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ACKNOWLEDGEMENTS. We thank Prof. D. Lal, Director, PRL, Ahmedabad, for kindly providing the meteorite samples to study their magnetic properties. We also thank the Director, NGRI, Hyderabad, for permission to publish these results.

Received 8 May 1995; revised accepted 24 January 1996

Low-moderate seismicity in the vicinity of Palghat Gap, south India and its implications

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Low-moderate seismicity has been detected within the Palghat Gap, a large physiographic feature in south India. An M_L 4.3 earthquake that occurred on 2 December 1994 near Wadakkancheri in Trichur district, Kerala was also located within the confines of this feature. A few small tremors have previously been reported from the source region of the 1994 earthquake as well. Historic records show the occurrence of two earthquakes near Coimbatore, on the northern extremity of the gap. Continued low level seismic activity, originating from this area is recorded by the stations of the Gauribidanur Seismic Array (GBA). Thus, regional seismicity points to the presence of active structures and enhanced stress concentration within the Palghat Gap. On the basis of these observations, we suggest a reevaluation of this regional feature in terms of its potential to generate larger earthquakes in the future.

MONITORING earthquakes in regions characterized as 'stable', is gaining more importance with the growing realization that undetected seismogenic faults may be responding to current crustal deformation processes. Earthquake reports from various intraplate regions indicate their association with faults of varying reactivation periods, sustaining the overall rate of both small and large earthquakes. Because these faults may have never been reactivated during the recorded history, an earthquake may occur as a total surprise. Peninsular India has been the site of several moderate earthquakes, some of them highly damaging (1967 Koyna and 1993 Killari events, for example). However, very little is known about their mechanisms and causative structures. Because of the sparse distribution of seismic stations in peninsular India, quite often the information on background seismic activity is inadequate, and the nature of precursory activity, seldom understood. Understanding patterns of earthquakes and their characteristics may help to constrain the nature of regional seismicity and identify potential seismic source zones. In this paper, we argue for the need to update the seismic hazard associated with the Palghat Gap on the basis of the historic seismicity and the characteristics of the recent seismicity (Figure 1).

The Palghat Gap is the most conspicuous physiographic feature in southern India (Figure 2). The east–west orientation of the geomorphic features, including that of the Bharathapuzha river, is in general agreement with the trend of this feature. Considered as a possible shear zone, this feature passes through Palghat in Kerala, and is marked by high rising hills to its north and south[1–3]. Rao and Srinivasan[1] detected several shear and fracture zones and minor faults around Palghat, between Coimbatore and Anaimalai hill ranges. More specifically, they suggested that the shear zones occur on the southern and northern margins which show variations in width, about 4 km in the northern and 2–6 km in the southern sides. Based on the structural map prepared for the area, a deep-rooted rupture in the E–W direction was proposed. In another study, Kesavamani and Bose[4] inferred three major directions of fracture zones, NW–SE, NE–SW and E–W, based on regional magnetic and resistivity surveys. The E–W-trending fracture zones along the margins, according to them, correspond to tensile fractures, while the NW–SE and NE–SW-trending fractures may be shear fractures. The magnetic lows identified in the area generally conform to the river and stream courses. These studies, in short, project a picture marked by high level of tectonic disturbance.

The rocks and the mineral assemblage in the gap area indicate upper amphibolite–granulite facies metamorphism (300–450°C), which may have undergone cycles

