HISTORICAL SEISMOLOGIST

Oldham's Lost Fault

by Roger Bilham, Bikram Singh Bali, Shabir Ahmad, and Celia Schiffman

INTRODUCTION

In 1888 R. D. Oldham, the seismologist best known for first quantifying the diameter of the Earth's core using seismic waves, provided a description of the surface rupture of an active fault at the southeast end of the Kashmir Valley. Intriguingly, he described it as a normal fault parallel to the strike of the trend of the Himalaya, with 2 m of slip that had impounded several sag ponds. He provided no map of its location, and the fault is not shown on recent maps, nor is it described by later authors. In September 2011 we retraced his footsteps and found the fault. Charcoal fragments embedded in layered sediments within a prominent sag pond indicate that slip of ≈1 m most probably occurred around ≈700 B.C., with a second event with similar slip in 680 ± 100 A.D. Although the fault is most probably a sackung, its association with fault gouge and slickensides, its strike orthogonal to a north–south ridge, and its relationship to a series of similar east-northeast-striking faults spaced at ≈5 km intervals in a north-northwest alignment, suggests that slip may in part be related to flexural stresses in southeast Kashmir.

Richard Dixon Oldham joined the Geological Survey of India at the age of 21 in the last few days of 1879, a year after the death of his father, Thomas Oldham, its founder. Within months of arrival he contracted malaria and was sent to the Himalaya to convalesce where he completed three of his father's manuscripts including a catalog of Indian earthquakes (Oldham, 1882). He was destined to spend several years in the Himalaya investigating its stratigraphy and structure. In 1881, while mapping the local geology between Sirmaur and Nahan (30°55′N, 77°59′E) he identified, for the first time in India, an active fault cutting the Earth's surface (Medlicott, 1882; p. 6). In 1888 he described a second surface fault, this time a normal fault, in the mountains at the southeast end of the Kashmir valley, but he omitted to provide details of its location (Oldham, 1888). The purpose of this article is to describe the successful rediscovery of this, the second active surface fault to be described in India (Fig. 1). Neither of these faults should be confused with the inferred blind thrust fault causal to the 1897 earthquake that Bilham and England (2001) named in honor of Oldham's contributions to Indian seismology.

Oldham's Kashmir fault was the more enigmatic of the two he describes in the following paragraphs:

> *A curious feature may be observed near the head of this tributary. On the hillside there is a sudden step or bank, commencing gradually and reaching a height of about six to eight feet; it runs along the hill side with a general course to W15°N, coinciding with the strike of the beds, but V-ing to the south in the valleys. It crosses the head of the next tributary, and in two of the minor drainage depressions which are not large enough to have a defined stream-bed, it has formed small hollows in which water appears to rest after heavy rain. On the watershed between the Shingam and Rajparan drainages it appears as a sudden step on the ridge, rendered more conspicuous by a talus bare of vegetation which contrasts strongly with the grass-clad slopes on either side.*
>
> *Westwards from the ridge it can be traced as a sudden step, or elevation on the down hill side, running across an old moraine deposit which once formed the bed of a glacier, and on this there is a small pond naturally dammed by the elevation. I was not able to trace the full extent of this feature owing to clouds but it appears to vanish about 1 mile west of the watershed.*
>
> *The only cause to which I can ascribe this is the actual appearance of a fault at the surface. I have already noticed a much more conspicuous instance in the hills south of the Giri valley between old Sirmur and Nahan, but it may be noticed that in the present case the fault is a normal one, i.e., it hades to the downthrow, while the Sirmur fault follows the almost invariable rule of Himalayan faults and is 'reversed.' The feature I have described is of recent origin as is shewn by the little effect that denudation has had on it, as well as by the manner in which it traverses what appears to be the bed of an old glacier. The fact that it has in one place been able to form a permanent pond points to the sudden origin of the feature, which probably accompanied one of the violent earthquakes which are known to have affected Kashmir in the past.*

Oldham was crossing the pass just three years after the $M_w \approx 6.3$ Kashmir 1885 earthquake (Jones 1885; Martin and Szeliga, 2010). The pass used by Oldham was not one used by many travelers, and in choosing this exit from the valley for its geological reconnaissance potential, he would have consulted the Kashmir gazetteer in which Bates (1873) summarizes Eleanor Hervey's traverse of the pass in 1851 (Hervey, 1853):

