

1957 Gobi-Altay, Mongolia, earthquake as a prototype for southern California's most devastating earthquake

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ABSTRACT

The 1957 Gobi-Altay earthquake was associated with both strike-slip and thrust faulting, processes similar to those along the San Andreas fault and the faults bounding the San Gabriel Mountains just north of Los Angeles, California. Clearly, a major rupture either on the San Andreas fault north of Los Angeles or on the thrust faults bounding the Los Angeles basin poses a serious hazard to inhabitants of that area. By analogy with the Gobi-Altay earthquake, we suggest that simultaneous rupturing of both the San Andreas fault and the thrust faults nearer Los Angeles is a real possibility that amplifies the hazard posed by ruptures on either fault system separately.

INTRODUCTION

Discussions of earthquake hazards in the Los Angeles, California, area commonly focus on two separate systems of faults (e.g., Wesson et al., 1974). The San Andreas fault passes north and east of Los Angeles; its nearest segment is only ~30 km northeast of the city (Fig. 1A). Major earthquakes in 1857 (Sieh, 1978; Sieh and Jahns, 1984) and apparently in 1812 (Jacoby et al., 1988) ruptured segments of the San Andreas fault near Los Angeles; that in 1857 was the largest known earthquake on the fault. Earthquakes occurring on thrust faults along the southern margin of the San Gabriel Mountains, the Sierra Madre–Cucamonga fault system, and beneath the Los Angeles basin (Fig. 1A), however, have caused Los Angeles's most recent earthquake losses, and future ruptures on such thrust faults are thought by some to pose Los Angeles's most immediate, growing hazard (e.g., Dolan et al., 1995). Although large intracontinental earthquakes commonly involve slip on more than one fault, the possibility of both fault systems in southern California rupturing simultaneously apparently has, to our knowledge, been considered only in informal presentations of the material we discuss here.

Although far from a plate boundary, the

local tectonic setting of the 1957 Gobi-Altay earthquake closely resembles that of the San Gabriel Mountains. A sharply defined strike-slip fault, analogous with the San Andreas fault, follows the northern margin of a high mountain, Ih Bogd (Fig. 1B), the highest mountain (3957 m) in the Gobi-Altay of Mongolia, and comparable in height to Mount San Antonio, the highest peak (3243 m) in the San Gabriel Mountains. A basin, analogous to the Los Angeles basin, lies south of Ih Bogd; the boundary between the basin and the high range is marked by a system of thrust faults, like those at the southern edge of the San Gabriel Mountains. Both the strike-slip system along the northern edge of Ih Bogd and the thrust system south of it ruptured in 1957 in a large earthquake, assigned magnitudes from 7.9 to 8.3 (Florensov and Solonenko, 1963; Richter, 1958). Estimates of the seismic moment confirm its place among great intracontinental earthquakes (Chen and Molnar, 1977; Okal, 1976). Moreover, both thrust-fault systems have slipped by amounts associated with earthquakes of magnitude >7. The high terrain in both regions, the San Gabriel Mountains and the Ih Bogd and Baga Bogd massifs, has formed where jogs or bends in the predominantly strike-slip regime require

components of shortening of one of the crust's horizontal dimensions. Thus, in both areas the two systems of faulting are intimately related.

We use both published reports and the results of two field seasons quantifying the surface faulting associated with the 1957 earthquake to compare the surface rupture with active faulting and seismicity of southern California. The full details of our quantification of the 1957 surface rupture will be presented elsewhere. Our study builds on the extensive work of Florensov and Solonenko (1963), who visited the epicentral region one month after the 1957 earthquake and then returned the following summer to carry out a study of its macroseismic effects. The senior among us, R. A. Kurushin, was the youngest member of that expedition.

SURFACE RUPTURE OF THE 1957 EARTHQUAKE

The strike-slip surface rupture of the 1957 earthquake (Florensov and Solonenko, 1963) bears a remarkable similarity to the 1857 Fort Tejon earthquake (Sieh, 1978; Sieh and Jahns, 1984). The 1857 earthquake was associated with 300 km of rupture along the San Andreas fault, with a maximum offset of 7–10 m. Amounts of slip varied mark-

