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Fault-plane Solution of the Koyna (India) Earthquake

THE peninsular shield of India has long been regarded as a stable region. The area had not been subject to orogenic deformation since the Pre-Cambrian, although a vast area (5×10^5 square km) was flooded by basalts during Late Cretaceous to the Eocene—the Deccan Trap. Several years ago, a small dam was built across the Koyna river, some 200 km south-east of Bombay (Fig. 1). The dam reservoir filled in stages[1], beginning with the monsoon of 1962, and reached a capacity of 2×10^9 m^3 and a maximum depth of about 70 m[1].

From about the spring of 1963, several mild tremors have been recorded in the area of the Koyna reservoir, presumably as a result of small crustal adjustments due to the imposed water load—a mechanism suggested[2] for the seismicity associated with the filling of the Boulder (Hoover) dam reservoir. The frequency of tremors gradually decreased from 1963 to 1965, but then increased again in 1966. On September 12 and 13, 1967, there were two shocks in the Koyna area which could hardly be called tremors[3], and the earthquake of December 11, 1967, was an even bigger surprise, being felt over an area of nearly 200,000 square km and recorded by seismograph stations all over the world. Fortunately, the dam was not broken and, despite the loss of hundreds of lives, intensive damage was confined to an area with a radius of 50 km around Koynanagar, a village near the dam site[4].

Because no major fault is known to exist in the Koyna area and because of the aseismic history of the Peninsular shield region, this major earthquake was quite unexpected. A meeting was held in New Delhi on December 19, 1967, which led to a special issue about the Koyna earthquake published by the *Journal of the Indian Geophysical Union* (**5**; 1968) and there were suggestions that the filling of the reservoir triggered the earthquakes. Too little is known, however, to decide whether the triggering mechanism consisted of an increase of pore pressure in rock stressed to near its breaking strength[5] as at Denver, Colorado, or some other means.

We believe that the Koyna earthquake is most likely to be tectonic in origin. Wadia[6] has suggested that it might have been caused by slippage along a fault, which is a subsidiary of the Malabar Coast fault about 100 km to the west. Because fault-plane solutions are valuable in the study of earthquake mechanisms, we now present such a study in the hope that it will stimulate research on the cause of the Koyna earthquake.

The epicentre[7] was within 10 km of the Koyna dam (17° 23′ N, 73° 45′ E) at crustal depth (Fig. 1). The US

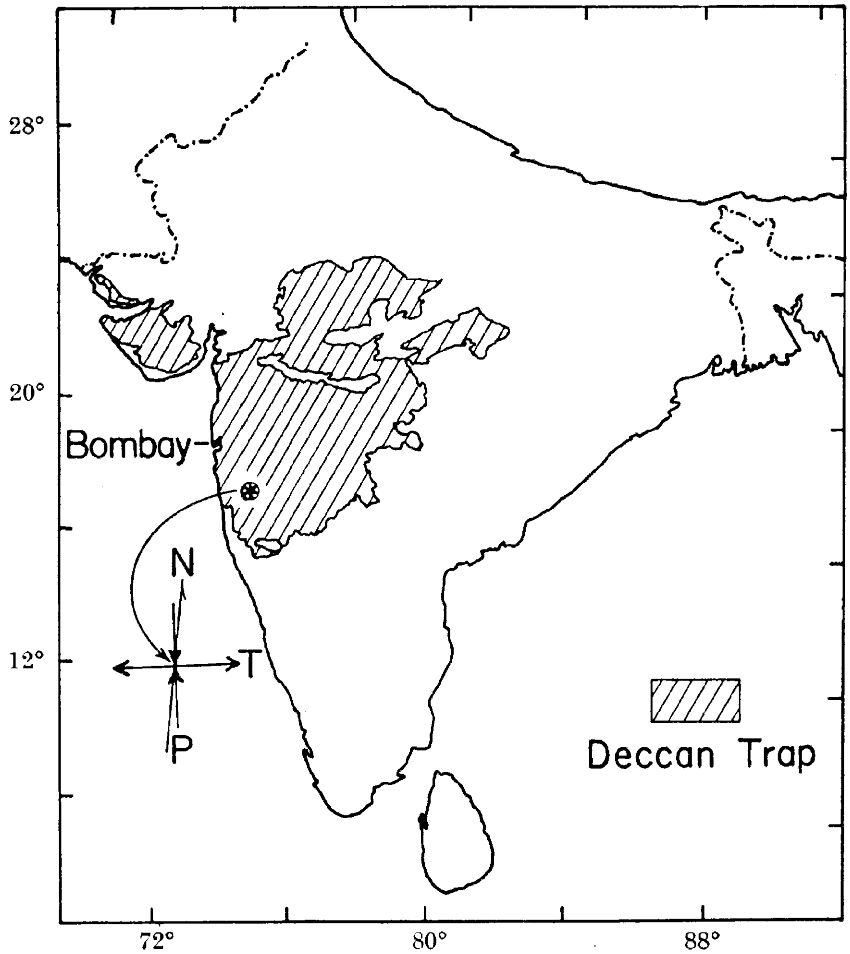

Fig. 1. Map of India showing the epicentre of the Koyna earthquake and the Deccan Trap. Compression and tension directions are shown by *P* and *T* respectively.

Coast and Geodetic Survey has given the following data[8]

Origin time:	22 h 51 m 24·3 s (GMT)
Epicentre:	17° 40′ N, 73° 56′ E
Depth :	Restricted to 33 km
Magnitude:	6·0

This places the epicentre about 35 km north-east of the Koyna dam. Because fault-plane solutions based on world wide data do not depend critically on the precise determination of the earthquake focus, we have used the above epicentre and an arbitrarily assumed depth of 8 km.

