the extension of the Bolnay fault appears in the digital elevation model as a system of NE parallel basins, within 10 km wide, bordered by normal faults in the northwest. The basins are oblique to the principal fault strike (Fig. 3) and are of pull-apart origin, which is confirmed by paleostress reconstructions for the area (Parfeevets and Sankov, 2012). Their geometry indicates relative left-lateral motion of the southern and northern blocks compensated by vertical offset on smaller NE faults in shallow crust (Fig. 3).

Thus, rather than being a single suture, the Bolnay fault east of its part reactivated in 1905 is a broad shear zone where deformation is distributed among multiple pinnate tension structures (pull-apart basins). The basins are filled with Quaternary (Q_2–Q_4) sediments indicating that the shear has been compensated by normal faulting at least since the middle Pleistocene. This idea is consistent with the earlier inference (Jolivet et al., 2013) that the northeastern end of the Bolnay fault system in Transbaikalia is a zone of extension hundreds of kilometers wide.

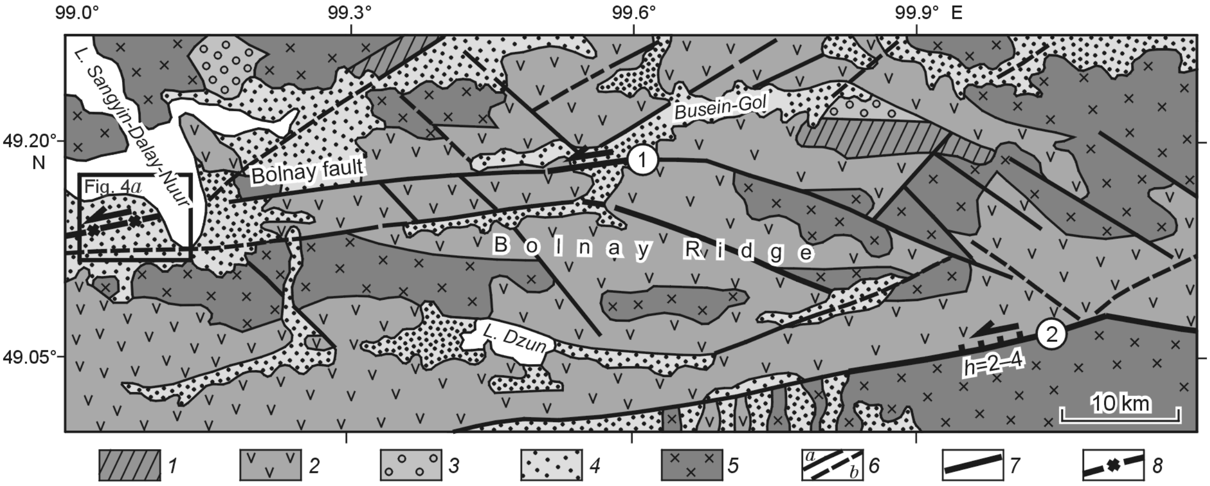

Fig. 2. Tectonic map of the eastern end of Bolnay fault, simplified after Khilko et al. (1985). *1*, Vendian–Early Paleozoic volcanic-sedimentary rocks; *2*, Permian lavas; *3*, Early Mesozoic molasse, *4*, Neogene–Quaternary deposits; *5*, Paleozoic–Early Mesozoic intrusions; *6*, observed (*a*) and inferred (*b*) faults reactivated in the Cenozoic, *7*, segments of seismogenic reactivated faults (teeth point to footwall); *h*, vertical offset, m; arrow shows strike slip direction. 1, Busyingol fault scarp; 2, Dzunnuur fault scarp; 8, rupture caused by earthquake of 23.07.1905. Box contours area of detailed paleoseimological studies.

