Kashmir Valley Megaearthquakes

Estimates of the magnitudes of past seismic events foretell a very shaky future for this pastoral valley

Susan Hough, Roger Bilham and Ismail Bhat

Flanked on all sides by mountain ranges, the Kashmir Valley has been for millennia both blessed and cursed by its geography and geology. The Himalaya and Pir Pinjal ranges have provided native Kashmiri people an inexhaustible source of water to irrigate naturally fertile soils. At the same time, would-be invaders have faced geography that has formed nearly impregnable lines of defense. But the massive forces that push these mountains upward pose a real and present danger to the pastoral setting of the valley. As the Indian subcontinent continues to push northward, stresses continue to build on massive faults along the Himalaya arc. These stresses let loose along a relatively small fault segment in the fall of 2005. More than 80,000 people died when the magnitude 7.6 Muzaffarabad quake struck the Pakistan Kashmir, reducing houses, even entire mountainsides, to rubble.

The Kashmir Valley itself has been rocked by many moderate and large earthquakes in historic times. Traditional architecture in the region reveals two basic construction styles: *taq*, which involves masonry infill walls and wood "runners" at each floor level to tie the walls together with the floors; and *dhajji-dewari*, which uses a timber-braced frame with masonry infill *(see Figure 3)*. The use of wooden structure elements provides a sometimes surprising degree of resistance to earthquake shaking. In the late 16th century, Abul Fazl, philosopher and court historian of Akbar, wrote "On account of the abundance of wood and the constant earthquakes, houses of stone and brick are not built."

Traditional Kashmir architecture might be well suited for earthquake country, but as the population of the valley has grown to 5 million, elegant traditional buildings have given way to a ramshackle hodgepodge of poorly built structures, most of which have little resistance to earthquake ground motions.

History as well as geology tell us that the Himalaya arc will experience much bigger earthquakes than the 2005 event—bigger than the damaging moderate earthquakes that have struck the Kashmir Valley in recent centuries. Given the massive scale of faults in this part of the world, and the enormous forces, earthquakes in the range of magnitude 8.5, maybe even greater, will inevitably strike. In recent years geologists have found the scars left behind by three monster quakes along the arc between Bhutan and Pakistan, around 1125, 1400 and 1505. *(see Figure 4)*. The first two dates are estimates precise to at best ±50 years. The 1505 event is documented in the historical record, the shaking having destroyed Bhuddist monasteries in Tibet along a 600-kilometer segment of the central Himalaya. Recent field investigations reveal that in each of these megaquakes the frontal hills of the Himalaya advanced in a few seconds more than 20 meters over the plains of India.

Bigger than Big

When any earthquake strikes, relative motion occurs suddenly on opposite sides of a fault, either horizontally or vertically. In the great 1906 San Francisco earthquake, the San Andreas fault moved on average about 4 meters horizontally over a distance of some 450 kilometers, producing an earthquake of estimated magnitude 7.9. With 20 meters of slip, the largest Himalayan megaquakes are in a different league from the iconic Big One feared by Californians. (Please see the sidebar for an explanation of magnitude.) Recent calculations moreover suggest that megaquakes, with magnitudes well above 8.0, are not just possible along the Himalayan arc; they are necessary to relieve the stresses generated by the continuing northward motion of India into Eurasia.

Figure 1. A homeless survivor sits near collapsed buildings in Muzaffarabad, Pakistan Kashmir, at the break of dawn after an October 15, 2005, earthquake killed 80,000 people. Quakes like this one take place frequently along the Himalayan arc to relieve accumulated stresses generated by the collision of the Indian and Eurasian tectonic plates. The authors have examined geological and historical evidence in the region and conclude that a temblor of magnitude 8 or greater probably has not hit the Kashmir region since the mid-1500s, making an imminent megaquake not just likely but necessary to relieve these stresses. The devastation that would accompany a magnitude 8+ earthquake would be many times greater that of the M7.6 2005 event that was centered near Muzaffarabad.

