Discussion of seismicity near Jaitapur

We thank Rastogi[1] for pointing out a number of factual errors in our article[2], and welcome this opportunity to correct several scientific misunderstandings that have crept into his manuscript.

Rastogi is in agreement with our statements and conclusions concerning the seismicity in the Jaitapur region that: (a) no significant $M > 6$ earthquakes have been recorded by seismographs located within 50 km of Jaitapur, and no historical reports of intense shaking can be attributed to such earthquakes near Jaitapur, and (b) shaking intensity from distant historical earthquakes has not exceeded MSK Intensity VI. We conclude, as we assume Rastogi does, that these observations do not place a reliable upper bound on shaking due to future seismicity in the Jaitapur region. This was the thrust of our article.

Some of Rastogi's comments are easily addressed with minor corrections or clarifications, but his main counter-argument requires a more thorough analysis. We provide the former first.

Rastogi incorrectly ascribes our analysis to data shown in figure 2 *b*. As stated in our text, it was calculated using a 16°35′N latitude for Jaitapur from data in figure 2 *a* as listed in our appendix. Figure 2 *b* shows a map of recent data, with one of the measurement sites labelled 'Jaitapur'. The source of figure 2 *b* is cited.

We mentioned incorrectly that several minor earthquakes have occurred within 50 km of Jaitapur. Rastogi asserts that 'no such earthquake has been located by the Koyna network operating since 1962…'. The Executive Director of the Nuclear Corporation of India, however, reports[3] an earthquake on '10 October 2008 of 3.1 magnitude at 44.9 km distance'. The closest globally recorded earthquake is 52 km from Jaitapur. It was an $Mw = 4.1$ earthquake that occurred at 16.82°N, 73.28°E on 26 March 2005, which resulted in a calculated intensity ≈ IV at Jaitapur.

With deference we correct Rastogi's arithmetic: a strain of 10^{-4} is 100, not 10, microstrain. Also he presumably agrees with most seismologists that estimates of earthquake magnitudes, *Mw*, from seismic data are typically uncertain to 0.2 *Mw* units. The values asserted by him depart from those used by us for the Koyna and Latur earthquakes by a lesser margin.

He writes that post-glacial sea-level rise results in stresses too small to fracture rocks. This is unwittingly deceptive, because in a region that is already critically stressed, the marginal stresses that he computes may suffice to trigger an earthquake, a central theme of his well-known, reservoir-induced seismicity articles. We cite as an example of present-day triggering by minor hydraulic loading[4], the increase of micro-seismicity attending the annual stressing of the Himalaya that accompanies monsoon flooding of the Ganga Plain[5].

Our rebuttal, however, mostly concerns his substantial commentary on geological observations, which he proposes as evidence for the absence of seismicity south of Koyna. The most important considerations include: (i) the presence or absence of possible active faults in the study area; (ii) constraints on timing of past ruptures on these structures that are provided by regional geomorphology and (iii) the existence, likely magnitude and rate of change of regional stresses related to lithospheric flexure.

Absence of faults offshore?

Faulting is ubiquitous in offshore ocean basins > 100 km from the west coast[6,7]. These faults are mantled by varying thicknesses of sedimentary cover and may host clues that can be used to place constraints on the recency (or otherwise) of slip on them (Figure 1); the publically available site report for Jaitapur[8] contains no discussion of potential activity on these faults. A 50 km gap exists between the present shoreline, where minor faulting has been reported[9], and the start of the multichannel data from which the profile in Figure 1 has been interpreted. Coverage closer to the shore uses different methods with shallower penetration. Continental shelf sediments in the area lie upon an Oligocene erosion surface that is tilted seawards. Widdowson[10] and Campanile *et al.*[11] interpret this to result from flexural loading of the lithosphere by the offshore sediment. Furthermore, notwithstanding the absence of relief on the continental shelf, several prominent short-wavelength NNW-trending features are evident in the gravity field[12,13], features that have been interpreted[14] as fault-bound subsurface structures. The onshore escarpment described by Rastogi himself[1], which we discuss below, is approximately colinear and contiguous with one of these > 200 km long gravity anomalies and clearly warrants a focused study.

