Seismogenesis in the stable continental regions and implications for hazard assessment: Two recent examples from India*

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Occurrence of three earthquakes in the Indian stable continental region (SCR) during 1993–2001 has triggered many questions on their nature of recurrence, characteristic size and mechanisms. Seismogenic sources in Killari and Kachchh may be considered as representative examples of two distinctive classes of SCR earthquakes, the former originating on discrete faults in the unrifted part of the crust, and the latter associated with larger structures in an ancient rift. Seismic-hazard evaluation in these regions must take into account the inherent characteristics of these causative structures, which are reflected in their respective seismic productivities. While the Killari-type earthquakes are of moderate size (M ~ 6) and repeat over intervals of several tens of thousands of years, the Kachchh-type earthquakes are larger (M > 7), and may have much shorter recurrence intervals. The observation that multiple sources related to unexposed seismogenic structures with unknown seismic histories exist in the Kachchh region, calls for concerted efforts to study this important seismogenic zone in SCR India.

FIVE damaging earthquakes occurred in India during the last ten years, causing substantial loss of life and damage to property. These earthquakes occurred at Uttarkashi (1991, m_b 6.5); Killari (1993, M_w 6.2); Jabalpur (1997, M_w 5.8); Chamoli (1999, m_b 6.3) and Bhuj (2001, M_w 7.7) (Figure 1). What is noteworthy about this sequence of earthquakes is that three out of these five events occurred in peninsular India, a part of the stable continental region (SCR), characterized by slow deformation and low seismic productivity[1]. The Killari earthquake occurred in a region that had not experienced any notable seismicity in the past and was regarded to be of low seismic risk. This earthquake came as a total surprise and is a grim reminder that a damaging SCR earthquake can occur even at the least expected location. On the contrary, the 2001 Bhuj earthquake occurred in a region that has experienced previous large earthquakes, the most notable being the one in 1819, a classic example of SCR-seismicity associated with passive rifts[2]. Both these events attracted global attention for a variety of reasons. For example, the Killari earthquake shares many characteristics of earthquakes in SCR–Australia. Geologic and tectonic settings associated with these earthquakes find many parallels elsewhere. Association with an ancient rift, a characteristic shared by many of the larger SCR earthquakes, such as the 1811–12 New Madrid events made the Bhuj earthquake a classic contemporary case. For example, analysis of the Bhuj earthquake is considered to be relevant for the assessment of earthquake hazards, most importantly, the liquefaction and ground failure potential of the New Madrid (Central US) seismic zone[3].

Despite its association with a known palaeorift that has generated large earthquakes in the past, there still was an

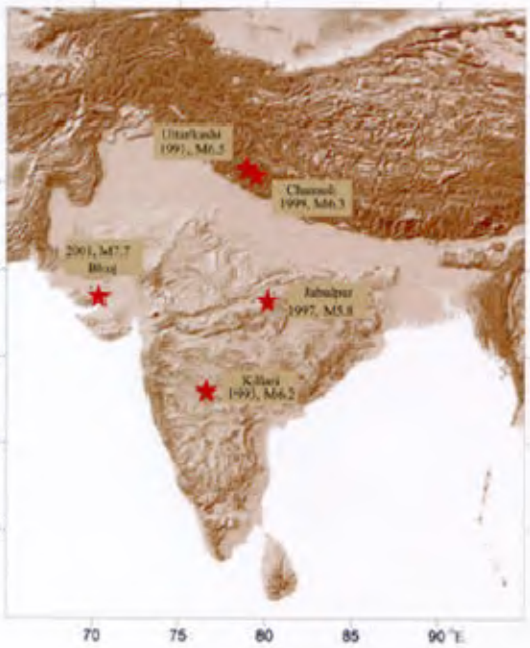

Figure 1. Map showing locations of Bhuj, Killari, Jabalpur, Uttarkashi and Chamoli earthquakes.

*Dedicated to Prof. S. Ramaseshan on his 80th birthday.

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element of surprise associated with the Bhuj earthquake because the previous large event in this region occurred less than 200 years ago. Going by the conventional understanding of recurrence patterns in SCRs, it was too soon for the region to experience another large earthquake. Furthermore, the 2001 earthquake occurred on a fault that was neither known previously, nor exposed at the surface[4], reminding us that within a known seismogenic zone, there may be unrecognized independent sources. Because the last earthquake may have occurred outside the time segments that we are generally concerned with, such sources may remain unnoticed, until a large earthquake occurs, as it happened in 2001.