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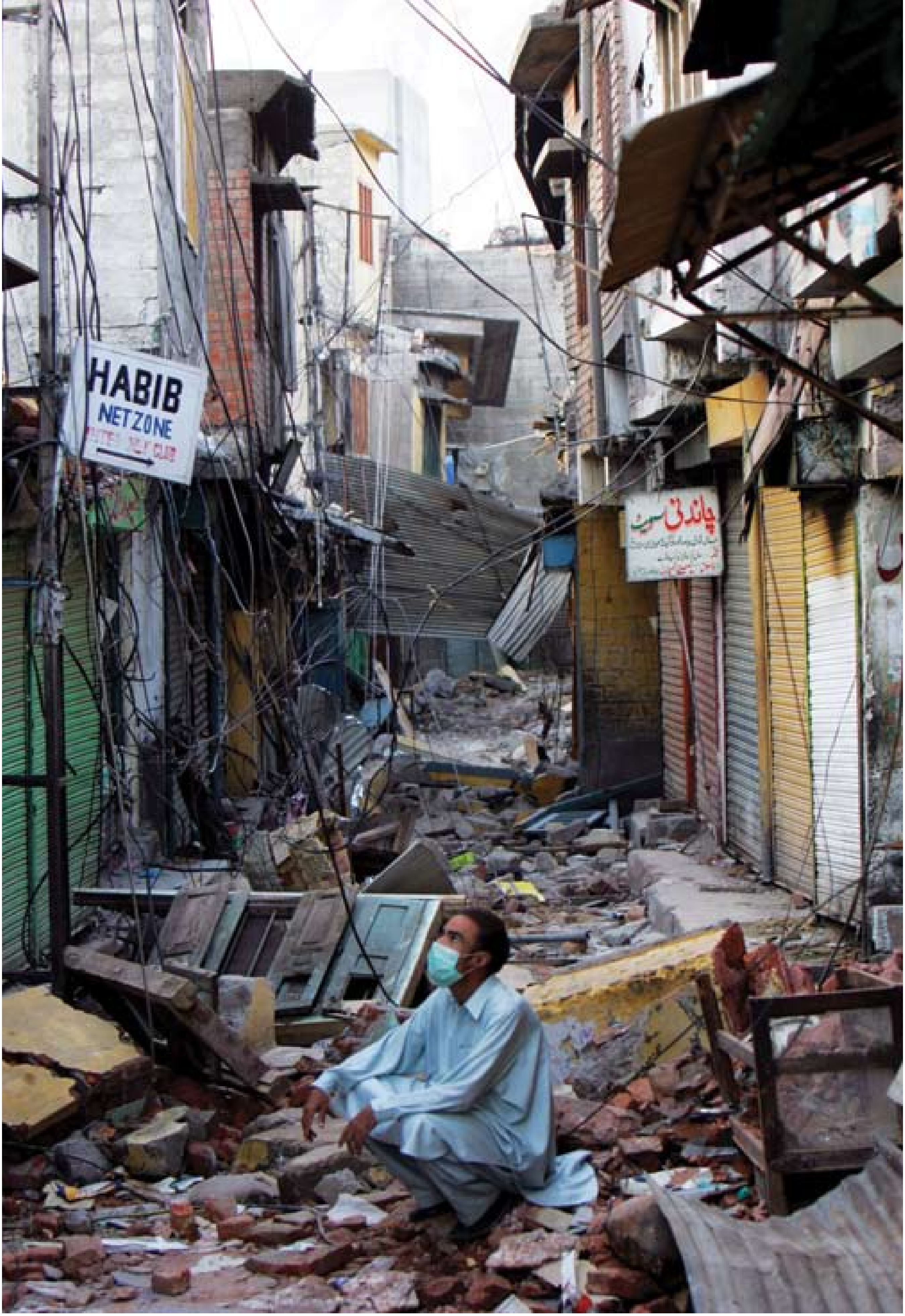
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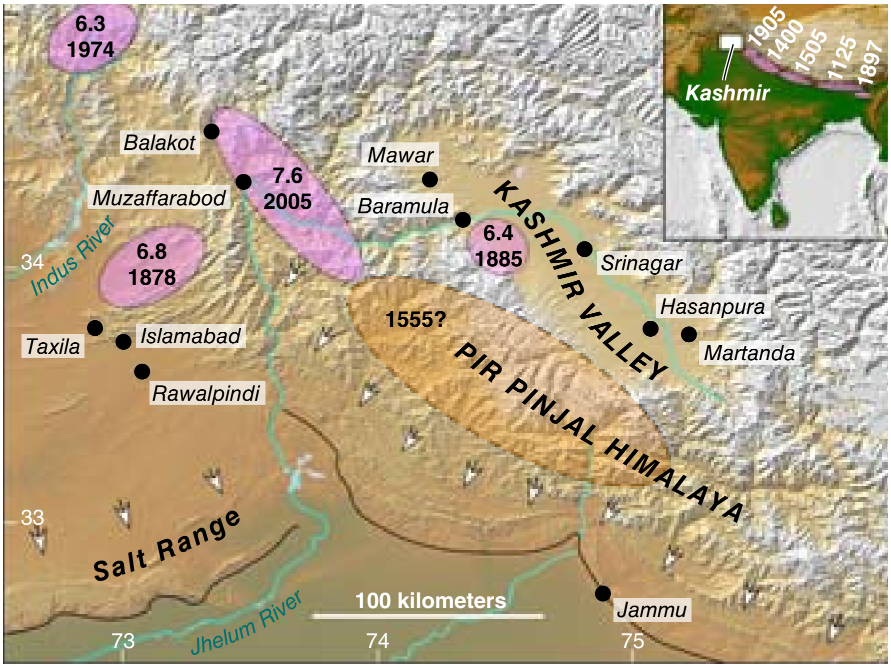