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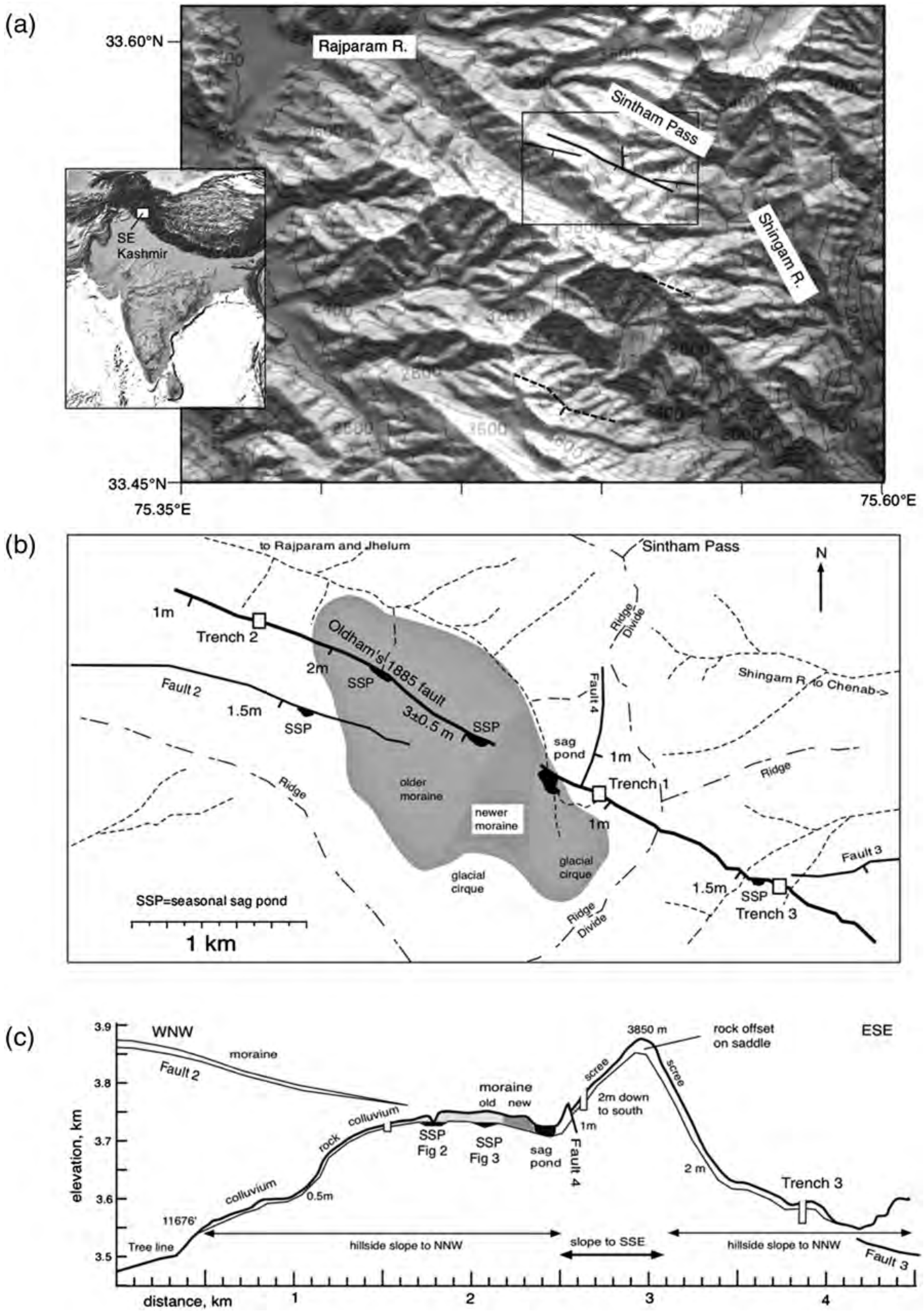


▲ **Figure 1.** Map and sections of Oldham's 1888 fault. (a) Location map and topography. Two similar faults (dashed) are visible on Google Earth imagery, ≈5 and ≈10 km south of Oldham's fault, that have not been visited in the field (Schiffman *et al.*, 2011). (b) Map of fault strands showing sag ponds and trench locations. (c) Longitudinal section through the fault indicating surface materials and offset (SSP, seasonal sag pond).

