Tectonic stress field in the epicentral zone of the Latur earthquake of 1993

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In situ stress measurements by hydraulic fracturing were carried out in the 617 m deep borehole specially drilled in the epicentral zone of the 1993 Latur earthquake for the purpose of research. The stress measurements carried out at 592 m depth in this borehole are the deepest of all such measurements made so far in the Indian shield. The maximum and minimum principal horizontal stresses ($S_{H\max}$ and $S_{h\min}$) have been derived from the hydrofracture data using the classical method. The $S_{H\max}$ and $S_{h\min}$ are found to be 16.5 and 9.6 MPa at 373 m depth, and 25.0 and 14.1 MPa at 592 m depth, indicating that the vertical gradients of $S_{H\max}$ and $S_{h\min}$ in the epicentral zone are 39 MPa/km and 21 MPa/km respectively. The principal horizontal stresses in the epicentral zone are comparable with those at Hyderabad and 30% higher than in most other comparable intra-continental regions. Analysis of the results indicate that the stresses in the focal region of the 1993 Latur earthquake have not undergone any significant change following its occurrence and this is in agreement with a similar inference drawn from the seismic data analysis. It appears that the Latur earthquake was caused due to rupturing of the overpressured fault segment at the base of the seismogenic zone.

1. Introduction

The globally-deadliest Latur earthquake of September 30th, 1993 points out that the Indian shield is seismically more active than hitherto thought of. The earthquake occurred in an area that was believed to be tectonically stable because it had little historical seismicity. This event is yet another good example of a stable continental region (SCR) earthquake that occurred on a fault which exhibited little neotectonic movement. In view of the assumed aseismicity of the region, the 1992 earthquake sequence of M2.0–M4.0 was not taken seriously as a forerunner of a major impending earthquake. Following the 1993 earthquake, several investigations have been carried out to understand the seismotectonics of the Latur region (Mishra *et al* 1994; Sarma *et al* 1994; Gupta *et al* 1995; Gupta and Dwivedy 1996; Seeber *et al* 1996; Rajendran *et al* 1996; Mandal *et al* 1997).

The intraplate stresses in the subcontinent including the Indian shield are primarily induced by plate tectonic processes (Gowd *et al* 1992). Gowd *et al* (1996) analysed the mechanisms responsible for the reactivation of the seismogenic faults, considering the stress map of the Indian subcontinent and strike and dip of the seismogenic faults and their disposition with respect to the local $S_{H\max}$ orientation, and pore fluid pressure in the fault zones. These two works have brought out the causal relation between the intraplate stresses induced by the plate tectonic processes and the seismicity (stable continental region earthquakes) in the Indian shield.

However, similar analysis of the reactivation mechanisms in respect to the Latur region could not be attempted due to the paucity of *in situ* stress data. Recent measurements of hydrofracture stress data in the Latur region permits a new analysis. Observations in the deep borehole and their implications for the mechanism of the earthquake at the Latur are presented in this paper. The results are presented and discussed in this paper.

Keywords. Stress magnitude; stress orientation; hydrofracture; seismicity; Latur; reactivation mechanism.