Figure 2. The Kashmir Valley is flanked by the Pir Pinjal Himalaya to the south and the Himalaya to the north. Located at the junction of the Indian and Eurasian plates, the area is routinely rocked by earthquakes. Those with relatively well constrained locations are shown in pink. Many more are mentioned in historical accounts but usually with insufficient detail to estimate location or magnitude. The dashed ellipses show a speculative location for a large 1555 earthquake. The inset shows the locations of great earthquakes along the Himalayan arc, showing that the Pir Pinjal Himalaya region may be long overdue for such an event.

Paleoseismological investigations remain in their infancy along the Himalayan arc; eventually they will tell us much more about historical as well as prehistoric events. Meanwhile, the historical record can provide valuable information about events in recent centuries. In particular, archival accounts provide a direct snapshot of the severity of shaking associated with past events. As seismologists we always seek to estimate magnitudes, locations and rupture parameters, but the key to hazard assessment and mitigation is how strongly the ground will shake in future earthquakes.

Focusing on the Kashmir Valley, one finds a written history that reaches back almost 5,000 years, but surviving historical sources reveal very little about earthquakes prior to the 16th century, and many reports are merely repetitions of earlier fragments, embellished or "corrected" by puzzled later historians. The records that have survived contain a spaghetti soup of place names of damaged cities that have been renamed a dozen times and misspelled and transliterated over and over. In recent years seismologists

What's the Meaning of Magnitude?

You may have noticed that the name of the father of earthquake magnitude, Charles F. Richter, seldom appears anymore when earthquakes are mentioned. Has the so-called "Richter Scale" been abandoned? Not really. It would be more accurate to say that Richter's mathematical constructs have been extended and refined to suit different situations.

At its simplest, the Richter magnitude scale is a logarithmic description of the amplitude of the movements of the pen arm on a certain type of seismograph (the so-called Wood-Anderson seismograph), normalized to a common distance. Richter designed the scale to describe earthquakes in Southern California measured by seismographs in Southern California.

Earthquake magnitude in Southern California was for many years reported on the Richter scale, a logarithmic calculation of the movement of the pen arm on a Wood-Anderson seismograph, an example of which is shown here. Photograph courtesy of J. B. Macelwane Archives, Saint Louis University.

Richter magnitudes reflect the high-frequency vibrations of ground movement. Seismometers in Southern California still record these vibrations from local earthquakes. Although you won't often see a strictly Richter-derived magnitude these days, you will see magnitudes noted as ML (for local), which are essentially equivalent to a classic Richter magnitude.

Things become more complicated when an earthquake is large. The Wood-Anderson seismograph turns out to be tone-deaf to the booming long-period energy that large earthquakes release. Above magnitude 5.5 or so, the level of high-frequency shaking does not reflect accurately the overall size, or energy release, of an earthquake. Refinements to the magnitude scale have therefore focused on the full spectrum of energy released by an earthquake, including the so-called surface waves, which propagate near the earth's surface. The gold standard is now generally assumed to be the moment magnitude scale, or Mw, which reflects the overall size of an earthquake: the size of the fault that moved and the amount of slip.