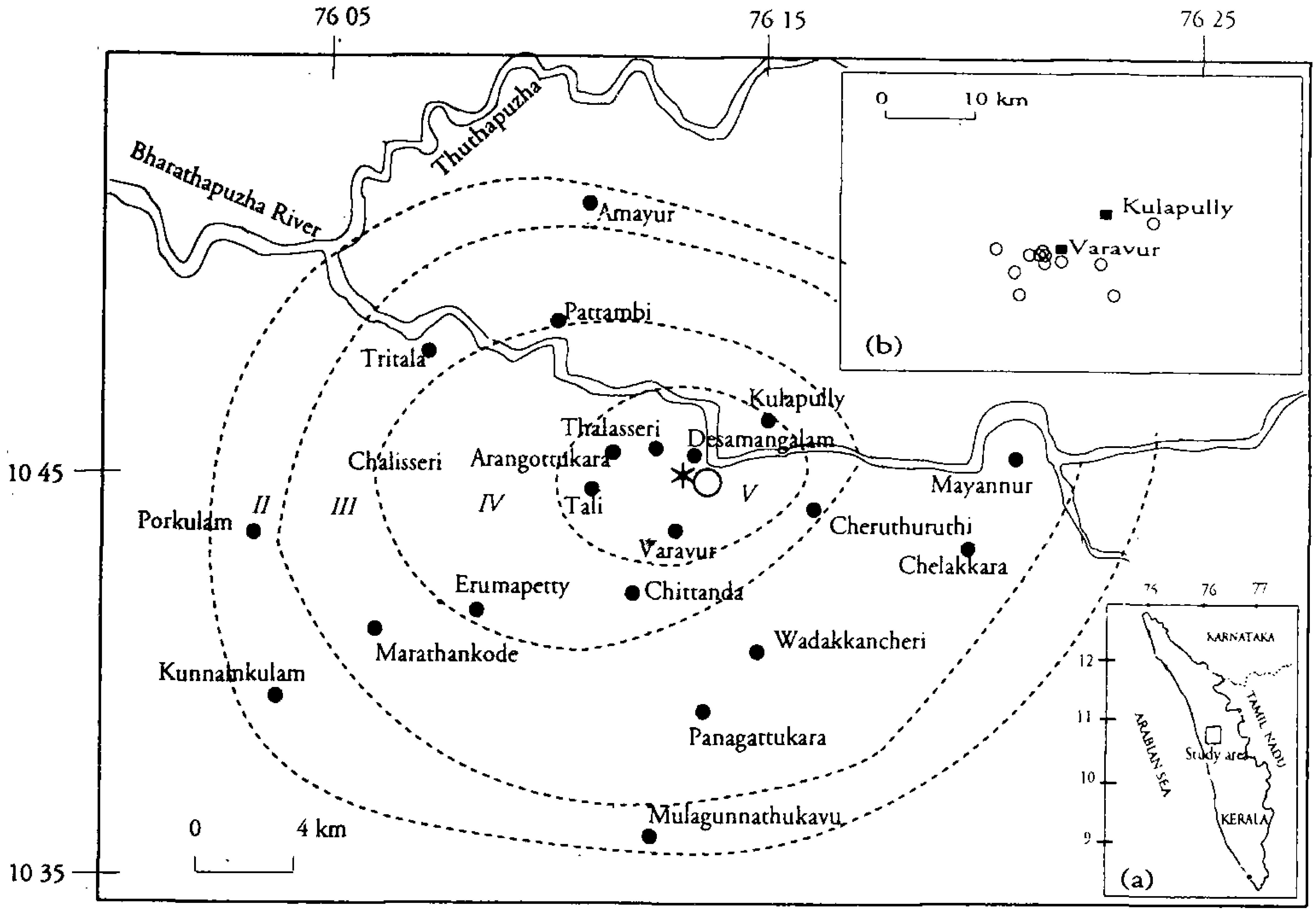

Figure 1. Isoseismal map of the 2 December 1994 earthquake. Location obtained from isoseismal is shown by asterisk. Open circle indicates location by IMD. Inset: *a*, map of Kerala, showing the study area; *b*, locations of temporary stations by IMD (filled squares) and aftershock locations (open circles).