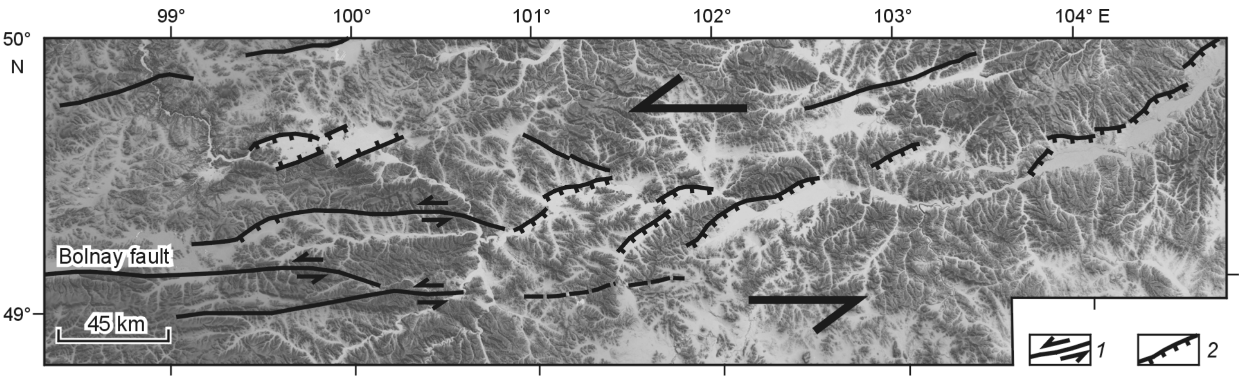

Fig. 3. SRTM digital elevation model of the eastern extension of the Bolnay fault. Black lines are active strike-slip (1) and normal (2) faults.

The earthquake of 1905 reactivated the Bolnay fault west of Lake Sangyin-Dalay-Nuur. We studied morphotectonics in its eastern end (Fig. 4*a*) in order to estimate the coseismic slip of the 1905 and previous events. The surface rupture is expressed as systems of en echelon tension gashes, tens of meters long, pressure ridges up to several meters wide, and features resembling mole tracks produced by ripping through thick alluvial sediments along a large strike slip (Fig. 4*b*, *c*). The geomorphic features apparently represent cumulative slip produced in several earthquakes, including that of 1905. East of the lake, no traces of the ultimate earthquake appear but there are left-lateral strike slip features, with a cumulative amount reaching 300 m.

Offset topography in the dry stream bed of the Hasan-Gol River, five kilometers west of the lake at 49.1482° N, 99.0358° E (Fig. 4*a*) is evident as up to 7 ± 0.5 m (Fig. 4*d*) and 13 ± 1 m (Fig. 4*e*) left-lateral displacement of pebble bars. The latter value most likely corresponds to cumulative slip of two events. Furthermore, a small stream bed is offset to 6.5 ± 0.5 m (Fig. 4*f*) 1 km west of the previous site along the fault (49.1461° N, 99.0205° E). This slip is smaller than the value obtained from GPS measurements at different sites in the western and central fault parts: ~8.9 m for one earthquake and ~17 m for the ultimate (1905) and penultimate (2300–3240 yr BP) shocks (Rizza et al., 2015). The difference may be due to deformation decay in the eastern fault flank. Hypsometry of the ruptured alluvial surface on elevation profiles across the fault strike (Fig. 5) showed gradual elevation increase toward the mountains, but without abrupt change across the fault. This attests to the absence of vertical motion and reactivation of the fault as a left-lateral strike slip.

Paleoseismology

Evidence of past earthquakes was studied in the zone of geomorphically expressed deformation in the eastern Bolnay fault. The fault striking at 80° crosscuts coalesced fans of streams flowing from the Bolnay mountains into Lake