These days seismologists often cite just a magnitude, M, not specifying which type it is. In such a case, if the earthquake is large, it's usually safe to assume that this is Mw. This scale, like all later refinements, was designed to dovetail smoothly with Richter's original formulation. That is, magnitude units are arbitrary; no physical units are attached. Thus the *meaning* of magnitude values—M3 as a small shock, M6 as a moderate shock—are the same meanings that Richter defined when he introduced earthquake magnitude in 1935.

"On account of the abundance of wood and the constant earthquakes, houses of stone and brick are not built."—Abul Fazl, 16th century philosopher and court historian of Akbar

Figure 3. Traditional construction in Kashmir incorporated a mixture of timber and masonry elements. Referred to as *dhajji-dewari*, this system served not only to make the best use of available local materials but also proves to be very robust in an earthquake. These buildings in Srinagar, Kashmir, are tied together by wooden posts and beams and have masonry infill. Note also the metal tie straps at the building corner in the right-hand photograph. Unfortunately, as the population of Kashmir has surged to five million in recent years, new construction has abandoned the time-tested techniques in favor of a ramshackle hodgepodge of masonry buildings with little resistance to ground shaking. (Photographs by Roger Bilham unless otherwise noted.)

have realized that one important key to understanding Kashmir's future earthquakes lies in these accounts, their confused and confusing nature notwithstanding. This has led several intrepid scholars back to early written materials archived in India and Europe. Rummaging through Sanskrit, Tibetan, Arabic, Moghul and Muslim texts has become much easier now that historians (and seismologists) have computerized search engines to scan these ancient works, many of them first available to western scholars in the 17th to 19th centuries.

In the past decade, two earthquake engineers have been responsible for focusing the readings of historians on the details of earthquakes in Kashmir: R. N. Iyengar of the Central Building Research Institute in India and N. N. Ambraseys of Imperial College London. Their historian counterparts were Shri Devendra Sharma, a scholar of Indian history at the Central Building Research Institute, and David Jackson, a Tibetan scholar at the University of Hamburg. When viewed through the eyes of these seismologists, the original texts often tell a much more explicit tale than that comprehended by the writers of histories now available to us.

Yet the texts sometimes remain ambiguous. For example, the Persian scribe, Pir Hasan Shah, writing in 1690, described a landslide that dammed the river near Jhelum in 883 In an independent Sanskrit account written circa 1400 we learn that this natural dam and its disastrous reservoir were ingeniously cleared by a Kashmir engineer named Suyya, after whom the present town of Sopor (Suyyapura) is named. Was this an earthquake-triggered landslide or one precipitated by torrential rain? Earthquakes frequently dam rivers, as in 2005 when the rivers of western Kashmir were impounded for minutes and in some cases months by rocks, trees and loose soil shaken from the steep hillsides. But even if we knew the cause of the 883 catastrophe, with one isolated account we could never distinguish a small local earthquake from a truly big one. Yet these are the disasters whose past scale and future likelihood are of most importance to Kashmiri society.

The magnitude of an earthquake in historical times must be inferred from its reach—the regional footprint of its damage and notice. A further clue can be the spate of clustered large aftershocks symptomatic of the adjustments in stress that follow a truly massive earthquake. One such Kashmir earthquake for which damage was reported from a wide geographic area occurred in 1555, or possibly 1554. (The date of the mainshock in historical accounts is 962 aH on the Muslim lunar calendar, which corresponds to the period from November 26, 1554, to November 15, 1555.)

The earliest and presumably most reliable description of this earthquake is from Shuka, who continued a long tradition of *Rajatarangini*—the history of kings—in the late 16th century, ending with Akbar's conquest of the region in 1586. Shuka tells us that the earthquake occurred in September of 1555, in the second watch of the night (4 to 8 hours after sunset).

The earliest accounts of this event describe frequent shocks in Kashmir during the month prior to the mainshock, and several reports describe a series of continuing aftershocks. The 1555 mainshock thus appears to have been part of a classic foreshock-mainshock-aftershock sequence that extended over a period of years. The documented effects as well as descriptions of strong aftershocks continuing for at least weeks point toward a shallow, large-magnitude event. Ambraseys and Jackson tentatively assigned a surface magnitude (Ms) value of 7.6, although the estimate is clearly imprecise, and the magnitude might have been higher (7.8–8).