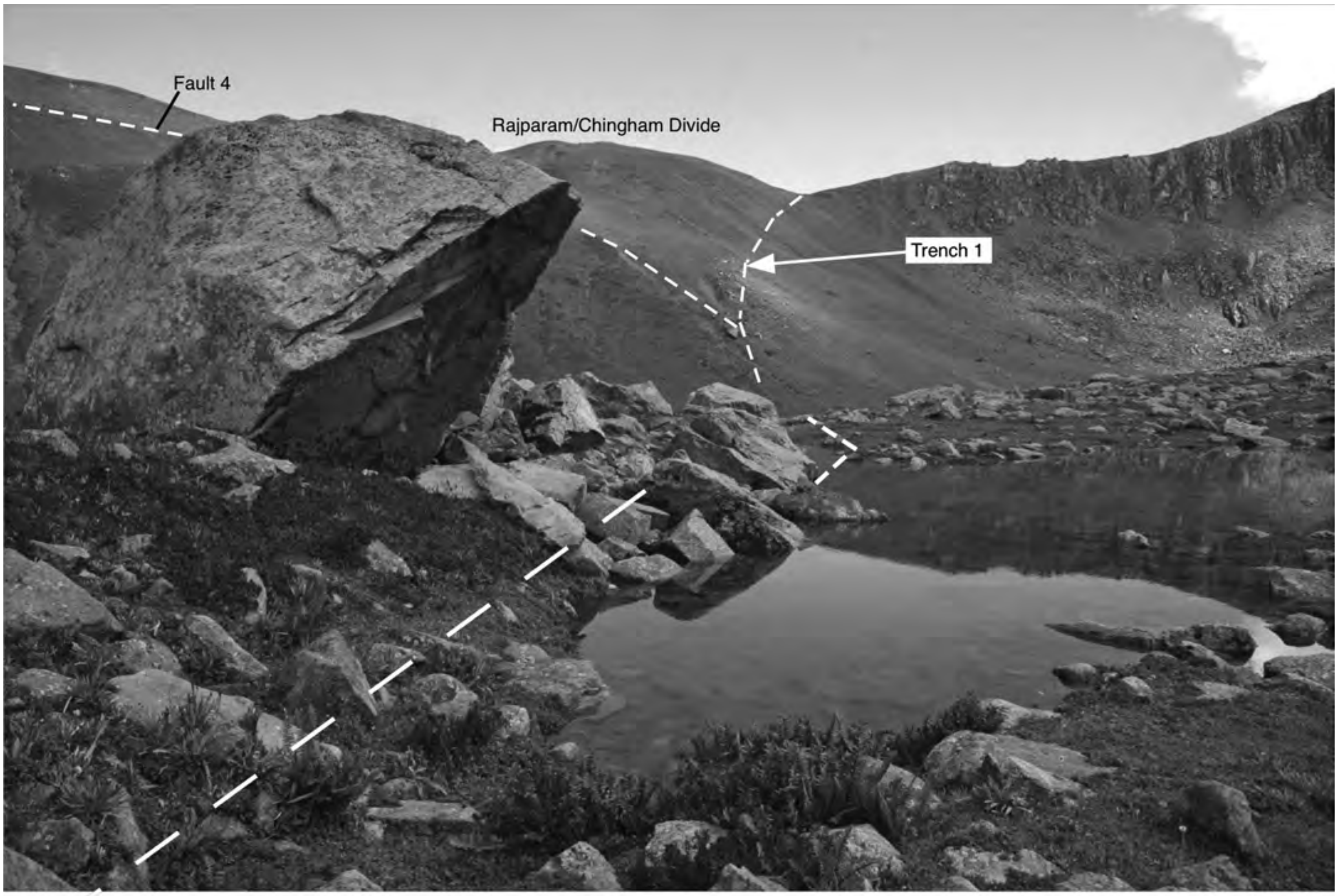
▲ **Figure 2.** The 20-m-long westernmost ephemeral sag pond (km 1.6) "in which water appears to rest after heavy rain."

> *The path for the first mile lies over a gentle wooded acclivity, the ground covered with grass, clover and wild flowers; the torrent must be crossed by snow bridge or trunk of a tree, as it is not safe to ford when in flood; the rest of the way to the crest of the Chingam or Sinthun pass lies over wastes of snow and ice, the last* 1/4 *mile being very steep. Judging from the forest line which is not 500 ft below the summit of the mountain, the height of the pass cannot exceed 11,500 feet. The descent for the first 2 miles is all snow, a mountain torrent flowing far beneath, above the right bank of which the rugged path runs.*

The starting point for our field search was the entry from La Touche (1938; p. 88) for the position of a recent fault at 33° 35′N, 75°31′E in his Geographical Index to geological investigations in India. La Touche, who compiled his geographical Index (La Touche, 1938) in Cambridge, may have corresponded with Oldham, then retired in Landrindod Wells, to clarify its approximate position. The fault was discovered between 33.573° N, 75.486° W and 33.555° N, 75.518° W, 2.5 km south of La Touche's location, along the same ridge as the new Sintham pass road.

The fault was much as Oldham described it 123 years before our visit, and we note that Oldham's two paragraphs of description reproduced above are remarkable for their brevity and their wealth of accurate information. The offset, the strike, and the presence of several sag ponds remain clearly expressed in the topography. The length of the fault is of the order of 4 km and at each end it steps to the left a few hundreds of meters in smaller splays that overlap the main fault and approximately double the total length of surface faulting. The fault lies mostly above the treeline (3550 m) cutting almost vertical shales and limestones, and can be clearly traced in Google Earth imagery. The colluvial fill in the wedge formed by the scarp offers a grassy horizontal path through the moraine and along the steep hillsides, and this has been exploited by shepherds and cattle, and on Google imagery it is evident that the trace of the fault has been worn clean by centuries of footprints.