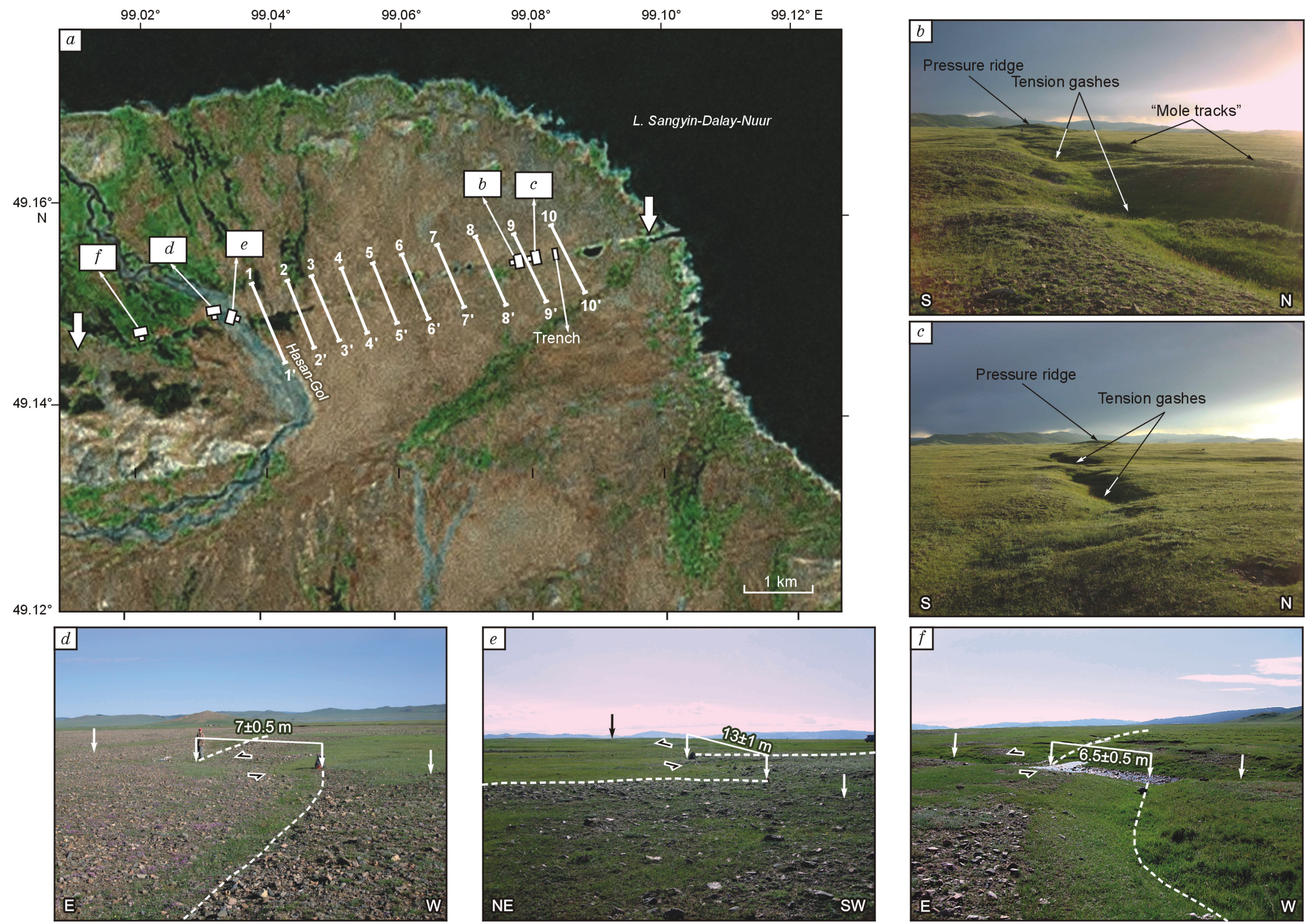

Fig. 4. Eastern end of rupture zone related to the ultimate great earthquake (1905) in Bolnay fault. White arrows in Landsat image (*a*) show area of 1905 rupture. For location see Fig. 2. Black lines across the fault strike (1-1—10-10) are elevation profiles of Fig. 5*b*, *c*: surface rupture along eastern fault end; *d*, *e*, *f*: offset surface topography along Bolnay fault (fault is shown by black arrows): left-lateral offset of pebble bars (dash line) (*d*, *e*) and dry stream bed of Sangyin-Dalay-Nuur (*d*, *e*), to 7 and 13 m, respectively, and 6.5 m offset of a small stream bed (dash line) (*f*). For location see Fig. 4*a*.