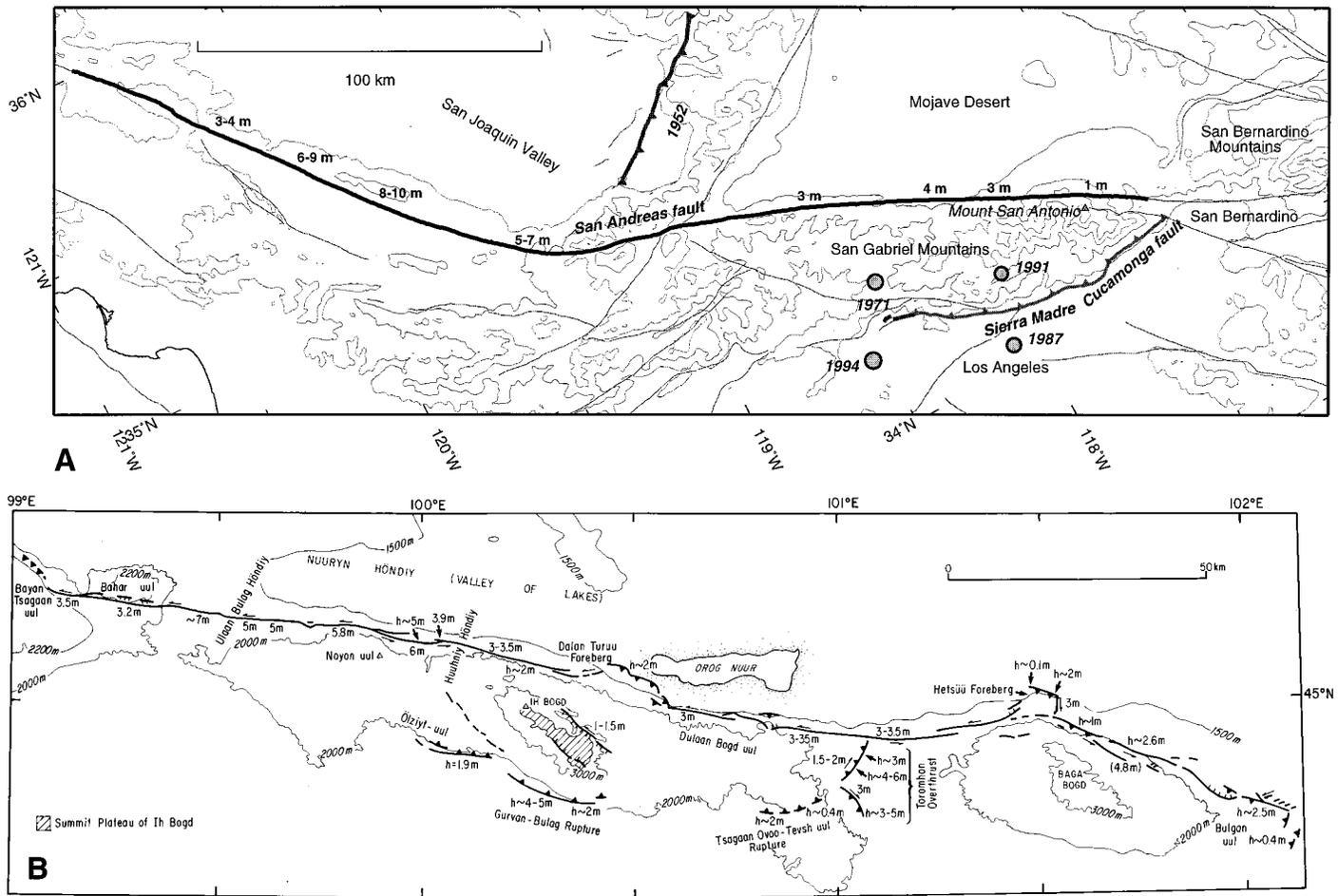


Figure 1. Maps of faulting in southern California (A) and Gobi-Altay region (B). A: Note thrust systems that lie south of San Gabriel Mountains and San Andreas fault, which passes north of this range. Measured right-lateral offsets in metres, associated with 1857 earthquake (Sieh, 1978), are shown along rupture, and dots denote epicenters of other major earthquakes (Dolan et al., 1995). B: Summary of 1957 rupture is shown. Strike slip characterizes main east-southeast-trending zone north of Noyon uul, Ih Bogd, and Baga Bogd, and thrust slip occurred along zones south of Ih Bogd and farther east (h indicates measured vertical components of slip). Some strike-slip faulting also occurred within Ih Bogd massif.

edly along the rupture, from 3–4 m in the northwesternmost part, 8–10 m of slip in the central segment of 110 km, to 3–4 m along the southeastern 90 km (the segment nearest Los Angeles), decreasing to 1 m at the southeast end (Fig. 1A). The Bogd rupture, some 250 km in length, follows the northern margin of Ih Bogd and Noyon uul to the west and Baga Bogd to the east (Fig. 1B). Along the western two-thirds of that rupture, nearly pure left-lateral strike slip characterizes the deformation. Both Florensov and Solonenko's (1963) team and we measured left-lateral displacements of 3–3.5 m in the western 25 km. In a segment ~50 km long, north of Noyon uul (Fig. 1B), displacements clearly reached 5 m (Fig. 2A), to perhaps 7 m (Baljinyam et al., 1993; Florensov and Solonenko, 1963) in places. Northwest of Ih Bogd, the displacement abruptly drops to 3–4 m again for about 100 km (Fig. 2B). Thus, not only are magnitudes of strike slip associated with the 1857 and 1957 earthquakes similar, but so is the distribution;

smaller amounts are adjacent to the regions with high mountains, and thrust faulting is to the south of them.