Deformation on the west coast of India

The Konkan coastal plain has been interpreted[10] as a relict erosional pediplain formed by eastward retreat of the scarp of the Western Ghats. Rocks denuded from the Ghats were deposited offshore in thick sedimentary basins[6,14], and subsequent unloading of the shore and loading of the ocean floor resulted in east-west flexure of the lithosphere, and seaward tilting of the Konkan coastal plain. As onshore erosion continued, isostatic uplift of the land by > 200 m led to stream incision[10]. The observed drowning[10,15] of the coastal inlets of these incised drainages is partly due to continued flexural downwarping that accompanies offshore loading[11] and partly due to post-glacial sea-level rise.

Estimates[16] for the elastic thickness (Te) for the western continental margin of India range from 5 to 15 km. However, the observed coastal uplift[10,11], even with a wider range for Te is larger than calculated, leading to the conclusion[11] that the amplitude of inferred offshore subsidence and onshore uplift cannot be accounted for by simple flexure of an unbroken plate, even when accompanied by isostatic uplift of the coast. A broken plate[11] better explains some of the observed features of the Konkan coast, but no major fault has been identified, with the exception of the controversial West Coast Fault by various authors[17–19].

Flexure of the continental margin continues to this day: erosion of material from the coast and its transport to the offshore margin continually alter the loading of the Indian plate. As a result, shear and normal stresses on existing steeply dipping normal faults, which formed when India and Madagascar separated, also continually change. We are aware of the possibility that these faults may have annealed and be no longer active, but unaware of any evidence to