Occurrence of three earthquakes during a brief interval of ten years naturally triggered a lot of discussion on the mechanism and pattern of recurrence of earthquakes in SCR-India. In particular, the Killari earthquake and the unprecedented damage it caused, raised many questions. How frequently do large/moderate earthquakes occur in the SCR sources? How should we assess the seismic hazard in these regions, especially while dealing with sources that have not been active in the recent past and are thus associated with indefinite seismic histories? The existing state of knowledge tells us that SCR earthquakes originating from different tectonic settings differ in their size and repeatability. For example, a typical rift-related earthquake may be larger ($M \sim 7$) and may recur during shorter intervals compared to a cratonic earthquake, in an unrifted part of the crust[5]. Seismic hazard assessment in the SCRs must recognize these diversities and their implications on the size and recurrence of damaging earthquakes. In this article, we present diversities in the source characteristics and pattern of recurrence associated with the Killari and Bhuj earthquakes, two representative examples of non-rift and rift related SCR earthquakes.

Understanding the intraplate seismogenesis

Understanding the seismogenesis in intraplate regions has long been an outstanding problem. Although several hypotheses have been proposed, no single model adequately explains the observed pattern of intraplate seismicity[2,6,7]. Stress amplification near plutons[8], reactivation of faults within ancient rifts[2] and stress concentration near intersections[9,10] are some of the mechanisms that explain earthquakes in the continental interiors. In the broad class designated as 'intraplate' regions, SCRs form a different category, a distinction based on the age of the crust (2.5–0.5 b.y.) and lower deformation rate compared to active intraplate and plate boundary regions. Within the SCRs, failed intracratonic regions are regarded as major contributors in terms of seismic moment release[1,2].

Diversities in the pattern of earthquakes have been noted even within the same SCR. Based on the differences in recurrence pattern, deformation style and characteristic sizes, Rajendran and Rajendran[5] have classified earthquakes in the Indian SCR into three groups: belonging to pericontinental rifts, intracontinental rifts and unrifted cratons. Sources in the Kachchh, Jabalpur and Killari regions have been cited as representative examples from each of these groups. Earthquakes belonging to these three groups exhibit differences in the source characteristics, one aspect being the focal depth. For example, the focal depth of the Bhuj earthquake is 25 km (ref. 11) and that of the Jabalpur earthquake is 36 km (ref. 12). Compared to these earthquakes which originated at mid/lower crustal sources, the Killari earthquake was much shallower, at a depth of 5 km (ref. 13). Due to the inherent differences in their source regions, these earthquakes may vary also in their size and repeatability.

One of the most important questions to be addressed in terms of seismic hazard of SCR regions is the recurrence rate of large/moderate earthquakes, which is related to the tectonic loading rate. Clearly, the loading rate is much lower in the continental interiors compared to active plate boundaries. For example, the average rate of shortening across the Himalaya has been estimated as 20 mm/year[14]. This deformation is distributed over a zone, only about 150 km wide. In contrast, shortening and strain rates are much smaller in the continental interiors because they are distributed over a much larger area. Measurements of baselines across the US interior using Very Long Baseline Interferometry (VLBI), suggest baseline length changes less than 3 mm/yr, corresponding to a net strain less than 10^{-9} strain yr^{-1} (ref. 15), suggesting the general range of strain in the continental interiors. Although the average strain in the continental interiors is low, generation of localized pockets of higher strain has been suggested as the major reason for intraplate earthquakes[16].

Localized strain accumulation observed in association with some of the well-known and relatively better-studied SCR earthquakes suggests that the regional low strain can be overprinted by anomalous pockets of higher strain. For example, higher strain rate has been suggested[17] in the New Madrid Seismic Zone (NMSZ). Higher localized strain and recurrence rate between 500 and 600 years for M 7 + are reported also from Charleston, another passive continental margin seismic source[10,18]. The penultimate earthquake in the 1819 source in the Rann of Kachchh is estimated to have occurred in AD 893 (refs 19 and 20), but the data are inadequate to suggest a credible recurrence interval. The occurrence of two large earthquakes at the same source and a third one on a parallel fault, all happening over a period of about 1110 years, suggest relatively high strain build-up.