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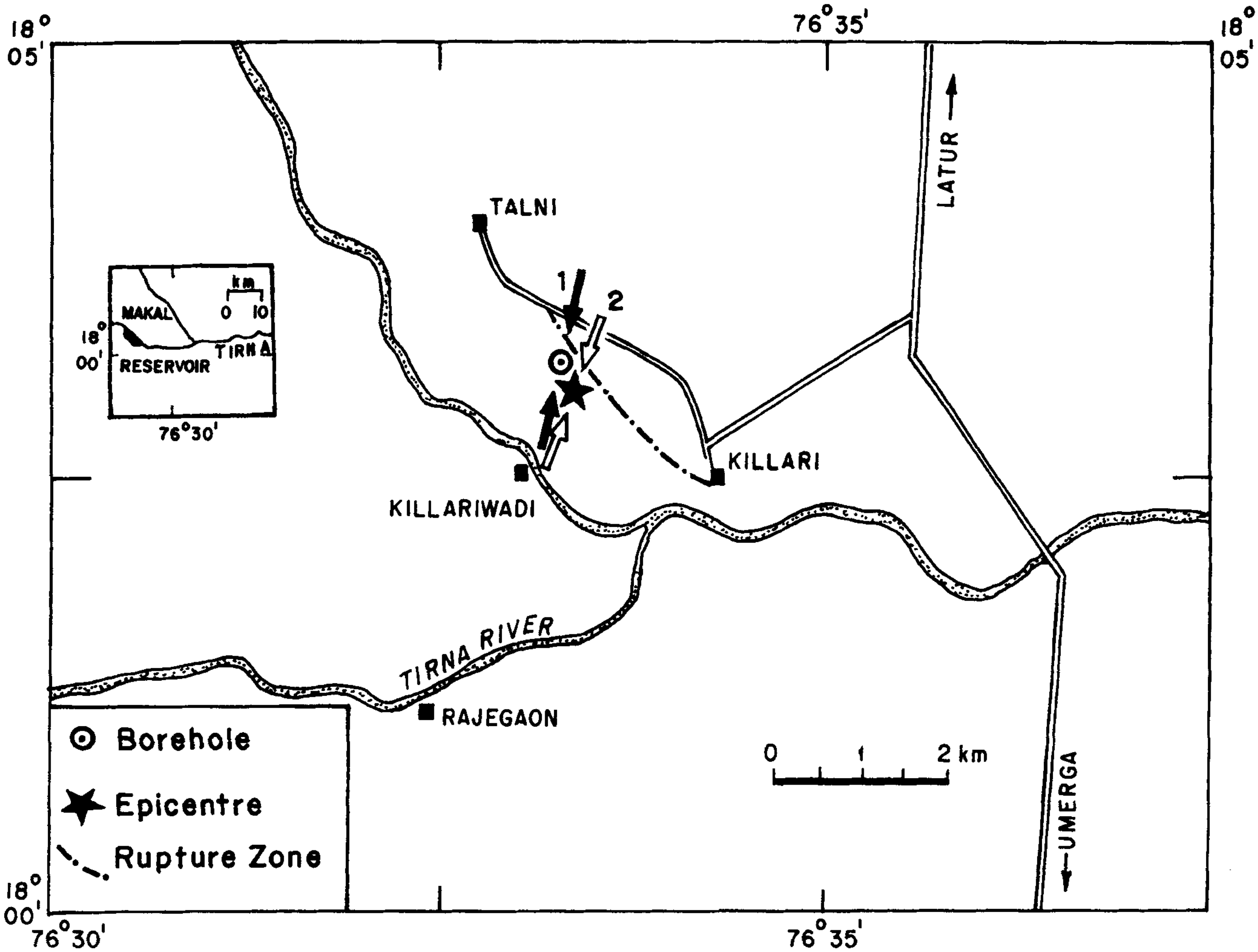

Figure 1. Site map showing the surface rupture, epicentre of the 1993 Latur earthquake, location of the borehole and $S_{H\max}$ orientation; Epicentre coordinates (18°03′N:76°33′36″E) are the average of the coordinates published by USGS, GEOSCOPE, NGRI and HRV. **(1)**: $S_{H\max}$ orientation (N14°E) from the present study; **(2)**: $S_{H\max}$ orientation (N22°E) from the fault plane solution by Gupta *et al.* (1995).

2. Experimental work

In situ stress measurements were recently carried out in the meizoseismal area of the 1993 Latur earthquake (Srirama Rao *et al* 1998). These measurements were made in a 617 m deep borehole specially drilled and planned for the purpose of research jointly by the National Geophysical Research Institute (CSIR) and the Atomic Minerals Division, DAE (Gupta and Dwivedy 1996). The borehole location, surface rupture and the epicentre of the earthquake are shown in the site map (figure 1). The borehole extends through the Deccan Traps (0–338 m), intra- and infra-trappeans consisting of sedimentary rocks (338–346 m) and the basement rocks of granite and granitic gneisses up to the well bottom (346–617 m). The borehole is cased up to 352 m depth with BX casing and the open hole section with a diameter of 60 mm (BX size) extends below this depth up to the well bottom. The granite and granitic gneiss cores recovered from the open hole section are characterised by a RQD value of 75–100% indicating that the basement rock is intact and is not significantly fractured and sheared.