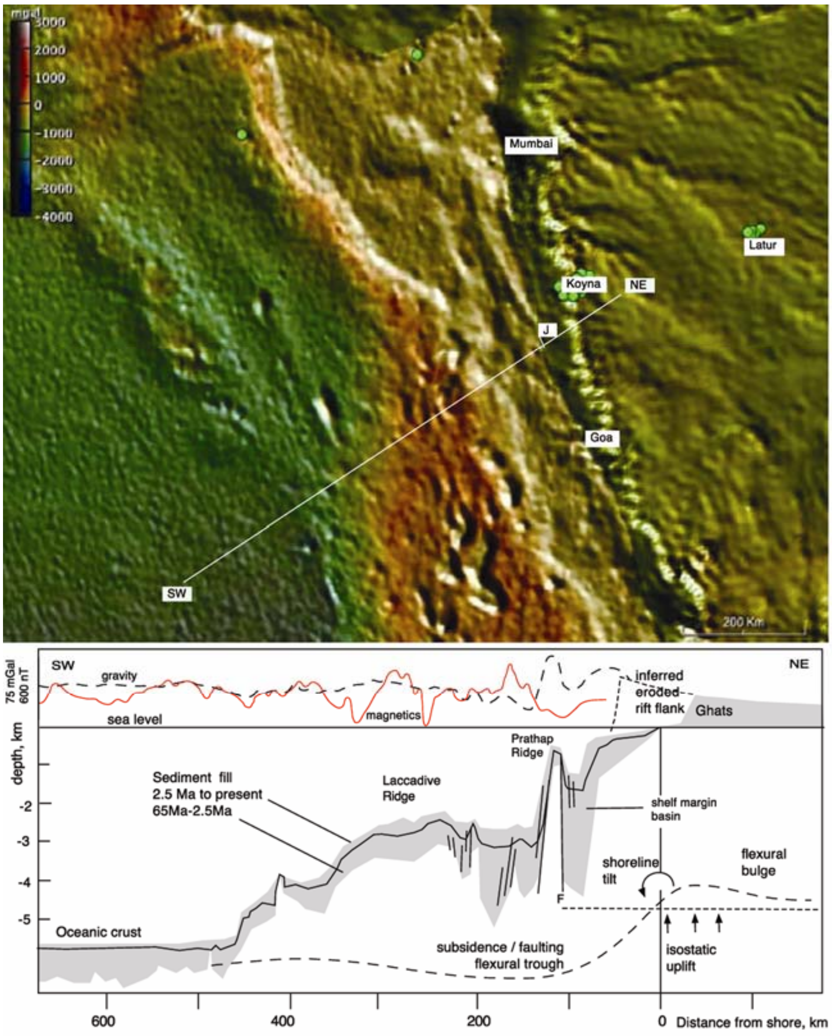

Figure 1. Ocean/land free-air gravity (Sandwell and Smith[24], Version 18.1, illuminated from the SE) and a simplified sedimentary cross-section approximately normal to the Konkan coast near Jaitapur (J). Green circles are globally recorded earthquakes from the PDE catalogue. Cross-section[11], with faults shown bounding basins near the Prathap Ridge (F), and free-air gravity and magnetic anomalies along the profile[6]. The Vijaydurg Fault crosses the section near J, colinear with a > 200-km long gravity trough in the continental shelf trending NNW.

demonstrate such inactivity. Present-day flexure results in east-west extensile stress near the shore, not unlike the stress distribution that caused these faults to form some 80 million years ago. In addition to these surface processes, the inherent stress distribution produced by the thermo-mechanical structure of a continent/ocean margin has been identified as potentially responsible for earthquakes 100–200 km inboard of continental margins[20], the locus of the current western shoreline of India.

The Vijaydurg fault offshore

We now respond to a matter that was not discussed in our article but which we believe merits further scientific study. Rastogi describes a 50-km long NNW trending escarpment south of Jaitapur that has offset the courses of several west-flowing streams and forms a 25 m high step in the marine terrace with the eastern side dropped down relative to the west. The terrace is clearly expressed for about 35 km on SRTM digital elevation data and the maximum offset on the east-facing scarp is roughly 25 m (Figure 2). We will refer to this east-facing escarpment as the Vijaydurg Fault, although Rastogi's description offers no evidence for recent faulting. From its irregular mapped trace we conclude that it is associated with relatively minor strike–slip movement and marks a normal fault. The proposed Jaitapur site is on the hanging-wall. From the prominence of the escarpment and the lack of a well-developed eastward drainage from it, we infer that the scarp and the associated ~ 25 m slip postdate uplift of the emergence of the terrace above sea level. The absence of significant scarp degradation[21] also suggests that it is of relatively recent origin. Alternatively, if scarp retreat rather than slope diffusion is invoked, and the scarp assumed to have been exposed for 2 Myr, the scarp retreat rates of 100 m to 3 km/Myr estimated nearby[10,22], would require that it has retreated from a former location situated 200 m to 6 km to the east of its present position.

Global data show that the cumulative slip on normal faults obey a law[23] of the form, $D_{\max} = kL$, where L is the observed fault length, $D_{\max}$ the maximum offset and $k \approx 10^{-2}$. Hence the 25 m offset and the 35–50 km length of the Vijaydurg Fault exposed onshore with $k < 10^2$ are consistent with global observations of normal faults. We note, however, that faults have been mapped offshore beneath recent sediment[9] near the seaward projection of the Vijaydurg Fault and within 5 km of the proposed Jaitapur construction site. This raises the testable possibility that the Vijaydurg Fault represents the onshore expression of a longer segmented fault. This is particularly important in view of the possible association of the NNW trending Vijaydurg Fault with the > 200 km long NNW-trending gravity anomaly that follows the continental shelf[12,24].

Rastogi[1] asserts that laterite deposits are undisturbed near this inferred fault, with the implication that its offset predates the emergence and tilting of the terrace. He claims no date for the laterite surface, which we assume is the uppermost of three laterite horizons in the area[15]. Palaeomagnetic evidence[25] suggests that laterites now exposed at the surface of the coastal plain are of Late Tertiary, possibly Late Miocene, age (2.6–12 Ma), but others[26] are of the opinion that the most recent emergence of parts of the Konkan terrace may date from ≈ 50,000 years BP. Laterite is not only difficult to date, but it also contains few features that may be used as piercing points to determine amounts of slip. As Rastogi presented no graphical or numerical data, we are not aware of any evidence to suggest that the escarpment marks the edge of a fossil platform that predates its emergence above sea level.