The 1957 rupture is not everywhere as simple as that shown in Figure 2. In many places, the single, simple trace splays into more than one surface trace, each commonly oriented obliquely to the main trace, and the total displacement is difficult to estimate. The largest such example lies northeast of Ih Bogd, where the rupture steps north into a zone of thrust faulting to form the "Dalan Tüüü foreberg" (Florensov and Solonenko, 1963). Farther east, however, left-lateral offsets of 3–4 m are again common (Fig. 2B). These splays could give the misleading impression of unusually complicated faulting at depth. Simple arguments, to be presented with all of the data, demonstrate that this complexity is superficial, confined to the upper 1–2 km. Similarly, Sieh (1978) suggested that minor thrust slip may have occurred in 1857 along the northeast side of the Elkhorn Hills, a few kilo-

metres northeast of the San Andreas fault. Thus, ignoring such superficial complexities, the 1957 rupture clearly is similar in dimensions and style to the strike-slip rupture of the 1857 earthquake.

In the eastern 75–80 km of the Bogd rupture, strike-slip faulting is not, in general, as clear as it is farther west. The zone of active deformation wraps around the northern margin of Baga Bogd. Large components of thrust faulting characterize deformation on the northeastern margin of the massif, and another clear foreberg, the Hetsüü foreberg, lies north of Baga Bogd. Moreover, deformation spans a wide zone, making it difficult to measure the total offset. Faulting is clear not only at the foot of the Baga Bogd massif, but also within the north slopes of the mountains, showing that surface deformation is distributed over a zone a few kilometres wide.

The principal thrust-slip surface rupture of the 1957 earthquake (e.g., Florensov and Solonenko, 1963) shows a resemblance to



Figure 2. A: View west-southwest across particularly clear offset just west of Hühniy höndiy (Fig. 1B). People on top of scarp and at its base define scales for 6 m of left-lateral slip and 5 m vertical component. **B:** View south across Bogd rupture just east of where Toromhon overthrust approaches Bogd rupture (Fig. 1B). We measured strike-slip offset of 4.1 ± 1.0 m, and vertical component of 0.7 ± 1.0 m. Photos by Molnar on August 22, 1994, and August 4, 1993, respectively.

that expected for the largest likely earthquake along the thrust system south of the San Gabriel Mountains (Wesson et al., 1974). Several earthquakes have occurred within the Los Angeles basin in the past 25 yr (Dolan et al., 1995); the 1971 San Fernando earthquake was the largest among them. That earthquake occurred on the main thrust fault dipping beneath the San Gabriel Mountains. The component of oblique thrust slip at depth apparently reached a maximum of about 3 m (Heaton, 1982), though only the rare vertical component at the surface reached 1 m (Kamb et al., 1971; U.S. Geological Survey Staff, 1971). The comparable seismic moment for the 1994 Northridge earthquake implies a similar amount of slip, if on a plane dipping south (Scientists of the U.S. Geological Survey and the Southern California Earthquake Center, 1994). Smaller earthquakes have

ruptured other segments of Sierra Madre-Cucamonga fault (Dolan et al., 1995), but the potential for an event rupturing the entire ~90-km-long zone clearly has been recognized for many years (Wesson et al., 1974).

The thrust faulting in 1957 along the southern margin of Ih Bogd, called the Gurvan bulag rupture (bulag means spring) by Florensov and Solonenko (1963), remains very clear, even at a distance (Fig. 3). The low hills south of Ih Bogd, which have formed by thrusting of the massif over the alluvial fans to the south, demonstrate that thrust faulting in 1957 was not unusual. Displacements in 1957 vary along the scarp, growing from nil at the east end to as much as 5 m of vertical offset near the center (Fig. 1B). In 1958, V. P. Solonenko and M. A. Solonenko (Florensov and Solonenko, 1963) found a recently eroded gully within