The stress measurements were carried out using the hydraulic fracturing method. Trailer mounted wire-line hydraulic fracturing equipment, a unique facility in India, has been employed in this investigation. Details of the hydraulic fracturing technique, wire-line hydrofracture equipment and testing procedures were discussed elsewhere (e.g. Gowd *et al* 1986). A number of intact rock zones without pre-existing fractures were selected as testing sections throughout the extent of the open hole for the purpose of conducting hydrofracturing tests, after thoroughly examining the cores recovered from the borehole. We have conducted the hydrofracture tests first at the shallowest testing section at 373 m and then at the deepest one at 592 m. After conducting some hydrofracture tests at 573 m depth, we were forced to abandon the testing programme as several difficulties were encountered during the hydrofracture as well as impression tests

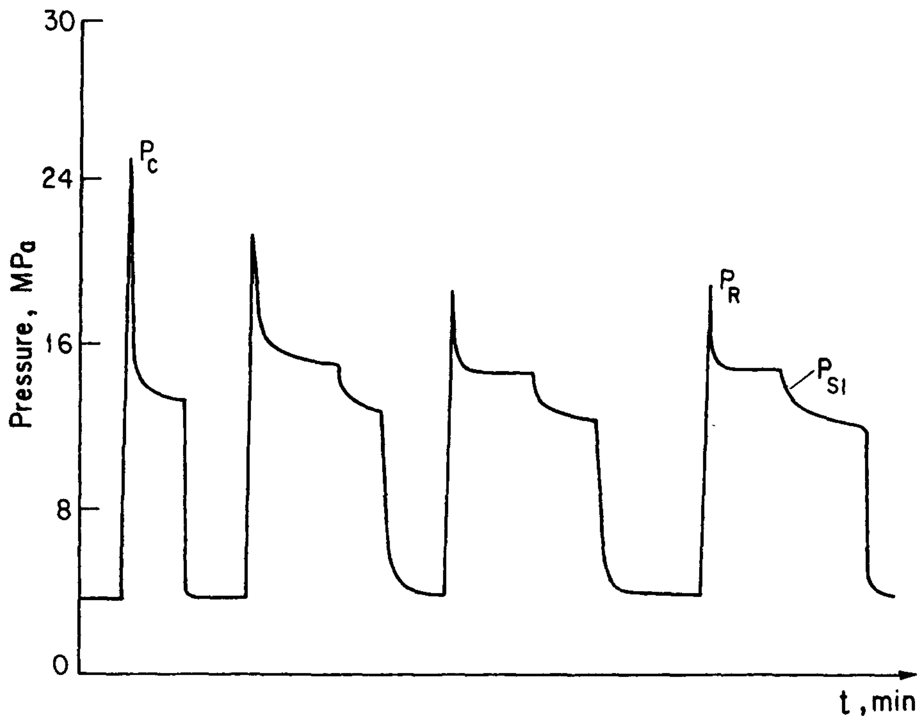

Figure 2. Pressure-time record of the hydrofracture test conducted at 592 m depth in the research borehole at Latur.

due to the constraints imposed by the small diameter of the borehole on the free movement of the hydrofracture tool. As a result, it was possible for us to do tests in this borehole only at these three testing sections. However, we are not disappointed with this outcome because it is for the first time in the world that stress measurements were carried out in boreholes of such a small diameter down to a depth of about 600 m. Such a tool was earlier never used outside India at depths more than 50–60 m.

3. Results and Discussion

The pressure-time record of hydrofracture tests conducted at 592 m depth is shown in figure 2. The breakdown pressure P_c, fracture reopening pressure P_r and shut-in pressure P_{si} were determined as shown in the figure. Similarly, values of these three critical pressures were determined for the other two sections at 373 m and 573 m depth. Fracture impression data revealed that vertical fractures were induced at 373 m and 592 m depth, suggesting that the classical method (Hubbert and Willis 1957) is applicable in this case. According to the classical method a vertical fracture striking in the direction of the maximum horizontal compressive stress is induced when the following conditions are satisfied.

$$S_{h\,\min} = P_{si}$$
$$S_{H\,\max} = 3P_{si} - P_r - P_o,$$

where P_o is the pore fluid pressure.