Near its center (km 2 on Fig. 1c) the fault has offset a coarse, unsorted glacial moraine on a gentle north-facing slope raising its downhill surface by up to 4 m. The surface boulders in the moraine here vary from 30 cm to 5 m in diameter suggesting high porosity, yet the moraine is apparently impermeable at a depth of a few meters for it to have retained numerous seasonal ponds, which are evidently gradually filling with colluvium. The sag pond described by Oldham at km 2.5 is the largest of these, measuring approximately 40 m × 70 m and has a depth of at least 2 m near its northern shore. The

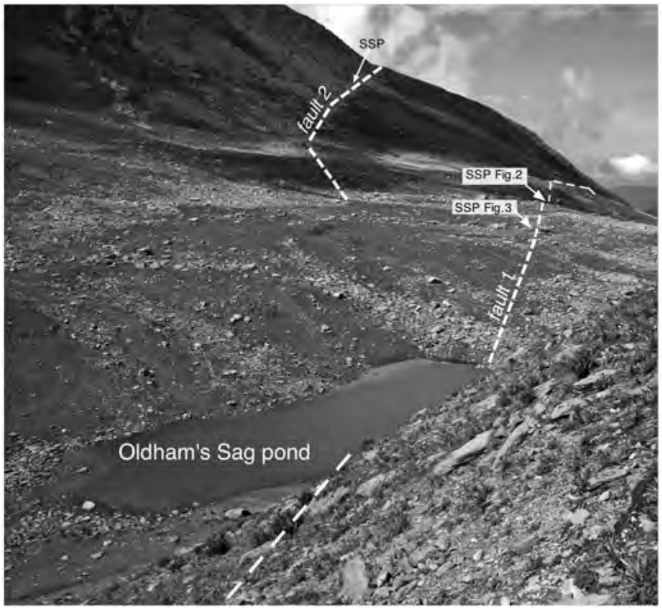


▲ **Figure 3.** View east of central ephemeral sag pond (km 2.1) with a 5 × 3 × 5 m boulder in old moraine lying on top of the 1.5-m-high south-facing scarp (33.564° N, 75.501° E). All trace of the fault between here and the permanent sag pond described by Oldham (hidden in this view by foreground moraine) has been erased by the presence of a recent moraine. The fault passes through the lowest notch on the skyline and can be followed as a faint trace following the scree slope down the south-facing distant hill. Trench 1 is in a rocky gully through this distant talus.

pond is populated by small fish despite being iced over in the winter months. At the time of our visit four seasonal sag ponds (SSP) were partly full of summer meltwater (Figs. 2 and 3). The overflow level in the sag ponds is indicated by a clear line that divides ancient dead lichens from those growing at the present day. Toward the west (km 1) the colluvial wedge has incompletely filled the fault scarp, and because it slopes downhill the fault is marked by hillside drainage without ponds. The fault peters out toward the tree line westward (km 0), but a second normal fault to its south, higher up the hillside, also with throw down to the south increases in offset westward over the crest of the ridge. On satellite imagery it continues westward a few km further, and is replaced by a third south-stepping fracture on a north-facing slope, on the south side of the ridge.

Directly to the west of Oldham's pond (km 2.4, Fig. 4) the fault passes indistinctly through newer moraine (Fig. 1). The absence of a scarp here suggests that the moraine has either moved since slip of the fault, or the moraine may have included significant stagnant ice at the time of slip, ice that has now melted. No clear offset by the fault is visible within this newer moraine, despite it being close to the zone of maximum offset in the older moraines to the west (Fig. 3).

East of Oldham's large sag pond, the fault follows a steep south-facing scree-covered scarp to the crest of the divide (km 3.1, Fig. 3) cut in places by small gullies, one of which afforded an opportunity to excavate the bedrock fault (Trench 1, Fig. 5). At the crest of the divide, rock is exposed in a saddle below a thin cover of loose material with a diffuse scarp of roughly 2 m up to the north. The fault continues down a 68% slope 500 m from the ridge to a lateral moraine (km 3.4), which in map-view appears to show strike-slip offset. Field inspection reveals this to be misleading and caused by an artifact of asymmetric vegetative cover. Continuing to the east the fault again follows a north-facing slope and crosses three small north-draining gullies, the middle one of which (km 3.8) at the time of our visit hosted a small ephemeral sag pond (Fig. 6 and back cover) with a maximum dimension of 8 m and shallow depth (< 1 m). To its east (km 3.85) a similar sag pond has been filled to the level of the downhill scarp with colluvium, which afforded easy excavation (Trench 3, Figs. 6 and 7). The fault