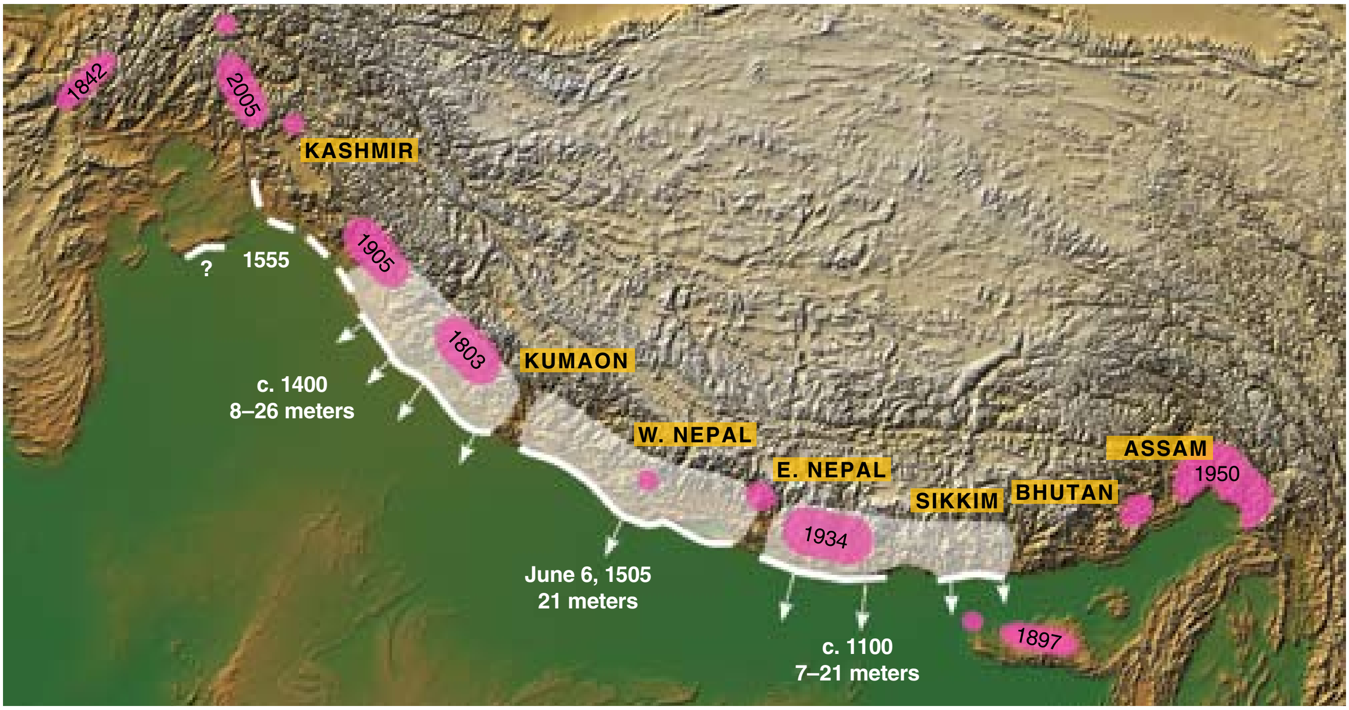

Figure 4. The Himalaya form a graceful arc separating the Tibetan Plateau from the Indian plate, which moves northward at more than 15 millimeters per year. The pink areas are the rupture zones of damaging earthquakes (magnitudes 7.3–8.6) in the past two centuries, and the grey areas are the inferred enormous rupture zones of Medieval megaquakes. Only one of these, in 1505, is recorded in historical texts. The arrows indicate the locations where trenches excavated by Steve Wesnousky (University of Nevada, Reno), Jerome Lave (Centre de Recherches Pétrographique et Géochimiques, Nancy) and Doug Yule (California State University, Northridge) have documented the slip in these earthquakes. The 1555 rupture zone is conjectural.