Values of $S_{H\,\max}$ and $S_{h\,\min}$ have been evaluated using the above relations and the same are plotted as a function of depth (figure 3). The results indicate that the maximum and minimum principal horizontal stresses, $S_{H\,\max}$ and $S_{h\,\min}$ are 16.5 and 9.6 MPa at 373 m depth, and 25.0 and 14.1 MPa at 592 m depth. The data imply that the vertical gradients of $S_{H\,\max}$ and $S_{h\,\min}$ in the Latur region are 39 MPa/km and 21 MPa/km respectively. It may be understood from the analysis of the global hydrofracture data (Gowd *et al* 1996) that the stress gradients in the Latur region are 30% higher than in most other intra-continental regions.

From the fracture impression data, $S_{H\,\max}$ is found to be oriented in the direction of N11°E at 373 m depth and in the direction of N17°E at 592 m depth, and has a mean value of approximately N14°E. This stress orientation of $S_{H\,\max}$ in the meizoseismal area is in good agreement with the average direction of $S_{H\,\max}$ (N23°E) determined for the midcontinent stress province of the Indian subcontinent (Gowd *et al* 1992) and the *P*-axis orientation (N22°E) derived by Gupta *et al* (1995) from fault plane solutions of the 1993 Latur earthquake.

On extrapolating the principal stress magnitudes determined at Hyderabad (Gowd *et al* 1986) to deeper horizons, we find that the magnitudes of $S_{H\,\max}$ and $S_{h\,\min}$ can be 19.5 and 11.9 MPa at 373 m depth and 29.4 and 17.4 MPa at 592 m depth in the area respectively. The stress magnitudes determined by us for the Latur region are comparable with the extrapolated stress values of the corresponding depths at Hyderabad, if the surface intercepts of the above mentioned

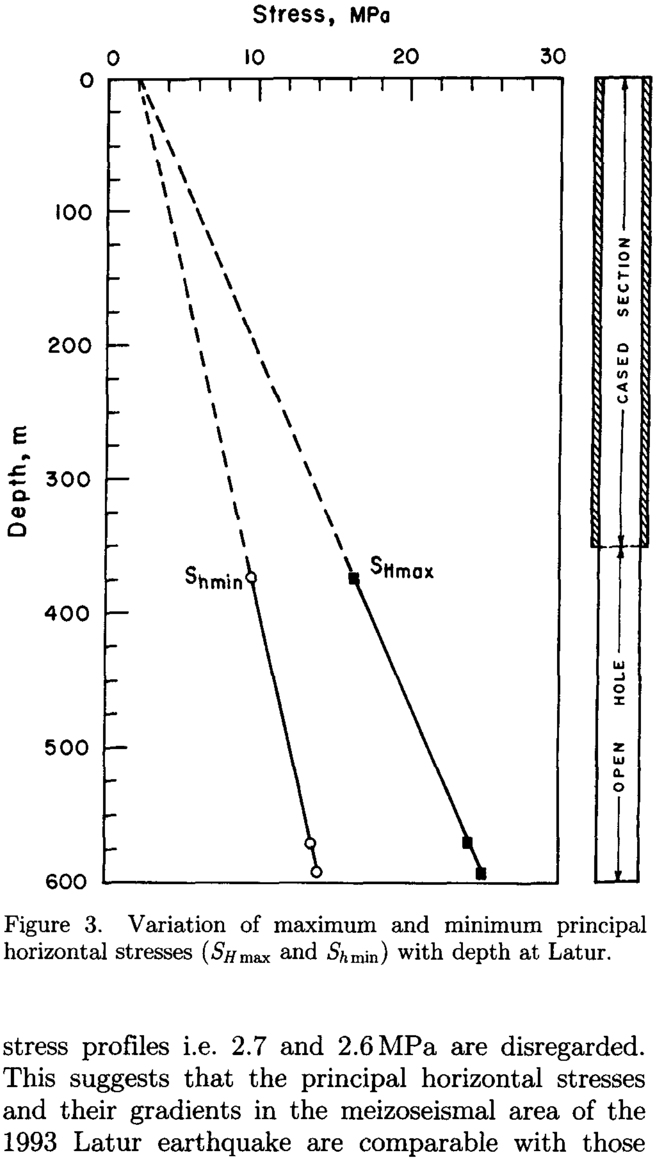

Figure 3. Variation of maximum and minimum principal horizontal stresses ($S_{H\max}$ and $S_{h\min}$) with depth at Latur.

stress profiles i.e. 2.7 and 2.6 MPa are disregarded. This suggests that the principal horizontal stresses and their gradients in the meizoseismal area of the 1993 Latur earthquake are comparable with those observed at Hyderabad, 200 km east of the epicentre.