Projections on the estimated size of the earthquake as well as the recurrence pattern in the NMSZ, probably the best-studied among the rift-related SCR sources, are also not unequivocal. Based on palaeoseismic data, Tuttle *et al.*[21] suggest that the New Madrid region experienced a sequence of large earthquakes ($M \geq 7.6$) around

AD 900 and 1450, in addition to the historic events in 1811–12. With a repeat time of the order of 400–500 years, these cannot be considered infrequent. However, not all observations support this suggestion. For example, based on the slow deformation rate (0 ± 2 mm) across the NMSZ observed in later GPS surveys, it is argued that earthquakes occurring every 500–1000 years are likely to be in the lower magnitude range[22]. Based on studies of fault-related folding, Mueller *et al.*[23] suggest about 1 m slip in 500 years, corresponding to a magnitude of M_w 7.0 ± 0.3, an estimate lower than what is projected by Tuttle *et al.*[21]. Recurrence rate, maximum size and hazard evaluation in the NMSZ are now topics of an ongoing debate[24,25]. The example of New Madrid is cited here to illustrate uncertainties in the assessment of seismic hazard, even in a relatively better-studied SCR site.

While the ancient rifts in SCRs may be classified as structures capable of generating larger earthquakes during an interval of 500–1000 years, there are other intracratonic seismogenic structures that remain 'quiet' for much longer intervals. For example, the recurrence rate of moderate earthquakes in some of the known seismic source zones in SCR–Australia is of the order of tens of thousands of years[26]. While the source zones associated with the rift-type structures may be spatially correlated to the morphologic and structural features of the rift, many causative structures in the SCRs are poorly expressed on the surface. The low background seismicity associated with such regions is another factor that makes them seemingly free of any impending seismic activity. Thus, the level of preparedness in such areas may be woefully inadequate, particularly in terms of design of the buildings. The 1993 Killari earthquake (M_w 6.2), which occurred in a region that was previously considered to be of lowest risk, causing unprecedented damage, illustrates this point.

In terms of vulnerability and seismic hazard assessment, the examples of Killari and Kachchh may represent two extreme cases. The Killari-type earthquakes may be separated in time by tens of thousands of years; they may be of moderate size and due to the long interseismic quiescence, such sources may remain unknown until an earthquake occurs. Sources such as those in the Kachchh rift are associated with a major tectonic feature; these sources seem to be capable of generating larger earthquakes, during much shorter intervals (hundreds of years) compared to the Killari-type sources. In the following sessions we illustrate some of the significant characteristics of these two earthquake sources.

Seismic sources in the Kachchh rift

Allah Bund: 1819

The 1819 earthquake (M_w 7.5) occurred on the northwestern flank of the Kachchh basin in NW India, a known seismic source in the Indian SCR (Figure 2). One of earliest documented earthquakes, this event is discussed in the early books on geology[27]. The damage caused by this earthquake at Bhuj, located about 150 km southwest of its epicentral region is quite revealing of its severity. Nearly 7000 houses were destroyed in this town, killing more than 1150 people. The shock was felt in far away cities such as Ahmedabad (about 300 km from the epicentre), where a 400-year-old mosque was damaged[28]. This earthquake generated one of the most dramatic of the surface deformation features formed by an SCR earthquake – a nearly 60 km-long, warped zone with an average elevation of about 2.5 m, popularly known as the *Allah Bund*. It caused widespread liquefaction in a large area, the farthest documented effect being at Porbandar, about 250 km south of its source zone[28,29]. Liquefaction of sediments appears to be the major cause for the submergence of the Sindri Fort, located about 8 km south of the *Allah Bund* (ref. 19).

With the experience of large earthquake so fresh in history, it was essential to explore this region to understand the past activity associated with this source. Palaeoseismic investigations in the epicentral area of the 1819 earthquake suggested occurrence of another earthquake about 1000 years ago[19]. By sifting through some rare historic documents, we could gather supplementary evidence suggesting that an earthquake had occurred in this region in AD 893 (ref. 20), providing additional constraints to the palaeoseismic evidence.