Historical descriptions tell of portentous but often ambiguous effects. Significant loss of life apparently occurred as a consequence of building collapse, ground failure and several large landslides triggered by the earthquake. The following was translated by Briggs in 1910:

> The year 962 (1554/5) was remarkable for a severe earthquake in Kashmeer; on which occasion the town of Dampoor, with several orchards and gardens, was removed from the eastern to the western bank of the Behut river; and the town of Jadra, situated under the mountains, was destroyed by the falling of great part of the mountain on the town, in which upwards of six thousand persons perished.

Most of the later accounts also describe the demise of a village under a large landslide. The name of the village differs in different translations: Jadra, Mardar, Mawar, Maru Pergam. Although the names differ, the similarity of the accounts suggest a common origin. The location of Maru Pergam, or Mawar, is uncertain. One of the challenges of interpreting early historical accounts in this part of the world is the inconsistent translation of place names. A present-day village of Mawar is situated northwest of Baramula, at the base of the Pir Pinjal Range in western Kashmir. Others have suggested the location to be a village 140 kilometers southeast of Srinagar.

The number of fatalities associated with the landslide is reported as 600, although some writers added an extra zero or two. Thus a 16th-century writer describes the village of Mardar being overwhelmed by a landslide in which 60,000 were killed—probably far more than its pre-earthquake population. Ferishta, a late-16th century Persian traveler ,puts the number of dead at 600, which is generally regarded as more realistic than higher figures.

Ambraseys and Jackson identify six locations in the Kashmir Valley that were damaged by the earthquake. The most westerly of these six sites is at Baramula, 50 kilometers west-northwest of Srinigar. The easternmost account that can be reliably located is the shrine of Martanda (discussed below), about 5 kilometers east of Anantnag. Although accounts describe effects in detail, a reliable intensity assignment cannot be ascribed for any location. For example, although historical accounts tell us that a "great part of the mountain fell," landslides are known to be unreliable indicators of shaking intensity.

The 1555 earthquake is most famous for the repetition, by several historians, of a curious swap in the positions of two towns across the Jhelum river. The puzzling statements are quite explicit. For example, Nizamuddin Ahmad, an officer in Akbar's court, wrote circa 1585 that, "The villages of Jalu and Dampur with their buildings and trees were removed from one bank of the (Jhelum) to the opposite bank." Later historians clearly echo these reports, sometimes adding their own embellishment. The roots of this famous and enigmatic bit of lore appear to be found in Shuka's account, which states simply that, "The confusion caused by the earthquake in two towns of Hasainapura and Hosainapura, situated at some distance across the river, can be seen to this day."

Shuka thus points not to some sort of magical transportation of two villages but to substantial disruption of both, most likely as a consequence of ground failure along the river bank rather than shaking per se. Once again, however, one cannot assign a shaking intensity based only on accounts of ground failure.

Unraveling the effects of the 1555 earthquake might start to sound hopeless. At a minimum there is no hope of mapping out the distribution of shaking effects at the level of detail that has allowed seismologists to investigate later historical earthquakes very closely. Still, the inferred locations of available accounts do provide us with enough information to draw some conclusions about the reach of this important event. Moreover, a sleuthing trip in the Kashmir Valley has helped provide useful clues to understanding the jumble of historical accounts. For example, along the river where the present-day villages of Hussainpur and Hossainpur are found, incised riverbanks reveal a propensity for slumping even in the absence of earthquake shaking *(see Figure 6)*.

On Solid Ground

With colleagues from the University of Kashmir the authors visited the famous Martand (or Martanda) Sun Temple (*see Figure 7)*, which is the subject of another curious legend. According to Sukha, "It was owing to the glory of the holy shrines of Vijayeshvara Martanda and Varahakshetra, that fears and apprehensions from earthquake were not felt by the inhabitants of these places." Later historians assert that the people of the valley believed the Martanda Temple itself was "saved by divine protection." Sukha suggests that the earthquakes were felt in the Anantnag region and present-day Baramula (Varahakshetra), but the damage was less severe in these regions than elsewhere.