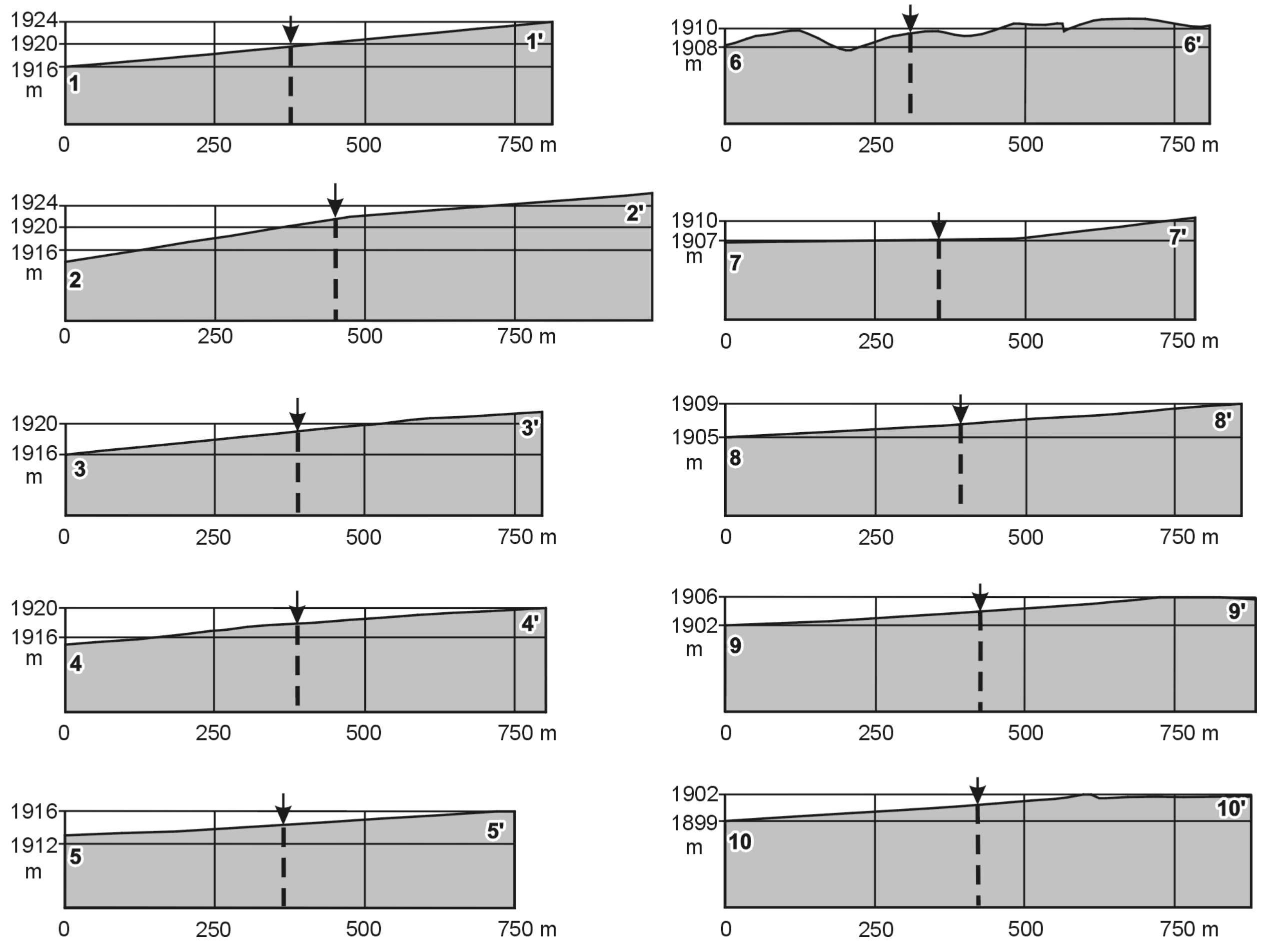

Fig. 5. Elevation profiles across fault strike. For location see Fig. 4*a*. Faults are marked by arrows.

Sangyin-Dalai-Nuur (Fig. 4*a*). The rupture occurs as pressure ridges, tension gashes, and pull-apart basins. The floor of one pull-apart basin was trenched at (49.1547º N, 99.0837º E) across the fault strike (Fig. 6*a*, *b*) in order to bracket the ages of prehistoric earthquakes.

