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Periodic variation of stress field in the Koyna–Warna reservoir triggered seismic zone inferred from focal mechanism studies

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ABSTRACT

The Koyna–Warna region in western India is globally recognized as the premier site of reservoir triggered seismicity (RTS) associated with the Koyna and Warna reservoirs. The region is characterized by continuous seismic activity observed since several decades, including the world's largest triggered earthquake of M6.3 which occurred in Koyna in 1967. While the role of reservoirs in triggering earthquakes has been widely discussed, the actual tectonic mechanism controlling earthquake genesis in this region is hardly understood. The Koyna–Warna region is exclusively governed by earthquakes of strike–slip and normal fault mechanism distinct from the thrust faulting seen in other active zones in the Indian region. In the present study, a comprehensive catalog of 50 focal mechanism solutions of earthquakes that occurred during the last 45 years in the Koyna–Warna region is developed, both from previous literature and from moment tensor inversion studies by the authors using broadband data from a local seismic network operating since 2005. The seismicity and fault plane data have enabled precise delineation of trends of the major causative faults, which are further accentuated using the double-difference technique. Stress inversion of the focal mechanism data has provided the best fitting principal compressive and tensile stress field of the region, which in conjunction with the deciphered fault zones provides a feasible model of seismogenesis in this region. Based on the observed temporal variation of faulting mechanism a model of alternating cycles of predominantly strike–slip and normal faulting is proposed, which is attributed to a periodic peaking and relaxation respectively of the horizontal compressive stress field in this region due to the Indian plate collision with Eurasia.

1. Introduction

The Koyna–Warna region in the Deccan volcanic terrain of western India (Fig. 1) is globally recognized as the best example of Reservoir Triggered Seismicity (RTS) (Gupta, 1992, 2002; Gupta and Rastogi, 1976; Rastogi et al., 1997; Talwani, 1997; Chander and Kalpna, 1997; Chadha et al., 1997). Seismic activity has been continuously occurring during the last fifty years, subsequent to the impoundment of the Koyna reservoir in the year 1962 followed by the Warna reservoir about 20 km south in 1985. The largest, damaging earthquake of M6.3 occurred in Koyna on 10 December 1967 (Narain and Gupta, 1968; Tandon and Chaudhury, 1968; Lee and Raleigh, 1969; Langston, 1976). Since then, 22 earthquakes with $M \geq 5$ have occurred apart from thousands of smaller events both in Koyna and Warna. While Koyna has been the focal point of intense seismic activity, a visible enhancement of seismicity has been observed in Warna during the recent years (Fig. 1). Earthquakes in the Koyna region occur within about 13 km depth, whereas they are much shallower, within about 8 km, in the Warna region. These seismogenic zones at depth appear as low velocity layers in the model of Krishna et al. (1989) inferred from seismic wide-angle reflection and refraction studies, as well as from inverse vertical seismic profiling gathers of local earthquake seismograms in this region (Krishna, 2006). In general, the region is characterized by a granite-gneiss basement with a high average P-wave velocity (Srinagesh et al., 2000; Shashidhar et al., 2011; Dixit et al., 2014; Rohilla et al., 2015). Generally, the focal mechanism solutions of earthquakes in the Koyna region, including the 1967 event of M6.3, are generally strike–slip type and those in the Warna region are normal type (Gupta et al., 1980; Talwani, 1997) although they often occur as a combination of the two (Shashidhar et al., 2011).

Several studies have been carried out that indicate a correlation between the occurrence of seismicity and changes in water levels of the reservoirs (Evans, 1966; Roeloffs, 1988; Simpson and Narasimhan, 1990; Gupta, 1992; Rice, 1992; Byerlee, 1993; Zoback and Beroza, 1993; Kalpna and Chander, 2000; Do Nascimento et al., 2004; Yadav et al., 2014). The basic mechanism of reservoir trigger seismicity (RTS) is attributed to fluid injection causing increase of pore pressure along faults which are already close to critically stressed by the ambient tectonic stress. Other effects include poro-thermo elastic effects and change in gravitational loading on fault system without the necessity of a hydrologic connection. While the RTS mechanism, which is known to have only a minor contribution, is liberally invoked to explain