Although our investigations led to estimating the timing of the penultimate earthquake in the 1819 source, this information is still inadequate to suggest a recurrence interval for large earthquakes. One reasonable conclusion that could be derived from our studies is that the 1819 source has the potential to generate large earthquakes over a period of 1000 years. Our studies also indicate the possible existence of a potential fault segment in the eastern

Figure 2. Major structures in the Kachchh region. Earthquakes and locations discussed in the text are identified.

terminus of the *Allah Bund*. The reduced structural relief in this part of the bund is interpreted as an expression of accumulated slip deficit[30]. Occurrence of another earthquake on an independent fault within the rift is an indication that earthquakes in the Kachchh rift are not just restricted to the *Allah Bund* source. The natural question that follows is whether there are similar sources waiting to generate future large earthquakes. Palaeoseismic data, although scanty, suggest the possibility for other potential sources, but their seismic histories remain hazy.

Bhuj: 2001

The 2001 source was not known to be associated with any previous large historical earthquakes, the only significant event in this region being the 1956 Anjar earthquake (Figure 2). Compared to the 1819 earthquake, the surface effects of the 2001 earthquake were less dramatic in that it was not associated with any primary surface folding or rupture. However, this earthquake generated ground fissures, minor strike-slip faults, linear mounds and small thrust scarps. Ground failure features include widespread liquefaction, lateral spreads and gas ejection, which were more intense within a radius of 50 km around the epicentre near Bhachau[4,31]. Depth distribution of aftershocks suggests that the earthquake occurred on a fault that dips 50° toward the south, but the projection of this plane does not match with any mapped faults in the area. The depth range of aftershocks is from about 10 to 35 km and the fact that they do not reach the surface is consistent with the observation that there was no obvious main fault rupture for this earthquake[32,33]. Thus, the overall style of deformation, lack of a primary surface rupture and absence of aftershock activity at depths shallower than 10 km are suggestive of a blind thrust.

Sandblows associated with the 1819 and the 2001 earthquakes are comparable in terms of dimension and spatial distribution, enabling a comparison of their magnitude. They show a more or less progressive diminution in size from the epicentre (but for a few site-specific exceptions), implying similar seismic energy for both these events[32]. The 2001 earthquake reactivated some of the older sandblow craters, which on further excavation revealed signatures of both 1819 and pre-1819 earthquakes. In many places, the fresh sandblows had reactivated older craters, exposing evidence of similar episodes from the past. For example, the fresh craters near the 1819 source revealed both 1819, and pre-1819 sandblows (Figure 3). Occurrence of three generations of sandblows formed by earthquakes originating from two different sources is also an illustration of the higher vulnerability of some sites to liquefaction.

The Bhuj earthquake caused widespread liquefaction and related features in a large area. However, trenching in a few large craters in the epicentral area did not expose any significant evidence of older liquefaction. A 3-m deep trench across the ground fissures formed near Bhachau exposed narrow vents (~ 2 cm) filled with dry sand, close to its base. These appear to be older features, and the recent earthquake has not disturbed them. Some of the other shallow trenches revealed smaller features, presumably caused by a smaller event nearby (1956 Anjar, for example) or a larger, distant event[4]. It is important to continue investigations in the epicentral area of the Bhuj earthquakes to document older features and constrain their ages.

One example where a 2001 sand dike has cut an older sandblow was observed in a river valley at Dholka near Ahmedabad, about 250 km south of the 2001 epicentre (Figure 4). This trench provided a single TL age constraint of 2948 ± 295 yr BP, for the older dike[32]. Causative source of this earthquake remains unknown, but the nearly 3000-year-long interval between the liquefaction events suggests two possibilities: one, that no earthquake may have affected this region during the intervening period and two, that the sandblows which formed during this period may have been eroded or disturbed by anthropogenic activities.

The history of damage to the ancient Harappan settlement at (2600 to 1600 BC), located about 60 km north of the 2001 epicentre, offers further constraints on the timing of the penultimate earthquake. This structure suffered only minor damages from the 2001 earthquake; some bricks at the entrance had fallen-off. However, the front wall was already tilted, possibly from an older earthquake. Subtle evidence of a previous deformation event, in the form of a flexure is preserved on the brick wall in the central part of the fort (Figure 5). The 1819 earthquake did not cause any damage to this structure; palaeoseismic investigations in this area did not expose any

Figure 3. Photograph showing the western wall of a crater formed in 2001, near the source zone of the 1819 earthquake. The 0.5-m deep trench shows three successive generations of liquefaction features formed by the 2001 and pre-2001 events, possibly the 1819 and AD 893 earthquakes (see ref. 20 for details).