these low hills, where they could measure both a vertical offset of 4 m and a northward dip of 45° near the surface decreasing to 35° at the base of the fresh gully, 8–10 m below the surface of an alluvial fan. The surface displacement decreases westward from this area of maximum slip and disappears where sedimentation and discharge from springs are particularly rapid. A clear scarp follows the southern foot of the Ölziyt uul farther west. Vertical offsets of ~2 m can be seen for 10 km, before the rupture dies out in another 5 km. The total length of this thrust faulting in 1957 is ~50 km, and the average vertical component of displacement along it is 2–3 m. Thrust faulting to a depth of 20 km and dipping at 45° , for which the width of the rupture would be ~30 km and the length 50 km, yield a rupture area of 1.5×10^4 km². For an average slip of 2–3 m and a shear modulus of 3.3×10^{10} N·m⁻², the seismic moment (Aki, 1966) is 1.0 – 1.5×10^{20} N·m. Hence M_w is ~7.3–7.5, using Hanks and Kanamori's (1979) relationship between moment and magnitude. This size is negligibly smaller than what Wesson et al. (1974) suggested for a maximum likely earthquake along the 90-km-long Sierra Madre-Cucamonga fault system ($M = 7.5$ – 7.75), and roughly 10 times larger than the largest such event in the historic record, the 1971 San Fernando earthquake of $M_o = 1.0$ – 1.7×10^{19} N·m and of $M \sim 7.1$ (e.g., Dolan et al., 1995; Heaton, 1982). The Gurvan bulag zone of thrust faulting is clearly comparable in style, linear dimension, and likely offset, with those associated with earthquakes larger than are known to have occurred south of the San Gabriel Mountains in southern California.

Major faulting in 1957 also occurred along three other clearly defined zones (Fig. 1B): the Toromhon overthrust, which is a north-south zone of thrust, and in some places reverse, faulting between Ih Bogd and Baga Bogd; the Tsagaan ovoo-Tevsh uul rupture zone along the southeastern margin of Ih Bogd; and a system of left-lateral faulting that crosses the summit plateau of Ih Bogd (Florensov and Solonenko, 1963). Vertical displacements of several metres (3–6 m), with smaller right-lateral components (≤ 2 m), characterize much of the Toromhon overthrust, which is only ~18 km long. Displacements are significantly smaller (≤ 1.5 m) along the Tsagaan ovoo-Tevsh uul zone. Cumulative left-lateral displacements across Ih Bogd seem to reach 2 m, but not 3 m. Although these three zones have no obvious analogs in southern California, they are a reminder that the faulting associated with a great earthquake need not occur exclusively on previously mapped



Figure 3. View (using 135 mm lens) north at thrust system south of Ih Bogd. Ih Bogd massif rises steeply in background above low hills at base of alluvial fans. Dark line at base of low hills marks fault scarp that formed in 1957. The yurts in the foreground, with camels and people, provide an analog to the city of Los Angeles, perhaps when the last earthquake comparable to the 1957 Gobi-Altay earthquake occurred. Photo by Molnar on August 22, 1994.

faults (e.g., Baljinnyam et al., 1993). The Toromhon overthrust, for example, probably would not have been recognized as an active fault before it ruptured in 1957; it has little obvious topographic expression (Baljinnyam et al., 1993). Despite the lack of obvious counterparts to the faults in California associated with these ruptures, they should serve as reminders that other faults, such as that on the northern margin of the San Bernardino Range or the White Wolf fault that ruptured in 1952, need not rupture independently of a major earthquake on the San Andreas fault. Sieh's (1978) observation of thrust slip along the Elkhorn Hills calls attention to the possibility that other faults did rupture in 1857, but have not yet been recognized.

Although we concentrate here on the similarities between the 1957 Gobi-Altay earthquake and faulting in southern California, the pattern of faulting in 1957 could apply to earthquakes anywhere oblique convergence, or divergence, occurs.

CONCLUSION

The quantitative aspects of the surface ruptures of the 1957 Gobi-Altay earthquake resemble those of the 1857 Fort Tejon earthquake on the San Andreas fault and those of the 1971 San Fernando earthquake and those expected for larger earthquakes along the Sierra Madre-Cucamonga fault system. The obvious implication is that the 1957 Gobi-Altay earthquake is a prototype

for the simultaneous rupture of both fault systems and hence a prototype for southern California's most disastrous earthquake. We do not mean to suggest that an earthquake with simultaneous ruptures of thrust and strike slip is imminent, or even that thrust slip occurs simultaneously with more 10% of great earthquakes along the San Andreas fault in southern California, which occur roughly once per century (Fumal et al., 1993). Rather, the similarities are too great for the possibility of such an event to be ignored.

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