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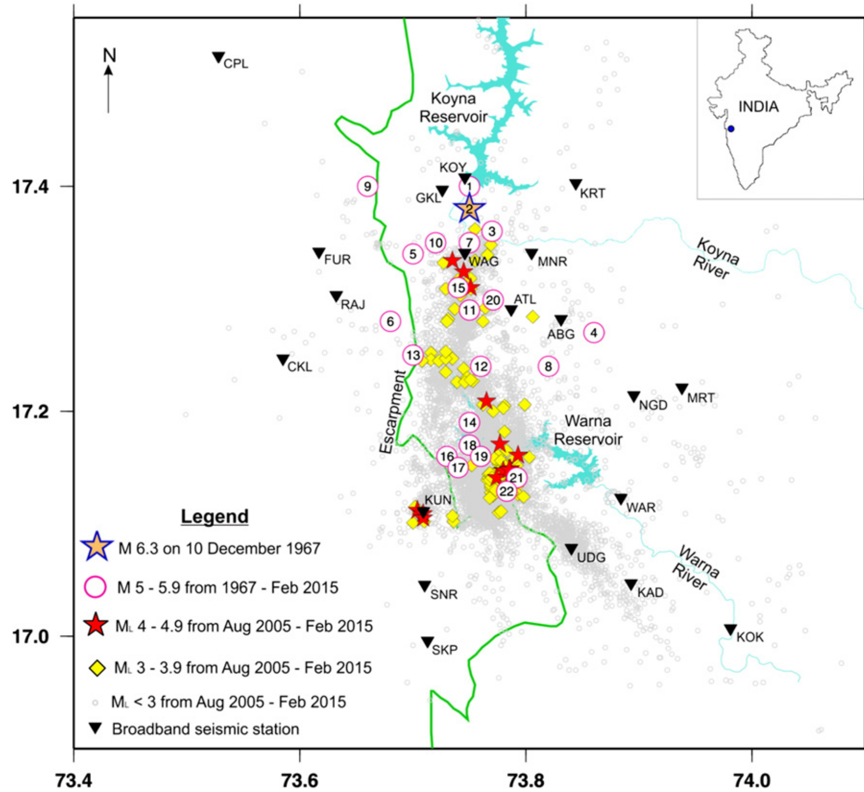

Fig. 1. Seismic station network of CSIR-NGRI in the Koyna–Warna region, along with seismicity distribution comprising earthquakes of M ≥ 5 since 1967 and smaller ones since 2005. *Inset*: Map of India indicating the Koyna–Warna region.

the seismicity, not much has been said regarding the actual tectonic mechanism controlling seismogenesis in the Koyna–Warna region, especially the reasons for the combination of strike–slip and normal faulting prevalent in the region. Based on high P and S wave velocities in the seismic zone, Rai et al. (1999) inferred that earthquakes are controlled by strain build up due to competent lithology in the crust. However, no definitive mechanism of earthquake occurrence is proposed. Gahalaut et al. (2004) suggested triggering of normal faults in Warna through stress transfer from strike–slip faults in Koyna. They cite the example of the M6.3 strike-slip earthquake of 10 December 1967 triggering a normal fault earthquake after two days. Catherine et al. (2007) proposed that the flexure of the elastic plate in the Western Ghats escarpment region promotes failure on the sub-parallel faults in conjunction with the reservoir loading mechanism. Most of these models, however, need to be verified with available seismological data. Catchings et al. (2015) proposed right-lateral strike–slip motion on NW trending fault system between Koyna and Warna. However, neither the seismicity distribution nor the aftershock distribution of the 14 April 2012 earthquake (Shashidhar et al., 2013) concur with this model.

In the present study a comprehensive data set of 50 focal mechanism solutions for the Koyna–Warna region is developed based on previous literature as well as our own solutions using moment tensor inversion of broadband waveform data from the local seismic network operating since 2005. This data set is also inverted to obtain the ambient stress field of the region, which in conjunction with the inferred fault plane orientations and revised seismicity trends provides a plausible tectonic model for seismogenesis in the Koyna–Warna region.

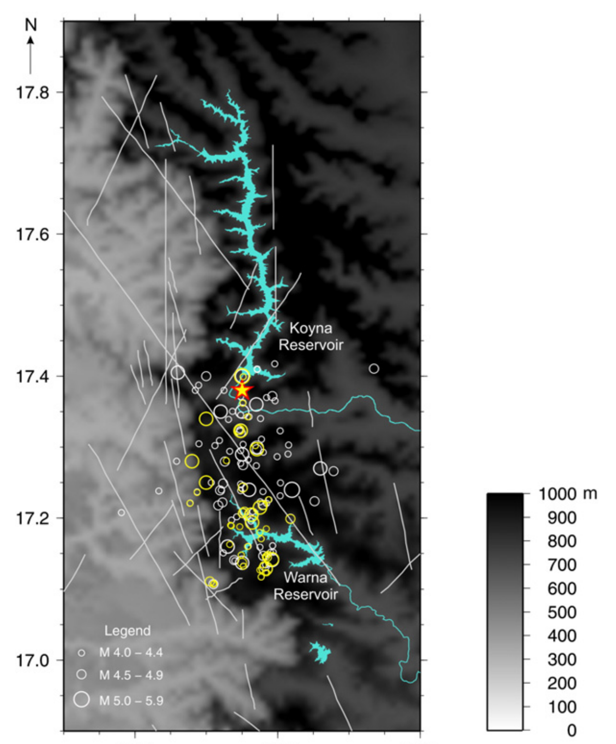

Fig. 2. Earthquakes of M ≥ 4.0 in the Koyna–Warna region since 1967, along with the topographic undulations (gray scale). The star (in red) denotes the largest earthquake of M 6.3 of 10 December 1967. The open circles in white are the locations of events without focal mechanism solutions, while the yellow ones are the ones with mechanisms and used in the present study. The lines are the faults/lineaments inferred from LANDSAT images (Langston, 1981). Also seen are the Koyna and Warna reservoirs situated about 25 km apart, just east of the Western Ghat escarpment.

2. Data and methodology

2.1. Focal mechanism solutions

Since the occurrence of the 1967 Koyna earthquake of M 6.3, more than 170 earthquakes of M ≥ 4.0 occurred in the Koyna–Warna region