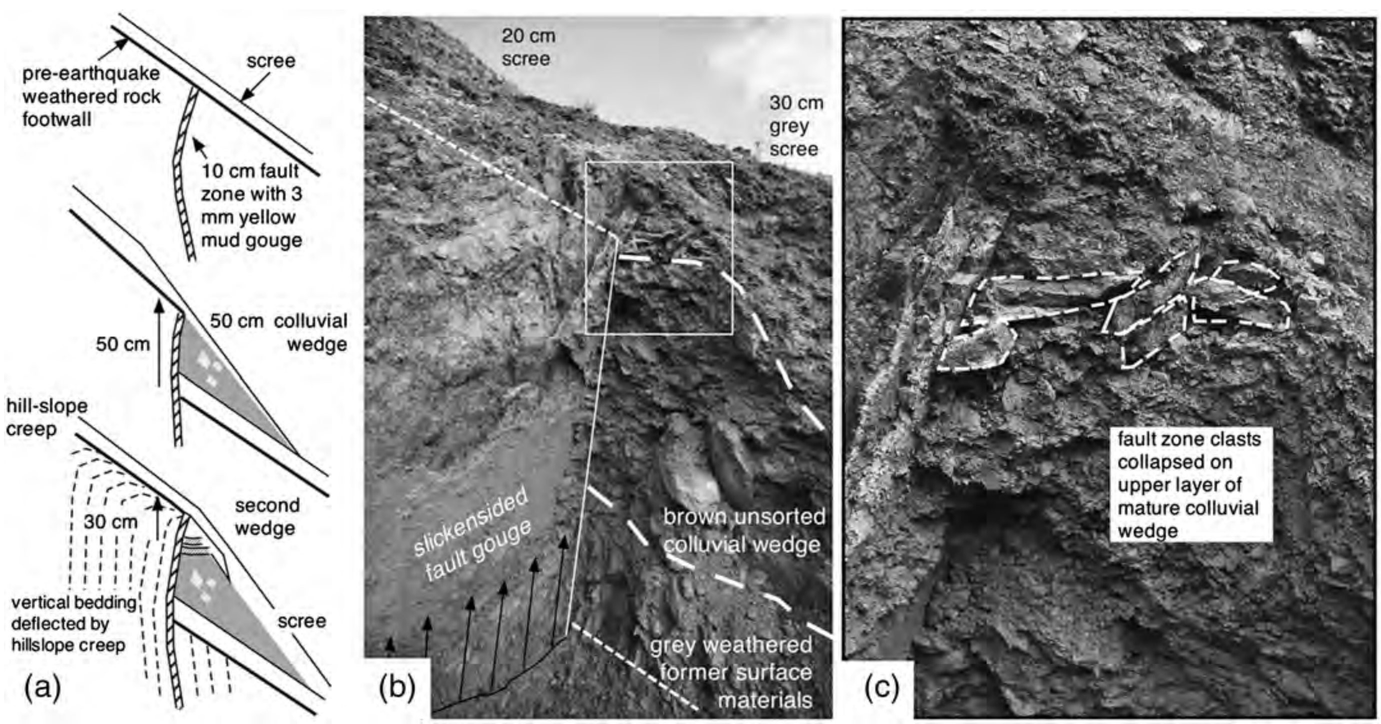
▲ **Figure 4.** View 2 km westward from near Trench 1 showing the sag pond described by Oldham in the foreground, and the locations of three seasonal sag ponds (SSP) on two branches of the fault (see Fig. 1). The fault is obscured by glacial moraine immediately west of the pond.

tapers to negligible slip 1 km to the east of this point, but normal faulting apparently is taken up (km 3.9) on an overlapping north-stepping strand downhill, with similar slip extending more than 1 km to the east.

A conjugate north–south fault (Fig. 1b, Fault 4) is visible on imagery extending northward from Oldham's fault (km 2.75), which field inspection shows as downthrown to the east (the uphill side drops). A consequence of this sense of slip is that fault offset more than doubles on Oldham's fault west of the intersection of the two faults (Fig. 1c).

FAULT EXCAVATIONS

We trenched the fault in three locations to determine its slip history. Trench 1 (Fig. 5) in a gully on a south-facing slope at km 2.8 (Fig. 1) revealed a 3 mm thick gouge-zone of yellow clay in vertical dipping rock, with vertical slickensides and a total apparent vertical offset of 0.8 ± 0.1 m between the inferred edges of the former bedrock slope. The fault zone is clearly defined by a partially cemented damage zone of approximately 10 cm thickness in the laminated shales flanking the fault, fissile to the north and blocky to the south. Although the dip of the fault at 2 m depth was measured in this trench as 75° N, there was clear evidence for downhill creep bending the fault zone to steeper dips near the surface, and we suspect the fault is



▲ **Figure 5.** The footwall of the normal fault exposed in Trench 1 is on the left (north), although the surface fault dips north as a result of hillslope creep. (a) Cartoon depicting the development of the observed colluvial wedge now covered by scree deposits. (b) A well-developed colluvial wedge faces a slickensided gouge zone revealing 80 ± 10 cm of offset of the former rock surface. (c) Close-up view of rectangular box in (b). Clasts of the footwall fault plane have collapsed on the upper surface of the colluvial wedge and have been overridden by the fault plane, suggesting development of the wedge following a 50-cm slip event, followed some time later by a second slip event with ≈30 cm of slip.