The focal depth of the 1993 earthquake, according to USGS estimates, falls in the range of 5–15 km while it had a centroid depth of 2.6 km only (Seeber *et al* 1996). The recent estimates by Grad *et al* (1997) based on the analysis of the waveform of the broad band *P*-wave pulse reveal that the focal depth is 6 ± 1 km. Assuming the stress gradients determined by us at the shallow depths of up to about 600 m are equally valid for the deeper horizons down to 6 km depth, the principal horizontal stress magnitudes in the focal region of the Latur earthquake are estimated to be 234 and 126 MPa respectively. The vertical stress, S_V in the focal region is estimated to be 156 MPa, assuming that the density of the basement rock is 2.6 g/cm^3.

Teleseismic moment tensor analysis of the Latur earthquake yielded nearly pure reverse faulting with strike and dip (α) 126° and 46° respectively (Seeber *et al* 1996). The orientation of $S_{H\max}$ (N14° ± 3°E) determined by us reveals that $S_{H\max}$ is not directed at right angles to the strike of the thrust fault but at 68° only. This suggests that the seismic slip of the Latur earthquake was not completely updip but had a minor strike slip component as indicated by the teleseismic moment tensor solution.

From the above estimated focal region principal stresses, we can show that the post earthquake shear stress acting on the thrust plane comes out to be

$$\tau_a = [(S_{H\max} - S_V)/2] \sin 2\alpha = 38.98\,\text{MPa}.$$

Baumbach *et al* (1994) estimated the stress drop ($\Delta\sigma$) associated with the Latur earthquake, assuming a rectangular rupture model and found that

$$\Delta\sigma = 7\,\text{MPa}.$$

This implies that pre-earthquake shear stress acting an the thrust plane was

$$\tau_b = \tau_a + \Delta\sigma = 45.98\,\text{Mpa}.$$

Assuming that $S_{h\min}$ remained unperturbed following the above stress drop, the pre-earthquake $S_{H\max}$ in the focal region turns out to be 248.02 MPa. These estimates demonstrate that the focal region stresses have not undergone any significant change following the Latur earthquake.

Based on the modified Omori equation, Baumbach *et al* (1994) estimated the *P*-value to be 0.80 for the 1992 earthquake sequence by assuming that it occurred in the source volume of the 1993 Latur earthquake. Similar analysis was done for the after-shock sequence (October 1993 – January 1994) that followed the main shock and found the value of *P* to be 0.90 only. The *P*-value indicates, according to Bowman *et al* (1990), stress level, and hence we may understand from the above estimated *P*-values that the focal region stresses have not significantly decreased following the main shock and appear to have undergone only some minor changes. This inference is in complete support of our above estimates of the focal region stresses.

According to the fault valve behaviour model (Sibson 1990), fault zones at the base of a seismogenic zone can be sealed due to hydrothermal cementation and as a result they can act as low permeability barriers. Supra-hydrostatic fluid pressures may develop beneath such barriers from a variety of causes. Shear failure of the fault is promoted through the accumulation of fluid pressures within the overpressured zone.

Gowd *et al* (1996) analysed mechanisms responsible for the reactivation of seismogenic faults in the Indian shield considering pore fluid pressure in the fault zones as one of the causative factors for inducing failure. According to them, thrust faults dipping at 45° can be reactivated if pore fluid pressures in the fault zones are as high as 2.2 times the hydrostatic pressures, implying that near lithostatic fluid pressures are required to reactivate Latur thrust fault dipping at 46°. Fault valve behaviour may be considered as a possible mechanism for inducing such high fluid pressures.