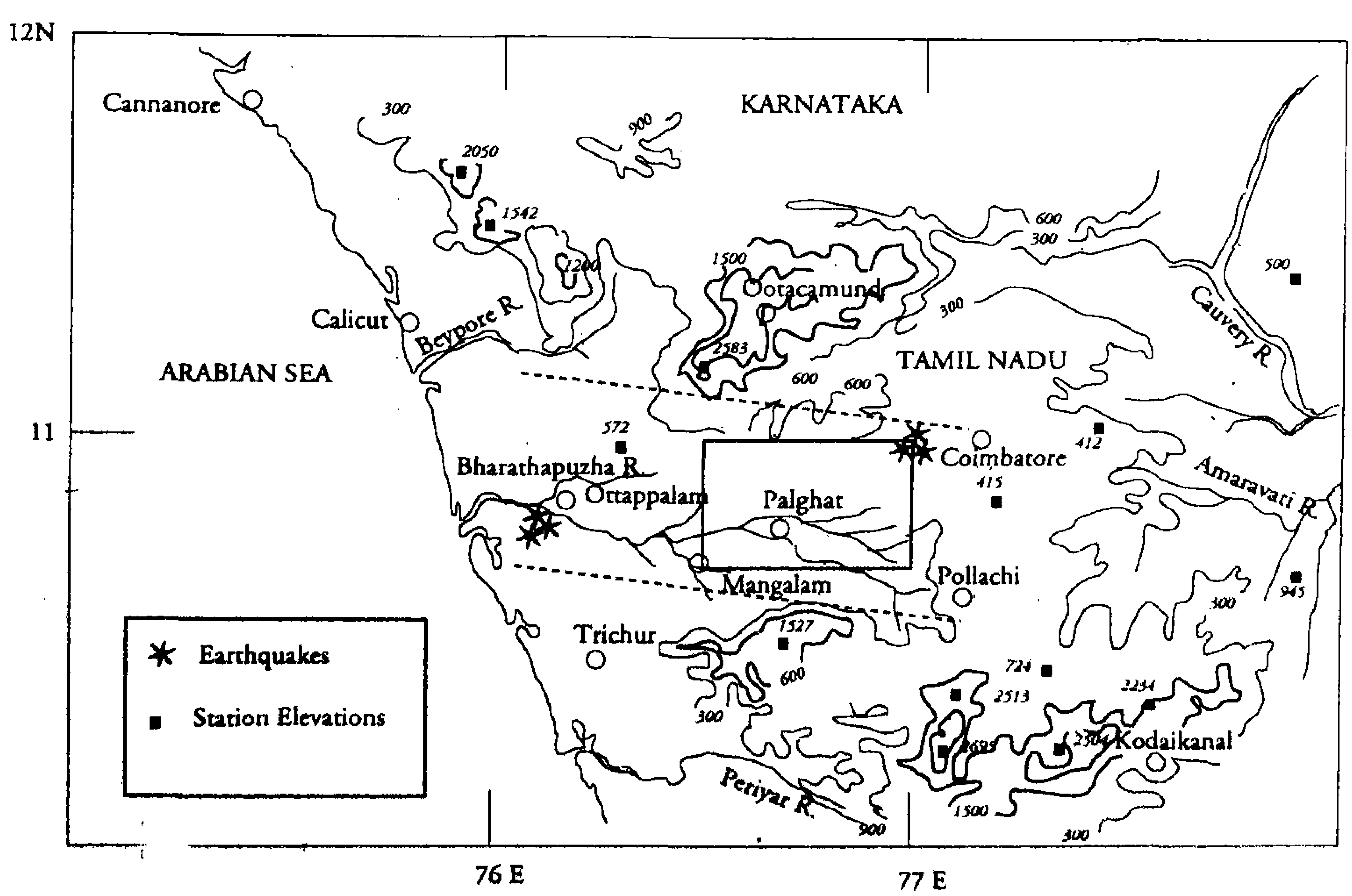

Figure 2. Regional physiographic map around Palghat showing the prominent contours (after Subramanian and Muraleedharan[3]). Dashed lines mark the approximate extent of the Palghat Gap. Sites of prominent earthquakes in the area are indicated. Rectangular area indicates zone of microseismic activity recorded by GBA.