The western wall of the trench (Fig. 6*c*) exposed alluvial fan deposits (units 10–50) and a soil unit (0). The fan deposits are sand and gravel with larger (units 10, 20, 40, 50) or smaller (unit 30) percentages of coarse material. The section stores record of five ruptures, which offset (horizontally) or cut (vertically) two units spotted easily among the others: unit 50 is whitish due to strong carbonatization and unit 10 is brownish being recycled in soil formation processes.

The ultimate earthquake of 1905 left traces as fault F1 deforming the modern soil (0) and the sediments below it. Fault F2 lies under unit 20 displaced by F1 and likely represents the penultimate event. Faults F3–F5 either originated during an earlier event or failed to reach the surface (fault F4) during the earthquake of 1905.

Dating of the offset sediments led to the following results. A ^{14}C age of 4130 ± 35 was obtained at the Poznan Radiocarbon Laboratory for bones of a rodent found in unit 50 (sample Poz-59995) and converted to a calendar age of 4689 ± 94 yr BP using the software from www.calpal-online.de. Samples of charcoal found in units 0 and 20 were dated by ^{14}C at 4360 ± 35 (Poz-59996) and 4365 ± 30 (Poz-59997) years, with the respective calendar ages of 4927 ± 46 and 4927 ± 42 yr BP. However, the older charcoals present in young sediments and in the modern soil are apparently redeposited and cannot provide time constraints on the host units; the age of unit 50 is reliable because the rodent bones occurred *in situ*.

Thus, there are at least two generations of faults associated with two seismic events that postdated the deposition of unit 50, i.e. after 4689 yr. The penultimate large earthquake in the central Bolnay fault occurred 2300–3250 years ago (Rizza et al., 2015). Inasmuch as the extensive surface rupture in the eastern Bolnay fault most likely results from multiple shocks, the large prehistoric earthquake recorded in the fault central part may have affected the eastern flank as well and produced faults F2–F5; fault F1 rather represents the ultimate event of 1905.

Conclusions

Coseismic slip of 6.5 m during the $M = 8.2$–8.5 earthquake of 1905 was inferred from an offset stream bed in the eastern