major features that could be related to that earthquake[19]. However, this 4000-year fort underwent some significant repairs during the closing decades of Stage III of the settlement (2500–2200 BC), possibly due to an earthquake[34]. No major repair work was undertaken since Stage III of this settlement. The question to be resolved is whether an older earthquake at the Bhuj source could have caused this damage, requiring major reconstruction. Could the same earthquake have caused the damage at Dholavira and liquefaction at Dholka? The single age data from the trench at Dholka is inadequate to suggest anything conclusive, but given the large uncertainties in the dates (of both the repair and the liquefaction event), it is conceivable that the same event is responsible for both these. The underlying assumption here is that we have only the Bhuj and *Allah Bund* sources to deal with, but this does not appear to be true. Palaeoseismic studies suggest the possibility for a third source in the vicinity of Bet Dwarka where the last earthquake seems to have occurred around 2000 years ago.

Figure 4. View of the shallow trench section (0.5 m) at Dholka shown in Figure 2. The top layer of whitish sand is part of the 2001 sandblow, located in a dry river channel. The 2001 vent has cut through an older layer of the emplaced sand dated (TL) at 2948 ± 295 yr BP.

Figure 5. Partially damaged entrance to the fort at Dholavira. Previous structural damage is preserved on the adjacent tilted wall, restored during 2500–2200 BC, presumably after an ancient earthquake (view to the north). (Inset) Flexured wall in the central part of the fort, possibly generated by an earlier earthquake.

A third source near Bet Dwarka?

Bet Dwarka, a coastal island on the coast of Gulf of Kachchh, is known to have hosted human settlements dating back to more than 3000 years (see Figure 2 for location). With the history of earthquakes in the Kachchh region, this site offers an excellent opportunity to use archeological data in combination with palaeoseismic evidence. In one of the trenches excavated here for archaeological investigations, we observed a palaeoliquefaction feature which shares most attributes of seismically-induced structures[35]. The habitation in this trench is dated as 2nd century BC to 5th century AD; the oldest layer dated to be about 2000 BP (ref. 36). Charcoal from the liquefied layer was dated to be 1859 ± 60 yr BP (cal. AD 25–328); the sediment immediately overlying this sandblow was dated as 1980 ± 40 yr BP (cal. 50 BC–AD 100). Based on these observations, it has been suggested that an earthquake affected this area ~ 2000 years ago, but its exact source remains to be constrained[35]. The age data from Bet Dwarka do not compare with those obtained from other sites, and the obvious question is whether we are dealing with a totally new source.

An important observation made during the 2001 earthquake is that large earthquakes can produce significant liquefaction and related features even at distances of about 150–200 km, if the site conditions are favourable. However, the Bhuj earthquake, whose epicentre is about 200 km from Bet Dwarka, did not generate any noticeable liquefaction even in its low-lying areas, where the groundwater conditions are favourable for liquefaction to occur. A preliminary inference drawn from this observation is that a similar-size earthquake from the same source is unlikely to have produced this 2000-year-old feature. The 1819 earthquake is reported not to have produced any liquefaction here. The trenches do not show any evidence of liquefaction from either the 1819 earthquake or its predecessor in AD 893. It is also to be noted that the age data do not compare with the dates of previous events obtained from the 1819 source as well as the trench at Dholka. Based on these observations, it was suggested that the causative earthquake might have originated from an independent source[35].

Earthquake at Killari

The Killari earthquake occurred in the eastern margin of the Deccan Plateau, formed by Late Cretaceous–Eocene basalt flows. The earthquake, which nucleated at shallow depth (5 km), was associated with hundreds of aftershocks[13,37,38]. This region has not experienced any significant earthquakes in the historic past and it was not considered as a potential site for a future damaging earthquake. Consequently, the level of awareness and preparedness in terms of construction practices for earthquake resistance was also low, a factor that increased the damages manifold. The long quiescence that preceded the Killari earthquake, together with the perceived stability of the region where it occurred, made it appear as an out-of-the-blue earthquake. The Killari earthquake triggered many questions on the mechanism of SCR earthquakes. Do they share common characteristics? Are they random or periodic? Do they repeat at the same source? Studies that followed the Killari earthquake have provided a variety of data helpful to address some of these issues.