▲ **Figure 6.** Oldham's fault viewed at 3580 m westward toward the crest of the divide (3850 m), with filled sag pond in the foreground prior to excavation (dashed rectangle, Trench 3; see Fig. 7). The scree slope near the ridge was described in Oldham (1888) "as a sudden step on the ridge, rendered more conspicuous by a talus bare of vegetation which contrasts strongly with the grass-clad slopes on either side".

either vertical (parallel to the regional stratification) or dips slightly to the south at depth, as inferred by Oldham (1888).

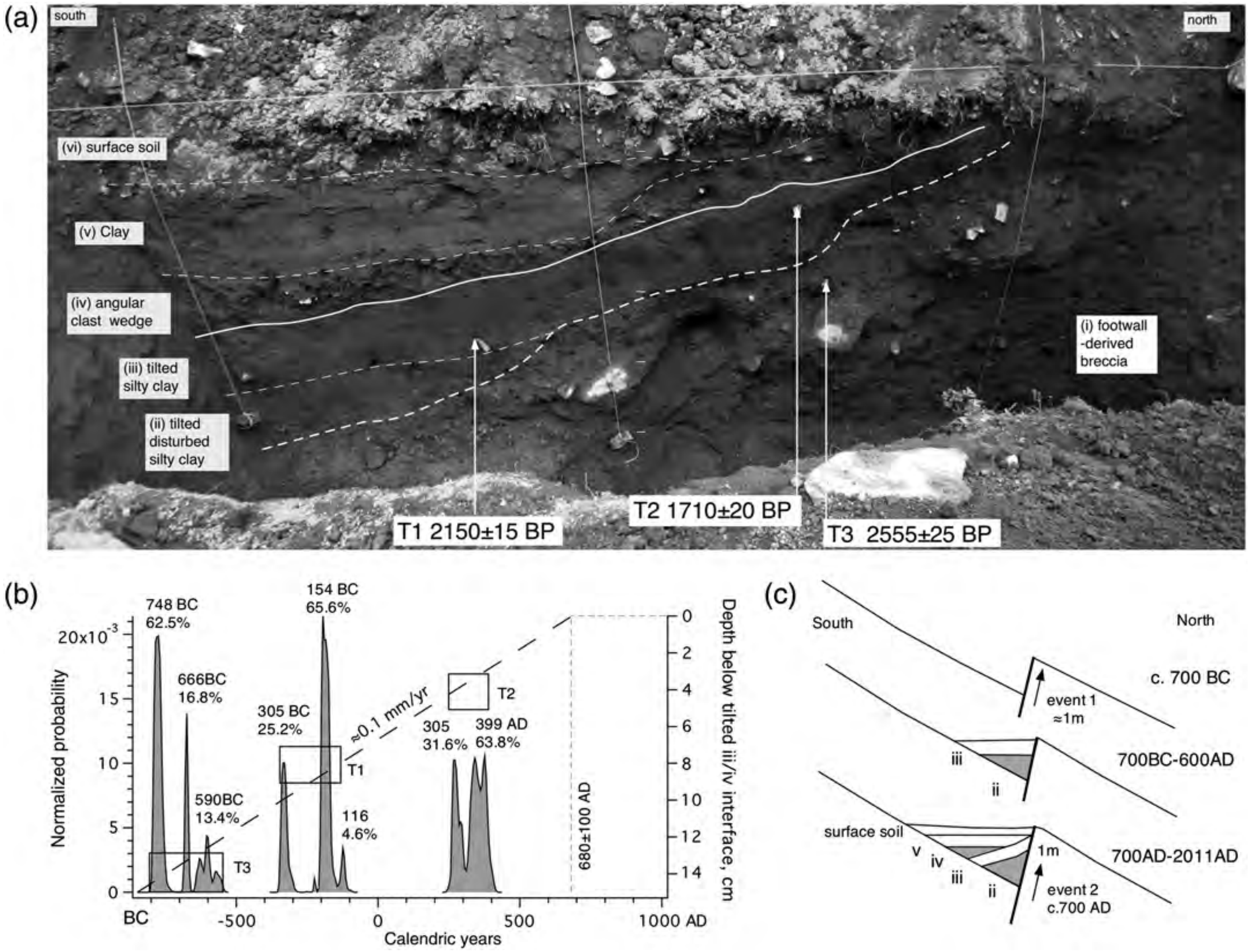
A brown-colored colluvial wedge of unsorted clasts embedded in angular gravel has developed downhill, below the present gray-colored surface scree. Segmented clasts of the distinctive damage-zone flanking the fault were found embedded in the upper layer of the colluvial wedge, close to their original locations on the fault plane, but overridden by the fault zone. We interpret these clasts as associated with a second slip event that formed a 20–30 cm high scarp, which collapsed onto the lower colluvial wedge. The clarity of this interpretation is rendered ambiguous by hillslope creep that has dragged other hanging-wall materials across the fault zone in the shallow subsurface. We found no materials with which to date its slip. It is possible that the northern flank of the fault (the footwall) has been partly eroded, which suggests that our measurement of maximum offset may be underestimated.