of deformation, metasomatism, remobilization and remelting[5,6]. K–Ar dating of pegmatites from some localities in the central part of the gap indicates ages between 484 and 512 m.y. (ref. 7). Quasi-plastic deformation with mylonitic structures with absence of cataclasis has also been identified in some localities[5]. These observations suggest that the area comprising the gap probably represents lower crustal equivalents of brittle fault zone in the upper crust, brought to the present level by the processes related to repeated uplift and erosion, as observed in other shield areas[8]. The reactivation of this structure during the Cretaceous–Tertiary is indicated by the development of NW–SE dike systems and fractures[9] cutting the older generation folds. Raised old river terraces and pebble beds have also been reported from the Palghat Gap[10].

Occurrence of three earthquakes in the Coimbatore region (Table 1) is an indication of the seismogenic potential of the structures in the Palghat Gap. The 1900 Coimbatore earthquake ($M \geq 5.5$) is the largest historic event that occurred in the southern part of peninsular India[11]. Occurrence of two smaller earthquakes, one in 1865 and another in 1972, in the same region indicates higher stresses in this region. These earthquakes occurred in a zone of low gravity[12]. In addition to these, several microtremors have also been reported elsewhere in the Palghat Gap, including the area around Mangalam dam and Sarkarpathi in the southern part of the gap[1]. Further, the seismic data recorded at GBA show occurrence of several small earthquakes in the area (Table 1). Within the margins of possible error, these microearthquakes are located within the Palghat Gap (Figure 2). The recent activity near Wadakkancheri (Figure 2) becomes significant because of its proximity to the same regional structure (Table 1). The earthquake that occurred here on 2 December 1994 was the latest event of the continuing seismicity in this region.

The 2 December earthquake (M_L 4.3) was felt in an area of about 1000 km^2 in Trichur and neighbouring districts (Figure 1). This is the second earthquake of magnitude ≥4.0 experienced in the Kerala State during the last ten years. The epicentre is located about 8 km north of Wadakkancheri town (Figure 1 and Table 2). Based on the felt reports, a maximum intensity of V on MM scale was assigned to the event. Field investigations indicated ground cracks and damages to a number of houses and minor displacement of objects in the epicentral area (Table 1). Most of the measurable dislocations occurred in the ENE to EW direction (see Rajendran and Rajendran[13,14], for details). Due to inadequate instrumental data, a focal mechanism solution could not be obtained. Based on the field observations, we infer that the faulting might have occurred on an east–west trending fault. The earthquake was followed

Table 1. Seismic events reported from the Palghat Gap area

Year	Location	Magnitude/Intensity	Comments
24 June 1865	Near Coimbatore	IV	Source: Chandra[17]
28 February 1900	Near Coimbatore	VII	Severe shock; roaring noise; serious damages to many houses; displacement of objects; no casualties reported; severely felt in Coimbatore and Coonoor. Source: Basu[11]
29 July 1972	Near Coimbatore	VI	Source: Chandra[17]
1981–1993	Central part of the gap. South of 11°N Lat. West of 77°E Long.	1–2	>40 microtremors have been detected during a period of 12 years. Source: GBA records.
15 March 1989	Near Wadakkancheri 10.64°N, 76.26°E	3.0	Rumbling sound and ground shaking. No visible damages; major axis of the felt region trends in E–W direction. Source: Singh and Raghavan[18].
25–26 February 1993	Near Wadakkancheri 10.64°N, 76.20°E	3.6	Located 8 km SE of the 15 March tremor. Loud sound, rattling of window glass and ground shaking. Another similar tremor reported from Chavakad on the Trichur coast on 25 February. Source: Singh and Santosh[19].
2 December 1994	Near Wadakkancheri 10.75°N 76.21°E	4.3	Located close to Desamangalam. A minor tremor reported in this area, near Varavur on 8 June 1994. Ground cracks, displacement of objects and moderate damages to many houses in the epicentral area. Maximum measurable displacement was less than 5 mm.