Today the Martanda Temple, which escaped the fate of most of Kashmir's early temples—being razed in the early 15th century by Sicunder the Iconoclast (literally the "destroyer of icons")—is far from having avoided the ravages of man and nature. Yet the delicate arches and towers that remain attest to it having been spared total destruction by an earthquake in 1555, if not serious damage by later conflicts. The temple sits more than a kilometer and half high but only about 90 meters above the elevation of the adjacent valley. Nearby villages are themselves elevated by about 60 meters relative to the rest of the valley. To the modern seismologically trained eye an interpretation suggests itself, namely that shaking was less severe, and inhabitants were left less fearful, because the temple and surrounding villages were constructed on competent rock and thus did not experience the strong amplification effects that would have almost surely taken place throughout the valley. The temple was also clearly in part saved by its construction, which consists of massive carved interlocking stone blocks, dressed on all sides and individually cut to fit together.

At the end of our sleuthing expedition we were still left with as many questions as answers. It still was not clear, for example, whether the large landslide reported to have buried Mawar had occurred at one end of the valley or at a similar village, Maru Petgam, at the other end. Nonetheless, all indications point to an earthquake that caused significant disruption over the full extent of the Kashmir Valley, consistent with a magnitude of 7.6-7.8. Although one cannot rule out an even larger magnitude, evidence suggests it was not a great Himalayan megaquake.

Attesting to the severity of the event we have Sukha's account of the scope of the calamity: "… it destroyed many people. It caused holes in the ground, and travelers going on their way were misled at every step. Houses fell into these holes at night." Sukha also wrote that "In the month of Ashvina (September) in the year 30 whose chronology (1555), there occurred frequent earthquakes on account of the wicked acts of the king, as if the earth suffered from flatulence." He goes on to distinguish the mainshock as by far the most severe of what must have been multiple earthquakes felt during the month.

Not Whether but When

From GPS measurements we know that no part of the Himalaya can be spared as the Indian plate eases north-

> *"The confusion caused by the earthquake in two towns of Hasainapura and Hosainapura, situated at some distance across the river, can be see to this day."*—Shuka

Figure 5. Tilted tree stumps show slumping along a tributary of the Jhelum River near the villages of Hussainpur and Hossainpur in Kasmir. Thus, the 16th-century reports of towns trading places across a river may be explained by ground failure along the river bank rather than by wholesale repositioning by earthquake shaking. (Photograph by Susan Hough.)

"It was owing to the glory of the holy shrines of Vijayeshvara Martanda and Varahakshetra, that fears and apprehensions from earthquake were not felt by the inhabitants of these places."—Shuka

Figure 7. Martanda Sun Temple has been spared the full ravages of not only Sicunder the Iconoclast, who razed many temples in Kashmir, but also the shaking of many large earthquakes. The authors attribute the temple's seismic survival to two important features. First, the temple was built about 90 meters above the valley floor on competent rock not subject to amplification of motion by unconsolidated sediments. Second, the masonry construction incorporates massive carved interlocking stone blocks fitted tightly together.

ward under the mountains—earthquakes are inevitable along the entire range. Further, the 1554/5 earthquake may have been the most recent of the irregular large earthquakes in the Kashmir region. Again, more by inference than by force of evidence, we suspect that the 1554/5 event focused at the base of the Pir Panjal Range (a triple tautology in that *Pir* and *Panjal* and *range* all mean mountain). This is the westernmost expression of the Himalaya, and the region that has not slipped in a large earthquake since 1555 is roughly 400 kilometers by 80 kilometers—big enough to host an M8 earthquake. The GPS data tell us that convergence in the region is now more than 15 millimeters per year. If this convergence has been continuous since 1555, we have more than enough potential slip (6.8 meters) ready right now to drive another earthquake of similar size.

The uncomfortable conclusion is thus that a repeat of the 1555 earthquake may be close at hand, and one cannot dismiss the specter of a future megaquake extending well beyond the confines of the Kashmir Valley. How close? Unfortunately, the unknowns currently far outweigh the knowns, and the mechanisms of earthquakes contain none of the elements characteristic of a clock. We note, however, that the stresses generated by the 2005 Kashmir earthquake, although only a relatively modest one at Mw 7.6, have not dissipated stresses already stored near the 1555 rupture zone. Indeed, they serve to enhance them. Looking at other major faults around the world, it is clear that adjacent fault segments sometimes break sequentially, like toppling dominoes, with major earthquakes separated by days, months, years … sometimes a few decades. If the Kashmir segment is the next domino to topple along the Himalayan arc, the future earthquake will unleash devastating ground motions on a corner of the world that is, in every sense of the phrase, on perilously shaky ground.

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