We have based our fault-plane solution on first-motion readings of *P*-waves derived from the following sources: (1) Our own readings on long period seismograms from forty WWSSN stations (twenty-six readings altogether); (2) seventeen readings from all available Indian seismograph stations (supplied by Dr A. N. Tandon, director of seismology, Indian Meteorological Department); (3) twenty-four readings on file at the International Seismological Centre, Edinburgh (Dr D. M. McGregor); (4) eighteen readings from the *Earthquake Data Report* No.

77–67 (US Coast and Geodetic Survey); (5) one reading from the *Seismological Bulletin*, 1967 (Canadian Dominion Observatories). These eighty-six first-motion readings were given weights (1 to 4) according to the source and the quality of the *P*-wave arrivals.

A fault-plane solution was made by a computer program[9] written by Wickens adapted to our computer (IBM 360/65) and with the addition of an equal-area projection plot of the focal sphere. Emergent angles were computed by ray theory, the rays to various stations were traced back to the focal sphere, and a pair of orthogonal planes at the focus were assigned a sequence of positions in each of which a score was computed based on the sign of the first-motion, theoretical radiation pattern and weight assigned to the stations. From 4,860 trial solutions, the five with best scores were refined to give the following fault-plane solution

	Φ (Strike)	δ (Dip)
Plane A	37°	72° NW
Plane C	126°	84° SW

This solution is well determined in the sense that none of the nodal planes can be rotated by more than 2 degrees without significantly reducing the score. There were seventeen stations (out of eighty-six) where first motion was inconsistent with our fault-plane solution, but if these were ignored, the solution would be essentially unchanged because most of them have poor quality first-motion data and are not heavily weighted.

Fig. 2 shows an equal-area projection of the lower hemisphere of the focal sphere. The two coordinates used to describe a station point are: (1) the azimuth from the epicentre to the observing station (measured from the north) and (2) the radial distance R which is proportional to $\sin(i/2)$, where i is the angle of incidence measured from the downward vertical. Closed circles represent compression; open circles, dilatation. The size of the circles indicates the weight assigned to the first-motion readings—large circles have weights of 3 or 4, and small circles have weights of 1 or 2.

The two nodal planes obtained from the fault-plane solution are also shown in Fig. 2. These planes are nearly vertical, and the sense of slip is left-lateral for plane A and right-lateral for plane C. Which nodal plane actually represents the fault cannot be determined from the first-motion data alone. The axes P and T represent the directions of greatest and least principal stresses for which the shear stress is maximum on either nodal plane. The orientations of P and T show that the Koyna region deformed by faulting in response either to north–south compression or east–west extension (Fig. 1).

Our study shows that the faulting at the time of the Koyna earthquake occurred on a nearly vertical plane

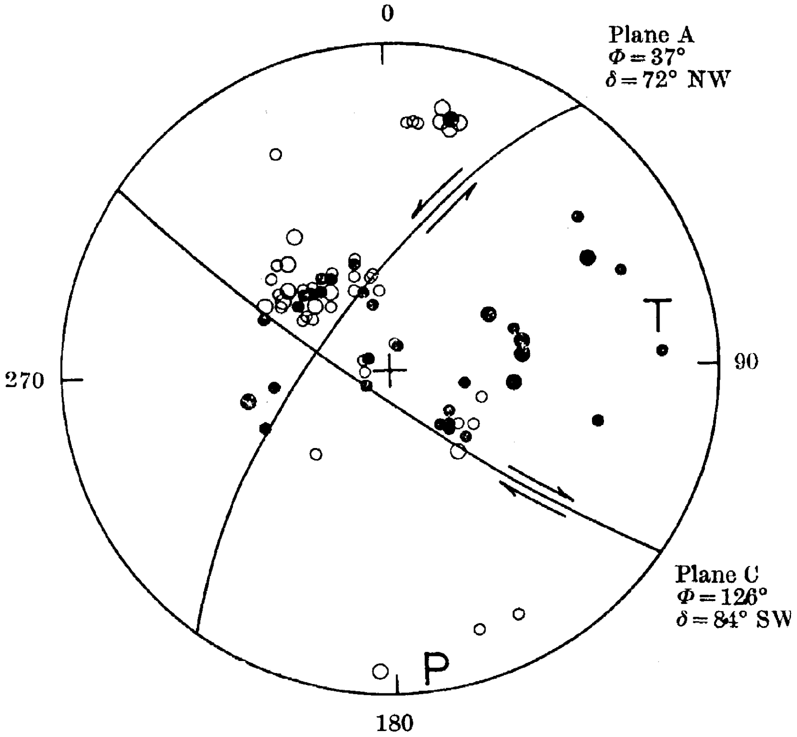

Fig. 2. Fault-plane solution for the Koyna earthquake. Diagram is an equal-area projection of the lower hemisphere of the radiation field. ●, Compressions; ○, dilatations.

striking either north-north-east or west-north-west and not north–south, as inferred from geomorphology[4]. This strike-slip faulting indicates that the maximum and minimum principal stresses are nearly horizontal. It follows that the vertical loading resulting from the filling of the Koyna reservoir cannot be the sole cause of the earthquake. We suggest that the tectonic strains stored in the rocks in the Koyna region were the source of the energy released from the Koyna earthquake.

We thank Dr A. J. Wickens for his fault-plane solution programme and his help in modifying it, and also Drs A. N. Tandon and D. M. McGregor for their first-motion data.

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