Earthquake catalogues for peninsular India[39,40] indicate no earthquake of $M > 6$ from this region during the recent or historic times (~ 800 years). Thus, the background seismicity associated with the Killari source is comparable to those in other cratons, such as Australia. Interestingly, location of historic earthquakes during AD 1201–1960 (Geological Survey of India) appears to be mostly confined to a 400-km-long NW corridor passing through Killari (Figure 6). Spatial correlation of this corridor of activity with a structure inferred from a variety of data as well as the fault plane solution of the main event suggested reactivation of a NW-oriented fault[41]. The 3D distribution of aftershocks suggests that the earthquake originated at the intersection of the NW and EW-oriented faults[37]. These observations suggest localization of strain build-up which may develop as future locations of earthquakes, as suggested by the intersection model[10].

The most dramatic effect of the Killari earthquake was the ground deformation structures that developed in the epicentral area, near Killari. Scarps of varying height (a few centimetres to about 80 cm) appeared at several locations along a 1-km-long discontinuous rupture. Since very few SCR earthquakes are associated with surface ruptures, the Killari earthquake presented a unique case for more detailed studies. The deformation zone at Killari has since then been the site of many investigations including trenching, deep drilling and other studies[41–43].

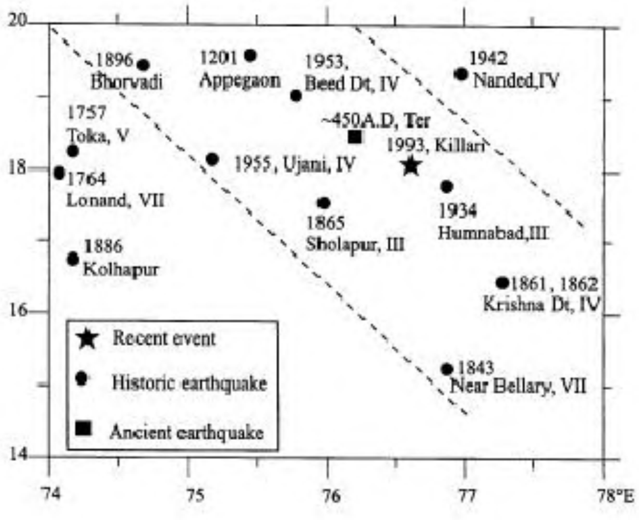

Figure 6. Location of historic earthquakes (AD 1201–1960) around Killari defining a northwest trend (source: Geological Survey of India).

Initial studies in the rupture zone were primarily concerned with obtaining evidence for past earthquakes that may have occurred in the same source. Early shallow trenching suggested that the 1993 earthquake originated on a new fault[42]. However, deep trenches cut across the rupture zone exposed a wide-impact zone comprising minute fragments of rocks and grounded mass with yellowish clay, which was interpreted as evidence of previous movement[41]. Indications of thrusting observed in the lateritized profile overlying the basalt flows were also considered as additional evidence for deformation in the basalt layers[44]. Thus, the field evidence seems to suggest that the movement occurred on a pre-existing fault, but the timing of the last movement remains uncertain. Preliminary analysis based on TL dating of gouge from the impact zone suggests an age of 18–20 ka for the penultimate earthquake at this source[44]. This appears to be in the range of repeat intervals observed for other cratonic regions, such as Australia[26].

Evidence for previous movement has been obtained also from deep drilling in the rupture zone. A maximum displacement of about 6 m, observed in the deeper basalt layers is suggested as evidence for repeated reactivation[44]. On a first approximation, this should suggest occurrence of at least six events (assuming constant slip) subsequent to the last episode of basalt flow, suggesting interseismic intervals of the order of several thousands of years.

Search for palaeoearthquakes in the vicinity of Killari led to the identification a deformation event dating to AD 350–450, at a location known as Ter, about 40 km northwest of Killari[45]. Evidence for the occurrence of another earthquake in the NW corridor defined by historic earthquakes as well as structural trend is a possible indication that other discrete parts of this pre-existing weak zone may have been reactivated in different segments of time. We have no data on the previous earthquakes on the Ter fault and going by the example of the Killari, it is reasonable to assume that the next event on this part of the fault may thousands of years away. The important question however is whether there are other discrete segments of this fault that might be the next candidates for rupture. Will it spring another surprise? The biggest lesson to be learned from the Killari earthquake is that seismic hazard assessment in the intracratonic regions must take into account even the less prominent and perhaps unexposed faults. They may not be active in the current time window, but without an understanding of their past histories, hazard evaluation will not be complete.