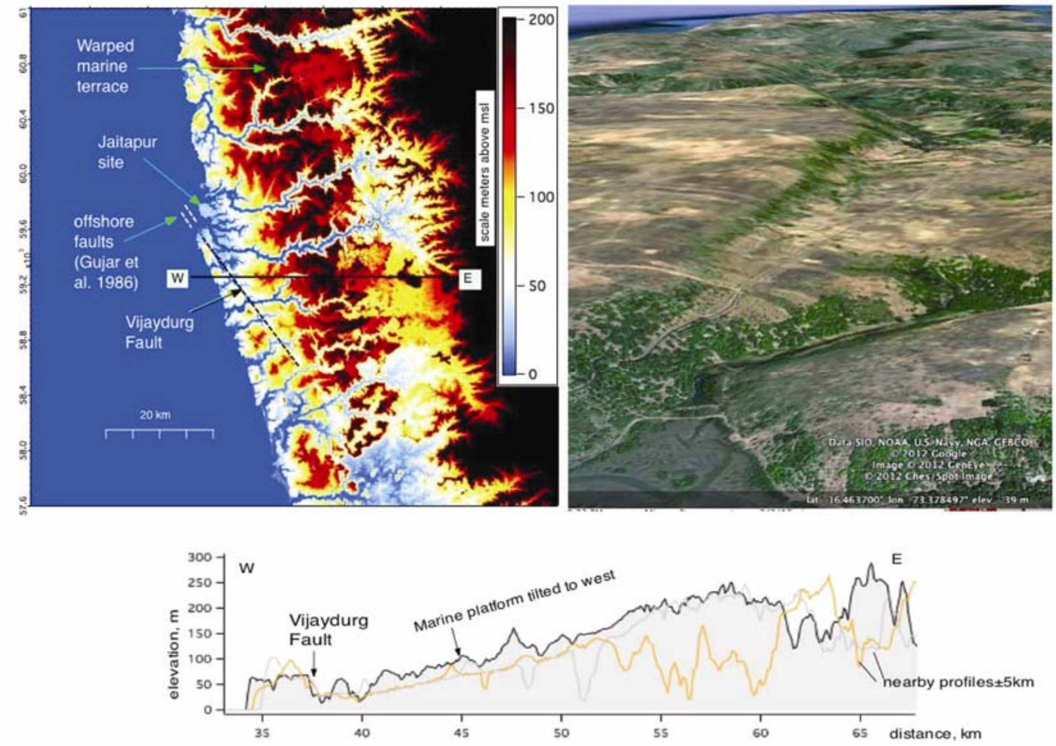

Figure 2. The Konkan marine terrace is tilted seaward near the coast (SRTM digital elevation data, top left). The Vijaydurg Fault offsets the terrace such that the eastern side has dropped 25 m relative to the west (see profile and oblique Google Earth image viewed from the SE). Its seaward projection passes within < 10 km of the Jaitapur site. Of interest to site characterization is whether slip on the fault predates or postdates emergence of the marine terrace. The oblique view (right) reveals a vegetated scarp running from lower left to top right, lacking well-developed, eastward-facing drainages, but incised by antecedent streams.

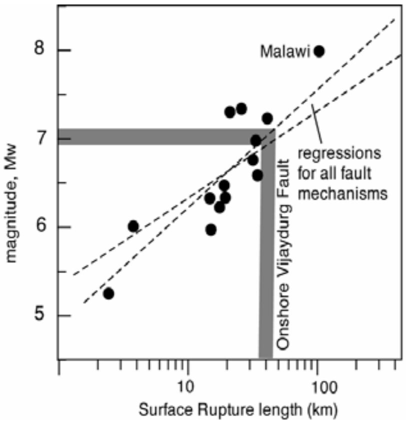

Figure 3. Scaling relations between moment-magnitude and rupture-lengths for normal faulting earthquakes[27]. 35 to 50-km-long faults are typically associated with earthquake magnitudes $6.5 < Mw < 7.2$. The Malawi earthquake was associated with 15 m of slip[78].

Our alternative interpretation – that the escarpment is a fault that slipped subsequent to the emergence of the terrace – implies a mean slip rate of 0.5 mm/yr to account for its 25 m offset if this occurred in the past 50,000 years. As far as we are aware no trenching has been conducted across this fault to test whether it is active, and if so to determine the slip rate, using recent deposits that may be more amenable to dating than laterite is. The laterites and surface materials mapped on river terraces near Vijaydurg show clear evidence for cyclic coastal uplift and subsidence[15].