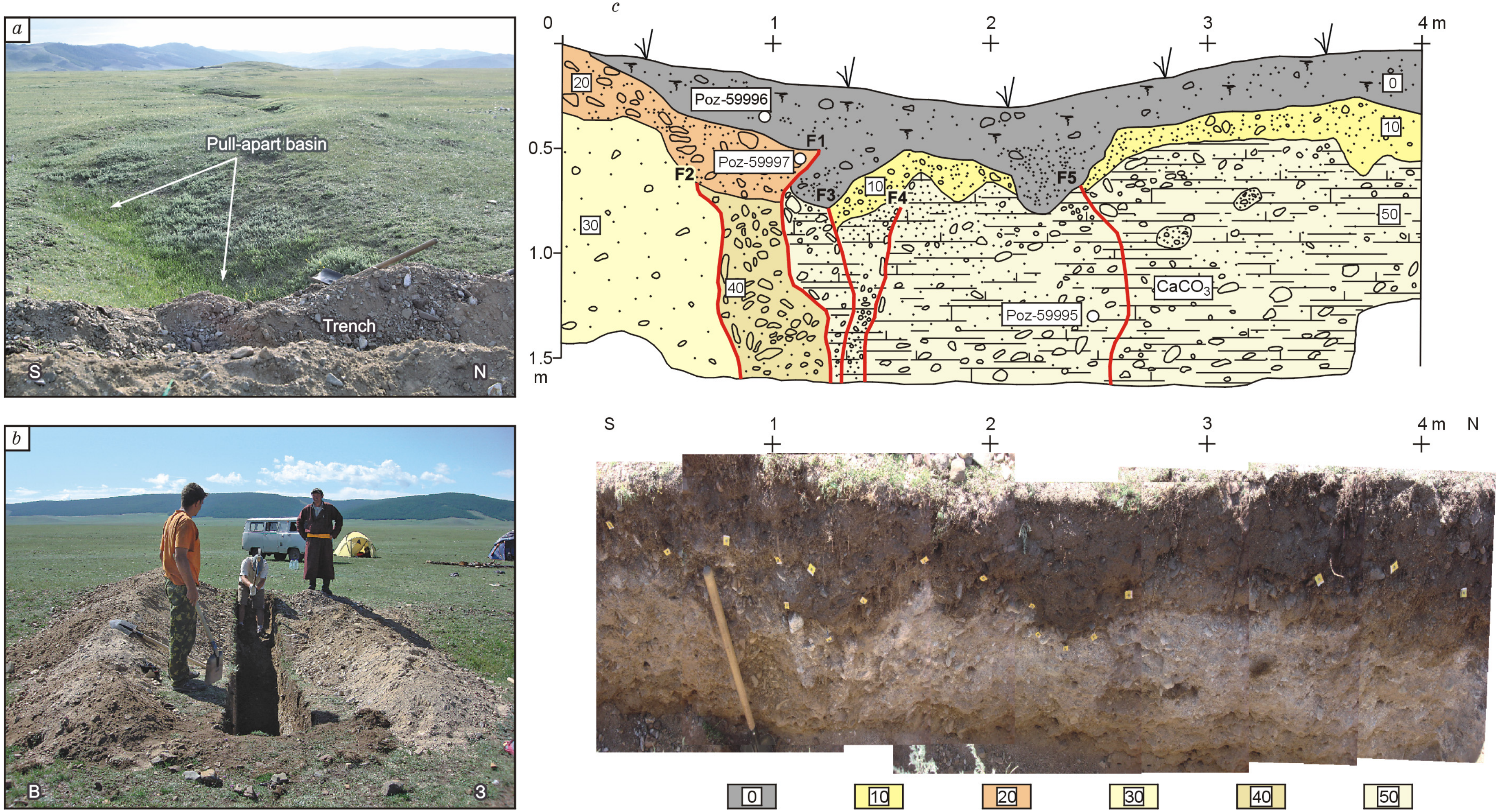

Fig. 6. Trenching in eastern end of Bolnay fault. *a*, *b*, Trench across a pull-apart basin (for location see Fig. 4 *a*); *c*, stratigraphic logs and field photographs of western wall. unit 0: modern soil, unit 10: brown sand and pebble with large percentages of coarse clastics and low humus contents; unit 20: dark-brown sand and pebble, with cobbles; unit 30: yellowish-brownish sand and pebble, with smaller percentages of coarse clastic than in other units; unit 40: light brown sand and pebble, with greatest amount of coarse clastics; unit 50: light brown sand and pebble, whitish due to strong carbonatization; F1–F5 are faults; white circles mark sampling sites.

Bolnay fault. Displaced pebble bars in different places of the Hasan-Gol valley record left-lateral strike slip reaching 7 ± 0.5 m and 13 ± 1 m. The latter value, almost twice the slip of 1905, is most likely cumulative displacement, which provides evidence of recurrent coseismic motion in the eastern flank of the fault, like that reported for its central part (Rizza et al., 2015). This inference is consistent with the records of two events found in the trench on the eastern end of the deformation zone roughly coeval with earthquakes in the central fault part (Rizza et al., 2015): both occurred after 4689 ± 94 yr BP.

No vertical offset associated with at least two (ultimate and penultimate) events generated by the Bolnay fault has been observed in the eastern end of the rupture zone. The surfaces of the northern and southern fault walls have similar elevations above sea level. Hypsometry of the deformed alluvial surface showed gradual elevation increase toward the mountains, but no abrupt change across the fault. This attests to the absence of vertical motion and reactivation of the fault as a left-lateral strike slip.

East of its rejuvenated part, the Bolnay fault is a broad shear zone where deformation is distributed among multiple pinnate extension features (pull-apart basins) rather than being a single suture. The basins are filled with Quaternary sediments indicating that the shear has been compensated by normal faulting at least since the middle Pleistocene. Thus, strain in the transitional setting between compression in northern Mongolia and extension in Transbaikalia produced pull-apart basins which opened in a passive way during relative motion of blocks along the Bolnay fault.

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