Sarma *et al* (1994) observed from magnetotelluric data that there exists a fluid-filled body at 6.0 to 7.0 km depth in the epicentral zone of the Latur earthquake. This implies that the fluid-filled body observed by Sarma *et al* (1994) exists at the base of the seismogenic zone, if we take into consideration the focal depth of the Latur earthquake (6.0 km) estimated by Grad *et al* (1997). This suggests that there is a possibility of fault valve behaviour being exhibited by the Latur thrust fault. We are therefore tempted to consider fault valve behaviour as a possible mechanism responsible for the earthquake activity in the Latur region and analysed the available data, though limited, from this angle.

The Latur thrust fault zone is not exposed anywhere and therefore evidences of fault related veins such as fault extension vein systems and fault fill veins and evidences for repeated opening and closing of cracks, which are characteristic of fault valve behaviour, cannot be obtained by investigating the internal structure of the fault zone, as it was done in the case of Wattle Gully Fault by Cox (1995). The only access to the underground in this region is the BX size borehole (KLR-1) drilled down to a depth of about 600 m. In this borehole, the fault plane was intersected at a depth of about 120 m within the basaltic cover. Cores recovered from the fault plane have shown slickenslides but no secondary veins were noticed filling the cracks (R. Srinivasan, personal communication). The fault zone is intersected at a depth which is too shallow to exhibit fault-related veins because such crack-fill veins are present at seismogenic depths. From this near-surface geological information, it is therefore not possible to infer about the fault valve behaviour mechanisms operating in the Latur thrust fault. However, deep-seated information such as temporal variations in earthquake activity could be of great value in this regard and hence we have examined the Latur region earthquake activity.

It is interesting to note that prior to the main shock, 26 tremors of $M \geq 2.0$ were recorded by the NGRI Seismological Observatory during the period 18th October – 15th November, 1992 (Baumbach *et al* 1994). The largest event with M4.0 occurred immediately after the sequence was initiated. Then the area remained seismically inactive for a period of about 10 months till the main shock occurred on September 29th, 1993. Whereas the aftershock sequence consisted of 41 events with M in the range of 2.0 to 4.4. The largest event of M4.4 occurred immediately after the mainshock and as many as four events with $M \geq 4.0$ occurred subsequently. No significant earthquake activity was recorded by the NGRI Seismological Observatory prior to the 1992 earthquake sequence or after the aftershock sequence.

According to the fault valve behaviour model proposed by Cox (1995), near-lithostatic fluid pressures are obtained at the end of stage 2 of the fault valve behaviour. Fluid pressures are much less than the near-lithostatic pressures during stage 1 and much of stage 2. Near-lithostatic fluid pressures at the end of stage 2 cannot last longer as they are increased to supralithostatic pressures, due to complete destruction of pore connectivity. A large number of hydrofractures are induced adjacent to the fault by these supralithostatic fluid pressures until the fault ruptures. Then fluid pressure suddenly decreases and becomes the least and much less than the lithostatic fluid pressure. As a result shear strength of the fault increases to its maximum, marking the beginning of the post-rupture stage 1 of the fault valve behaviour.

The above model offers the possibility to infer temporal variations in the earthquake activity caused by the fault valve behaviour. This model suggests that an intense earthquake activity occurs for a short duration just before the main shock due to near-lithostatic fluid pressures attained at the end of pre-rupture stage 2. Then the fault becomes seismically inactive between this earthquake sequence and the main shock due to the fact that the supralithostatic fluid pressures are utilised to induce hydrofractures adjacent to the fault during this period. This model also implies that aftershock activity occurs for a short duration until the beginning of the post-rupture stage 1 and then the fault remains seismically inactive for sufficiently long periods during stage 1 and much of stage 2 of the fault valve behaviour, until near-lihostatic fluid pressures are obtained at the end of stage 2. The intense 1992 earthquake sequence that occurred in the Latur region prior to the main shock of September 29th, 1993, absence of earthquake activity between this sequence and the main shock and insignificant earthquake activity till date following the intense after-shock activity up to January 20th, 1994 – all these temporal variations strongly suggest, in the light of the above discussion, that the earthquake activity at Latur might have been caused by the fault valve behaviour of the Latur thrust fault dipping at a fairly steep angle, implying that the globally deadliest earthquake occurred due to rupturing of the over-pressured fault segment when fluid pressure within the segment attained critical value as estimated by Gowd *et al* (1996). However, mechanisms other than fault valve behaviour are not ruled out.

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