We next address the question of maximum magnitude earthquakes that might be associated with movements of the Vijaydurg Fault, regardless of its antiquity. Scaling laws[27] suggest that typical amounts of slip associated with normal faults 50 km long are of the order of 1 m and therefore with earthquakes of $Mw = 7.0$ (Figure 3). This assumes, however, that the down-dip rupture width of the Vijaydurg Fault is approximately 20 km. The geometry of this fault, with slip down to the east, is observed in rifted margins, where antithetic faults merge with a larger listric fault with opposing dip at depth. This geometry can also occur in models of listric faulting[28,29], where slip is accompanied by surface flexure of the hanging-wall. If the gentle anticlinal 40 km wavelength warping of the marine terrace evident in Figure 2 is related to slip on the Vijaydurg Fault, we might anticipate the width of the fault to be ≈ 20 km. If we allow for a narrower down-dip width of only 5 km, globally established scaling relationships[27] would imply a maximum credible earthquake magnitude of $Mw = 6.6$ with slip of the order of 0.5 m. Using a slip rate of 0.5 mm/yr, the recurrence interval would be 2000 or 1000 years for earthquakes with $Mw = 7$ and $Mw = 6.6$ respectively, and we deduce that the fault would have grown to its observed offset in a minimum of 25 earthquakes during the past 50 millennia.

Discussion

We present several lines of evidence to show that Rastogi's assurances concerning the impossibility of future earthquakes near latitude 16°N are oversimplifications of the current state of our knowledge.

First, Rastogi's dismissal of flexural stresses in the Indian subcontinent is inconsistent with numerous theoretical and observational data supporting their existence[30–40]. Filament stresses associated with flexure establish a latitudinal variation in stress throughout the Indian subcontinent[39], with maximum compressive lithospheric deviatoric stresses in the range 60–250 MPa (Appendix). A longitudinal variation of stress exists also across the Konkan coast caused by flexural loading of the shelf and offshore basins[11,36] and isostatic rise of the region east of the coastline due to ongoing denudation[10]. The existence of north-directed compression and east-west extension results in complementary Coulomb failure conditions for reactivating existing faults near the Konkan coast.

Given that stresses are close to failure levels throughout the subcontinent, it follows that minor changes of stress are sufficient to trigger seismicity. Rastogi has himself co-authored several articles on the triggering of earthquakes that require this mechanism to prevail[41,42]. The prolific literature on Coulomb triggering of aftershocks following the development of tools to quantify these effects[43] is predicated by the concept that minor increments in stress are sufficient to trigger moderate aftershocks and, occasionally, damaging main-shock/aftershock sequences.

The case for a surface fault close to Jaitapur is raised independently by Rastogi. He considers that if the escarpment he describes is indeed a fault, it passes offshore within 10 km of Jaitapur, but that it has not been active since Miocene times. His claim is based on the observation of a putatively continuous laterite surface of unstated age at 10 locations near the fault scarp. No authoritative documentation is presented in support of this observation, but the hypothesis he proposes is testable, and we look forward to results from palaeoseismic trenching and the dating of overlying recent colluvial deposits on the eastern face of the scarp that will confirm or refute his assertions. In the absence of supporting evidence, however, we contest his claim, with the counter observation that the 25 m offset at the Vijaydurg scarp appears fresh and the escarpment shows no evidence of deep incision by eastward-flowing streams, despite their development on the lower gradients of the gently west-sloping marine terrace. On the basis of a possible date of emergence[26] of the surface 50 ka BP and scaling relationships between length of ruptures and magnitudes of earthquakes[27], we estimate a recurrence interval of 1–2 millennia for earthquakes with $Mw \approx 6.6–7$ on this escarpment. These estimates are consistent with Rastogi's mention of the absence of a damaging earthquake in the past 500 years[1], which, given the above reasoning, suggests that the fault has now exceeded a minimum 25% of its renewal time.