Discussion

The earthquakes at Kachchh and Killari may be considered as representative examples of two distinct types of

SCR earthquakes. The former occurred in a pericontinental rift, where large earthquakes seem to recur during short intervals of time whereas the latter originated in the shallow, unrifted part of the SCR crust. The Kachchh seismic zone shares characteristics of other well-known sources associated with failed rifts elsewhere. For example, the recurrence period of the Kachchh-type earthquakes may be of the order of only hundreds of years, as seen also in the NMSZ, Central US. The sizes of these earthquakes are also comparable.

The current picture of the seismic history of the Kachchh region is sketchy. Limited palaeoseismic investigations in the region suggest existence of multiple sources associated with different fault systems (Figure 2). Seismic histories of these sources are barely known – two events separated by an interval of about 1000 years are known from the *Allah Bund* source, but the data are insufficient to suggest a recurrence pattern. The Bhuj source seems to be associated with a different recurrence pattern; it does not seem to be generating large earthquakes in the same way as the 1819 source. The penultimate earthquake in this source is yet to be constrained and only after we gather more data, a comparison can be made. The ~ 3000-year-old sandblow observed in the Dholka and the reported damage caused to the structure at Dholavira around 4000 years ago, leave the intriguing question whether both these are related to the same event, large uncertainties in their time estimates notwithstanding. Until we constrain the sources of these earthquakes and develop better age constraints, this issue will remain unresolved and it will be tempting to attribute these effects to an older event originating from the Bhuj source. Occurrence of another sandblow, belonging to an independent age bracket (2000 years), in the trench at Bet Dwarka brings up the possibility of a third source.

Hazard evaluation (which must start with estimation of timing, location and size of future earthquakes) is not a simple task, as evident from better-studied examples such as the NMSZ. In addition to the inherent uncertainties originating from the complexities of the source zone, what makes it more difficult at Kachchh is the lack of a wide variety of basic data. That some of the potential structures in this region remain hidden beneath the thick sediment deposits, adds a more difficult dimension to this problem. A more or less complete picture of the active faults and their earthquake histories, quantification of strain using GPS-based observations are the basic inputs required and the existing database is far from complete. The investigations at Kachchh are only beginning; only through a concerted effort to combine geological observations with seismic reflection and GPS data, can we present a clearer picture of the seismic hazard associated with this important seismogenic source in the Indian peninsular shield.

Killari-type earthquakes in the unrifted crust may be considered as an outcome of slow tectonic processes, and by the very nature of that definition it is expected to repeat only during much longer intervals of time, compared to rift-type earthquakes. Typically, such earthquakes are smaller in size (M_w around 6) compared to the rift-related earthquakes. With its shallow focal depth, abundance in aftershock activity and subdued neotectonic expression of the source zone, the Killari earthquake is comparable to typical SCR events in the Australian shield[46,47]. However, such earthquakes can be relatively more damaging due to the inadequacies in building practices and the general lack of preparedness.

It must be recognized that SCR events may appear as temporally isolated, only when viewed from a restricted time window. Perhaps, the important question to be addressed is how much time may have elapsed since the last event. Another problem is that earthquakes may occur on discrete segments of a fault that may fail at different times. Field studies in the epicentral region of the Killari earthquake and the aftershock distribution suggest that the rupture area is fairly small (~ 38 km^2) involving only a fault length of 5.5 km, a small portion of the regional structure[44]. It is likely that the 1500-year-old earthquake at Ter, located 40 km northwest of Killari occurred on another segment[45]. In this kind of a scenario where discrete segments of a fault may fail independent of each other, recurrence models would be more realistic if developed for the whole region, rather than for a single site/source. Seismic hazard assessment of SCRs is complicated also because of the incompleteness in data. In the absence of high quality data from each of the SCRs, assessment of the seismogenic processes may have to rely also on data from analogous settings elsewhere. As more data are generated from various source regions, it may be possible to identify analogies in their characteristic sizes, patterns of recurrence and deformation mechanisms, taking us closer to realistic hazard assessment.

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