Trench 2 at the west end of the fault (km 0.9 in Fig. 1) revealed no structure or dateable materials. The colluvial wedge consisted of an unstratified brown colluvial unit filled with tabular rocks varying from a few cm to 1 m in size within thick clay. In contrast, Trench 3, at the western end of the fault (km 3.8 in Fig. 1) in a low-energy hillslope channel, revealed clear stratification and sequential filling by laminar layers of silt, small angular pebbles, and ponded muds (Fig. 7a). Charcoal fragments at three levels in this trench range in age from ≈750 B.C. to ≈400 A.D., suggesting that filling of the sag pond occurred initially ≈700 B.C. Because we did not excavate to the base of the infilled sag pond, we conclude that fault offset occurred at or before this time (Table 1). The uphill (south-southwest) tilt of units (iii) and (iv), which are fine silty-clay sediments, requires us to invoke a second slip event here with slip of at least 30 cm and possibly as much as 1 m. The date is inferred by assuming a uniform sedimentation rate below the top of layer (iii) as suggested by the plot of calendric age versus depth in Figure 7b. An initial depositional slope to units (ii) and (iii) are excluded because there is no source for sediments on the north lip of the sag pond (Fig. 7c). The sag pond is bounded to the north by a 1–2 m wide scarp that falls off steeply to the north (Fig. 6). The recent age for slip is consistent with Oldham's observation that several of the sag ponds have yet to be completely filled in with colluvium and downhill slope wash, and their downhill surfaces have not been denuded.

DISCUSSION

The association of ridge-crest faulting resulting in uphill-facing scarps is typical of fractures in deglaciated terrain known as sackungen, gravity collapse fractures (sackung = singular) caused either by deglaciation or by hillside erosion resulting in debuttressing of steep hillsides (Kinakin and Stead, 2005; Ambrosi and Crosta, 2006). Typical sackungen have scarp lengths of 15–300 m, scarp heights of 1–9 m, slope heights of 400–1200 m, and occur on slope gradients of 25°–50° (McCalpin and Irvine, 1995). The Oldham fault occupies the uppermost 600 m of a 3700 m high recently glaciated divide, and records pure dip-slip, typical of sackungen. In the case of the Oldham fault, however, we have clear evidence for slip of an existing fault with a well-developed, albeit thin, gouge zone, flanked by ≈20 cm wide damage zones indicative of a long history of slip. Moreover, although the east and west ends of the main fault and its secondary splays downthrow steep north-facing slopes typical of sackungen, the central 1 km of the main fault cuts a north–south-trending ridge at right angles. Oldham's fault is 4 km long, which is longer than typical sackungen.

Sackungen frequently follow existing weaknessess in rocks (McCalpin and Irvine, 1995; McCalpin, 2009), and we found in our exploration of the nearby mountainsides that fractures with weakly developed gouge zones are exposed in gullies with 20–50 m spacing and at arbitrary azimuths and dips. Within them we saw evidence of chemical corrosion, mineralization, and fluid pathways, which presumably represent weaknesses and zones of lowered friction that could be exploited by the stresses of gravitational collapse, or tectonic stress. That is, we interpret the Oldham fault as a complex fracture system



▲ **Figure 7.** (a) View of east-facing wall of Trench 3 after excavating 1 m into the filled sag pond shown in Figure 6. Vertical strings are spaced at 1 m intervals. Radiocarbon dates of charcoal samples are from Table 1. The fault trace was not exposed but is presumed to lie below the south end of the trench dipping steeply to the north. Fine silty units (iii) and (iv), now tilted toward the hillslope, accumulated at ≈0.1 mm/yr between 700 B.C. and 600 A.D. in a sag pond. (b) Illustration of the probability distributions of calendric date conversions (Table 1) for units i–iii. Boxes indicate age/depth uncertainty below the tilted surface of unit (iii), with a least squares intercept indicating its age as 680 ± 100 A.D. (c) These were tilted down to the south by a second slip event at an inferred date of circa 700 A.D., corresponding to the top of layer (iii) and covered by coarse gravel layer (v), after which slow sediment accumulation resumed.