No significant faults have been mapped on the Konkan continental shelf despite a controversial discussion of the existence of a 'West Coast' Fault by various authors[16–19]. A record of earthquakes, if significant west-coast earthquakes have occurred in the past 10 ka, is most likely to exist in the form of synchronous turbidite deposits on the ocean marginal basins along the Konkan coast. Turbidity deposits have clearly been identified in the distal regions of the Indus fan[6] and on the continental slope[44,45], and their presence in the eastern Konkan basin[46] offers an opportunity for studying the frequency and severity of earthquakes along the Konkan coast. A 1 : 1 relationship between synchronous turbidites and great earthquakes exists along the Pacific NW coast of North America[47–49]. The relationship between major strike–slip earthquakes and turbidites is less regular in Haiti and the Marmara Sea[50–53] but shows promise in passive margins subject to occasional earthquakes[54–58]. McHugh *et al.*[59] report the successful application of isotopic methods to distinguish between turbidites loaded with remobilized earthquake-triggered seafloor sediments, from those triggered and supplemented by sediments derived from severe coastal run-off.

The Portugese record of a probable tsunami in 1524 near Dabhol[60] at latitude 17°34′ is associated with no known earthquake or any unequivocal source zone. Although it is possible to speculate that an earthquake in the Makran subduction zone or a slump of sediments on the nearby continental shelf could be responsible, we find no mention of this in site investigation reports available to the public. Although onshore faulting in 1524 has been proposed[61] as a possible source zone, a source zone near the Konkan shelf edge appears to us more probable. Moderate earthquakes can trigger submarine slides that may generate a disproportionately large coastal tsunami[62].

Conclusion

We thank Rastogi for his diligent criticism[1] of our earlier article[2]. The focus of the earlier article was that no significant earthquakes have been recorded instrumentally or historically within 50 km of Jaitapur, but that this absence of evidence provides no evidence for the absence of significant past earthquakes or the possibility of future ones. Jaitapur lies in a region where plate tectonic stresses are locally close to critical failure, and where minor perturbations in stress can trigger earthquakes. Geologically, the Jaitapur region meets many of the criteria known to be conducive to intra-plate seismicity[63]. Tectonically, the Jaitapur region is precisely in the same state of seismic quiescence and historical ignorance as the regions of Latur or Koyna were, prior to the damaging earthquakes for which they are now famous.

Despite his assurances, Rastogi provides scant supporting evidence to demonstrate seismic inactivity of the Konkan coast. We list here several lines of scientific studies and analyses negative results from which would strengthen his case for the absence of historical earthquakes in the region.

1. Seismic profiling of the continental shelf 'gap' between onshore and mid-shelf regions with high-resolution seismic lines to identify subsurface structures associated with potentially active near-shore faults.
2. Improved high-resolution shallow seismic and core analysis studies to resolve uncertainties in the interpretation of the already identified offshore faults and inferred igneous dikes near Jaitapur[9].
3. High-resolution imaging of the continental slope in a search for incipient scarps, and slump features associated with historical turbidites and tsunami.
4. Coring and dating of depositional turbidites in offshore basins to quantify, or refute, the existence of synchronous triggering of turbidites along the Konkan shelf by significant earthquakes.
5. Palaeoseismic trenching across the Vijaydurg scarp to establish the absence, or timing and amount of slip of the Vijaydurg Fault.
6. Trench studies of onshore palaeo-liquefaction, clastic dikes and buried sand vents[64] in terrestrial low-energy sedimentary environments within 50 km of Jaitapur.
7. A systematic search for palaeo-tsunami deposits[65] along the western coast of India within 100 km of the Jaitapur site using shoreline and lagoonal deposits, cores and trenching.