Note: Microtremors have also been reported from the area around Mangalam dam.

Table 2. Epicentral parameters of the 2 December 1994 Wadakkancheri earthquake

Date	Origin time hr:min:sec (IST)	Lat°N	Long°E	Magnitude	Data
02-12-94	16:06:34:00	10.82	76.22	–	KSEB
02-12-94	16:06:57:00	10.75	76.25	3.8	IMD
02-12-94	16:05:00:00	10.75	76.21	4.3†	Field studies

Note: NGRI (National Geophysical Research Institute) assigned a magnitude of 4.0; Location from KSEB (Kerala State Electricity Board) is based on the data recorded at Idukki and Idamalayar Stations. Programme used: HYPO 71, no. of stations: 7 and quality of location: D (poorest); IMD (India Meteorological Department) location is closer to the epicentre obtained from the isoseismals;† magnitude derived from maximum intensity.

by a large number of aftershocks. Over 100 small tremors were reported by the local residents until 15 February 1995. In the absence of a close network, locations could be obtained only for 13 aftershocks (Figure 1, inset), based on data from IMD stations that became operational two weeks after the main event[16]. The largest of these tremors (M_L 2.5) occurred on 1 January. Even after 15 February, occasional tremors were felt by the local residents.

Structurally, the 2 December earthquake appears to be associated with a rectangular turn of the Bharathapuzha river (Figure 1). The general E–W trend of the river takes a WNW swing beyond this point, before the E–W course is resumed further west. The regions west and south west of this bend occur at higher elevations. The regional lithology being the same (charnockite suite of rocks) on either side of the river, we infer that the abrupt change in the direction might have resulted from tectonic movements. This kind of structural and geomorphological barriers in several regions are known for their potential to localize stresses, and develop as possible seismic source zones[15]. Many of them may remain unnoticed until an earthquake occurs in their vicinity. The source zone of 2 December earthquake may have also developed so, through slow stress accumulation. Maximum effect of the tremor was observed in the Desamangalam–Thalasseri area, to the west of this bend (Figure 1). The area around Mayyanur in the east (Figure 1) was noted for the highly localized nature of damages. A house at this location, built in brick and clay, totally collapsed during the earthquake whereas there was very little damage in the regions between this site and the immediate epicentral area. This region may be the termination point of the current rupture on the eastern side. Reports of NW-trending dikes mapped near Ottapalam, near Mayyannur[5] lend support to the possible existence of structural discontinuities/segments in this region.

The reactivation intervals of various segments in the Palghat Gap region may be of the order of hundreds of thousands of years, as common in stable regions. In the absence of data on spatial and temporal pattern of sesimic events, it is difficult to forecast whether these earthquakes are temporally isolated or they form part of an ongoing seismogenic process. The existing seismic zonation map of peninsular India may not reflect the actual seismic threat, especially when major earthquakes in the region seem to be generated on unknown faults with undetected seismic record. A realistic seismic hazard assessment should be based on the long-term pattern of earthquake occurrences in a region. This emphasizes the need to monitor even smaller earthquakes, like the one reported in this study, more closely and systematically. Isolating seismogenic structures and reviewing their potential have to be identified as an important component of seismic hazard assessment in stable regions. Considering the above characteristics of seismogenic processes in these regions, the studies have to be done for prescribed time windows. These efforts can result in more realistic time-dependent seismic hazard maps.

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ACKNOWLEDGEMENTS. We thank Dr K. M. Nair, Director, CESS for his keen interest. Instrumental data were provided by BARC, IMD, KSEB and NGRI. We are thankful to Dr. Harsh K. Gupta, Director, NGRI and two anonymous reviewers for their helpful suggestions to improve the manuscript. Funding provided by the Department of Revenue, Kerala Government is thankfully acknowledged.

Received 16 October 1995; revised accepted 25 January 1996.