Table 1
Radiocarbon Results and Calendar Ages

Sample	Depth below iv (cm)	^{14}C yr B.P.	Mass C (mg)	From	To	Probable	%
CURL 14021 T1	7±1	2150±15	0.4	305 B.C.	116 B.C.	154 B.C.	65.6
CURL 14014 T2	4±1	1710±20	0.5	305 A.D.	399 A.D.	399 A.D.	63.8
CURL 14012 T3	14±1	2555±25	0.6	748 B.C.	590 B.C.	748 B.C.	62.5

Upper and lower 2-sigma limits (95.4% confidence interval) of the estimated calendar-age solution from OxCal 4.2 (Bronk Ramsey, 2009). The most probable dates are listed in the last two columns. Probability distributions representing the normalized calendar-age solutions for each charcoal sample are plotted in Figure 7b. CURL numbers are University of Colorado Laboratory for Radiocarbon Preparation and Research accession numbers.

linking existing faults, fractures, and sackungen with general east-southeast strike.

If the Oldham fault is not a gravitational collapse sackung, its setting and strike is difficult to explain in the context of the sense of inferred maximum principal stresses in the Kashmir Himalaya. Focal mechanisms at depths of 20 km (Global Centroid Moment Tensor [CMT] catalog, available at www.globalcmt.org/CMTsearch.html, last accessed 1 May 2013) and Global Positioning System displacement vectors (Khan *et al.*, 2008) indicate north-northeast–south-southwest contraction, precisely opposite to the sense of extension implied by the Oldham fault and its associated splays.

Three flexural mechanisms occur to us that could result in tensile stress near the Earth's surface and especially at high elevations: (1) erosion, isostatic adjustment, and upwarping of the Chenab drainage, (2) translation of the Himalayan accretionary wedge over a ramp thrust at depth, or (3) passage of a bulge on the surface of the underthrusting Indian plate beneath the Himalaya (Schiffman *et al.*, 2011). The first of these would generate a series of circumferential faults centered on the region of maximum uplift, whereas the second and third would be consistent with a region of extension parallel to the Himalayan trend, for which the stress amplitude would be greatest at high elevations.

A sequence of five faults subparallel to the Oldham fault with similar lengths in a north-northwest-trending line, and with an approximate 5 km spacing in the 30 km region south-southeast of the Oldham fault, was described by Schiffman *et al.* (2011). Others can be identified with less certainty to the north, but with the same trend, strike, and spacing. This alignment of faults is consistent with the presence of a mountain, or ridge, on the Indian plate advancing beneath southeast Kashmir. The pattern of faults and their association with the Jammu re-entrant is suggestive of the patterns generated in synthetic laboratory models of seamount subduction (Dominguez *et al.*, 1998, 2000). However, the 5 km spacing of fractures is unlikely to represent the successive positions of a high point on the Indian plate because the current convergence rate is ≈10 mm/yr (Khan *et al.*, 2008), and five or more faults would thus require a 2 million year formation span. This is inconsistent with the recent dates of slip of the Oldham fault and the fresh appearance of similar subparallel faults.

The narrow, well-developed and slickensided clay gouge found in the rock exposure in Trench 1 and the presence of a narrow (10–20 cm) damage zone adjoining the fault plane suggests that the fault has moved many times in the past. However, the two slip events that we describe presumably followed a long period of quiescence on the fault, because the fault scarp is clearly of recent origin and has not reactivated any well-established fault-controlled morphology. Slip varies along its length. Supposing that the entire 8-km-length of the fault system slipped 50 cm in a single earthquake with a fault width of 3 km, it could have done so with $5.6 < M_w < 5.8$. A lower rigidity modulus might prevail at these shallow depths, which would result in smaller magnitudes, and it is possible that the fault slipped in part aseismically. The collapse of fault-zone clasts in Trench 1, however, suggests that slip was probably abrupt. Although slip could have occurred here over a few hours or days, it is tempting to interpret the presence of the coarse gravel wedge (iv) in Trench 3 as the product of surface pebbles in the hillslope above the sag pond rolling downslope during severe shaking.

CONCLUSIONS

Active surface faults in the Himalaya are uncommon, and it is fortuitous that Oldham encountered an active fault during his reconnaisance in 1888, a finding that was especially serendipitous given the short length of the fault in glacial terrain. That his observation was effectively lost can be understood in the context of its unimportance to the economic mission of the Geological Survey of India at the time. It paled to insignificance just nine years later, following the occurrence of the M_w 8.1 1897 Shillong earthquake, which indirectly led to Oldham distinguishing between P and S waves (Oldham, 1899) and subsequently to his observations on the diameter of the Earth's core (Oldham, 1906).

We interpret the fault as a sackung that slipped ≈1 m around 700 B.C., and again ≈700 A.D., partly in response to gravity collapse in the mountains, but possibly assisted by stresses associated with flexure along an east-southeast axis. The principal fault is shorter than 5 km and consists of a reactivated, almost vertical, normal fault down-throwing the mountains to its south. Several of the hillside sag ponds formed by the fault have yet to fill, attesting to a low sediment accumulation rate (< 1 mm/yr). A suite of similar, short, ridge-top faults, aligned at approximately 5 km intervals, sub-parallel to Oldham's fault in southeast Kashmir suggests an underlying cause for focusing tensile stresses in a narrow longitude range.

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