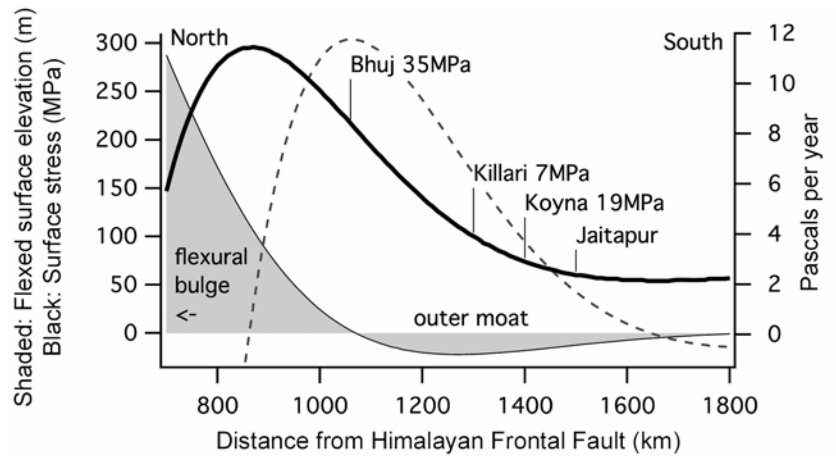

Figure 4. Surface filament stress calculated for the outer moat of the flexed Indian plate, showing synthetic stress and observed stress drop for recent earthquakes at the locations indicated. The dashed line indicates the rate of change in surface stress at each location. The surface stress near Jaitapur is 60 MPa, increasing at a rate of ≈ 2 Pa/yr. The deviatoric stress at 45 km depth is uniformly 65 MPa (in these models Te = 90 km).

8. An onshore search for precariously balanced rocks[66,67] symptomatic of an absence of strong shaking in the past several thousands of years.

We do not pretend that our list is complete, and we suppose that the geological site study, which has yet to be made public, addresses some or all of these issues.

Our point in providing this lengthy response is that science does not progress by silencing scientific discussion, but by encouraging it. Rastogi's note, written in the spirit of a refutation (and correction) of our original article, would normally have been printed in *Current Science* along with a reply invited by the editor of the form that we now provide. We recognize the sensitive nature of the site investigation surrounding Jaitapur, but our article and that of Rastogi's are not about nuclear power stations. We and Rastogi are discussing seismicity. We maintain that Rastogi's confidence in future regional seismic quiescence near latitude 16°N is not supported by India's recent seismic history, and that routine palaeoseismic studies that might support or refute his claims are incomplete or have yet to be undertaken.

Appendix. Flexure of the Indian plate due to plate convergence with Asia

Rastogi dismisses 'crest and trough' models that quantify flexure of the Indian plate. Numerous analytical solutions of flexural parameters for northern India[30–39] are available. These have been extended southward constrained by the observed denudational surface of central India[39]. Southeast of the subcontinent, buckling of the ocean floor and upper mantle is evident in the gravity field and in seismic profiling data. Calculations of the forces required to initiate and sustain buckling provide quantitative estimates of in-plane forces (i.e. with maximum principal compressive stress parallel to the closure velocity between India and Asia) in the oceanic plate[68–73]. The seafloor stratigraphy within 'troughs' between 'crests'[72] provides evidence that the strength of these forces has been modulated by significant events in the last several million years of Indo-Asian collision[74].

In Figure 4 we illustrate the geometry, surface filament stress and its temporal rate of change between Bhuj and Jaitapur assuming a flexural wavelength of 670 km, with a Te of 90–110 km (refs 38 and 39) and an in-plane deviatoric stress of 65 MPa (refs 31–34, 73). The north-south in-plane compressive stress inferred to exist at Jaitapur (Figure 4) is 60 MPa, a value that is calculated to have increased by 5 MPa in the past million years.

The inferred variation in surface filament stress is numerically consistent with stress-drops calculated for recent earthquakes in the region: the Bhuj earthquake occurred near the transition from outer rise to outer moat, at the locus of maximum stressing rate (≈ 12 kPa/ka). The stress released by the Bhuj earthquake was 35 MPa (ref. 75), 16% of the estimated surface filament stress of 217 MPa, and > 40% of the filament stress at epicentral depths. Stress release in the 1993 Killari/Latur earthquake was estimated as 7 MPa (ref. 76), 7% of the calculated 100 MPa surface filament stress. Stress release in a Koyna $Mw = 4.7$ aftershock was estimated to be 19 MPa (ref. 77), 26% of the available 74 MPa filament stress, although many of the Koyna aftershocks are reported to exhibit lower stress drops (2 MPa). These observed stress drops are quantitatively consistent (7–26%) with the computed available flexural stress.

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