Phosphorite concretions in a sediment core from a bathymetric high off Goa, western continental margin of India

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A sediment core collected from a bathymetric high off Goa on the western continental margin of India, has yielded phosphorite concretions with an average P_2O_5 content of 32.75%, the P_2O_5 concentrations being highest ever reported from the margins of India. These concretions vary in size from < 1 to 5 cm, are subrounded, oval to irregular in shape, dark grey to yellowish grey in colour and consist of carbonate fluorapatite (CFA) as the single mineral phase. The concretions are present in the sediments at various levels below 110 cm from the core top and appear to be older than at least 250,000 yrs. Our study indicates that the phosphate released into the interstitial water due to decomposition of organic matter and dissolution of fish debris is precipitated as microgranular phosphorites which are consolidated and progressively become concretions with time.

PHOSPHORITES are generally found in diverse geographic and physiographic settings in marine environment. Modern phosphorites are reported from the continental margins of Namibia and Peru–Chile, in association with diatomaceous ooze and organic matter-rich sediments where coastal upwelling is strong[1–5]. On the other hand, phosphatic nodules of Quaternary and Neogene ages occur in organic-poor sediments on the shelf off eastern Australia, an area known for its weak upwelling[6–8]. Several workers have reported the occurrence of marine phosphorites in the Indian Ocean[9,10]. On the western continental shelf of India, phosphatized algal limestones of Holocene age have been reported[11–13]. The average P_2O_5 content of these phosphorites is less than 10% (ref. 13). In this paper we report the occurrence of phosphorite concretions, with an average P_2O_5 content of 32.75%, in a 5.85 m long core collected in the water depth of 320 m from the summit of a bathymetric high, off Goa, western continental margin of India.

The core consists of light olive grey to olive grey coloured siltyclays and clay-bearing calcareous oozes, along with organic-rich biogenic carbonate sediments and fish debris, mostly hemipelagic in nature. Other sedimentary facies conspicuous in the core are phosphatic concretions. Phosphorite concretions are distributed at various levels in the core below 110 cm (Figure 1). They are dark grey, yellowish grey and light yellow and subrounded, oval or irregular in shape with a size range of < 1 to 5 cm. Their surfaces are rough with small depressions and cracks (Figure 2). The larger concretions were hand-picked during subsampling onboard, while smaller ones were separated through wet sieving (230 μm mesh). The concretions were washed with distilled water, dried at < 50°C till all the moisture was removed, powdered in an agate mortar and analysed for mineralogical (X-ray diffraction) and chemical composition [Inductively coupled plasma atomic emission spectrometry (ICP-AES)]. Major oxide geochemistry was determined by electron probe micro analyser (EPMA). Polished sections and freshly broken parts of several concretions were studied using scanning electron microscope (SEM) for microstructures and minerals present in it. Thin sections of representative samples were studied under petrological microscope.

The only mineral phase identified in the X-ray diffraction analysis of these concretions (Figure 3) is pure carbonate fluorapatite (CFA). Other minerals such as quartz, feldspars, glauconite, pyrite, dolomite and clay minerals, generally associated with phosphorites[3,14] are not found in these samples. SEM studies reveal that the voids between CFA crystallites are not filled with any detrital and/or diagenetic minerals (Figure 4). Petrological study of thin sections also confirms that the concretions consist of only CFA phase, devoid of any other minerals. P_2O_5 content in the concretions range between 30.90 and 33.91% with an average value of 32.75% and CaO content from 52.82 to 55.15% with an average value of 54.15%. The CaO/P_2O_5 ratio varies between 1.56 and 1.78 with an average of 1.65. EPMA analysis reveals that the composition is similar both at inter-concretional and intra-concretional levels. The P_2O_5 content in these concretions is much higher than the reported value (highest average value for the outer layers = 9.5%) for phosphatized algal nodules of western shelf of India[13]. Comparisons of offshore phosphorites from various locations (Table 1) indicate that the