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# Earthquake swarm activity in south Gujarat

D. T. RAO, B. B. JAMBUSARIA, SANJAY SRIVASTAVA, N. P. SRIVASTAVA,
ABDUL HAMID, B.N. DESAI and H.N. SRIVASTAVA*

*Gujarat Engineering Research Institute, Vadodara*

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**सार** — 1986 की फरवरी के प्रारंभिक दिनों से भारतीय प्रायद्वीप के पश्चिमी तट के एक भाग–दक्षिण गुजरात में हल्की मात्रा में भूकम्प के समूह अनुभव किये जाने लगे। इस क्षेत्र में दूर तक गड़गड़ाहट की आवाज के साथ झटके महसूस किए गए। दिसम्बर 1988 तक 23000 सूक्ष्म-भूकम्प दर्ज किए गए। इनमें 27 अप्रैल 1986 को हुई मुख्य घटना $M_L = 4.6$ भी शामिल है। उकाई, दमनगंगा, झुज, केलिया आदि बहु-उद्देशीय परियोजनाओं का स्थान होने के कारण इस कार्यवाही का तत्काल ही सात अस्थाई सूक्ष्मभूकम्प अभिलेखन स्टेशनों से मानीटरन किया गया। इसके बाद अन्य विभिन्न विषयों जैसे भूगणितीय, भूचुंबकीय, रेडान गैस मानीटरन और गर्म चश्मों के तापमान की मापों का अध्ययन किया गया। इस क्षेत्र में स्थित ऊनाई और मोला-अम्बा गर्म चश्मों ने सामान्य वायुमण्डलीय तापमान 33 डिग्री से. के स्थान पर क्रमश: 57 डिग्री. से. तथा 37 डिग्री. से. दर्शाया।

भारत मौसम विज्ञान विभाग, नई दिल्ली के आई. बी. एम. कम्प्यूटर पर कोयना क्षेत्र के लिए वेग मॉडल प्रयोग द्वारा किए गए हाइपो-71 प्रोग्राम के विश्लेषण ने 7×10 कि. मी.$^2$ के क्षेत्र में भलीभांति संकेन्द्रित भूकम्प सक्रियता और 1 से 15 कि. मी. तक केन्द्रीय गहनता दिखाई है। सक्रियता का स्पष्ट स्थानान्तरण दिखाई दिया। फरवरी से अप्रैल 1986 में जो सक्रियता केलिया बांध के आसपास केन्द्रित हुई थी, वह उसके दक्षिण में 18 कि० मी० स्थानान्तरित हुई और सितम्बर 1987 में उत्तर की ओर, फोकी की गहनता हल्की होकर फिर से केलिया जलाशय की ओर मुड़ गई। 1.04 का "बी" मान, प्राद्वीपीय भारत के कुछ विवर्तनिक अनुक्रमों की अपेक्षा अधिक है। सक्रियता की क्षय की गति 0.52 थी, जो कि क्षेत्र के अन्य अनुक्रमों की तुलना में धीमी थी। इसलिए वर्तमान विभागों/स्थलानुरेखों का पुन: सक्रियकरण, हाल में हुई हलचल का कारण हो सकता है। इस क्षेत्र में भूचुम्बकीय अध्ययनों ने उ. प.– द.पू. से उ. उ. पू.–द.द. प. प्रवाह चालन विभागों के अस्तित्व की पुष्टि की है। पिछले वर्षों की तुलना में, 1988 के दौरान भूकम्प सक्रियता काफी कम थी।

ABSTRACT. South Gujarat, a part of western coast of Indian Peninsula started experiencing earth tremors of mild intensity since early February 1986. The shocks were widely felt with rumbling sound in these areas. More than 23000 microearthquakes have since been recorded till December 1988, with a major event, $M_L=4.6$ which occurred on 27 April 1986. In view of the location of multi-purpose projects like Ukai, Damanganga, Jhuj, Kelia etc the monitoring of this activity was immediately started through a network of seven temporary microearthquake recording stations. This was followed by various other studies such as geodetic, geomagnetic, radon gas monitoring and temperature measurements of hot springs. The Unai and Mola-Amba hot springs situated in this area have indicated the temperature of about 57 °C and 37°C respectively against the normal atmospheric temperature of 33° C.

The analysis by Hypo-71 program on IBM computer of India Met. Dep., New Delhi, using a velocity model for Koyna region has shown a well concentrated seismic activity over area of 7 × 10 km² and focal depth of 1-15 km. Clear migration of the activity has been observed. The activity which concentrated around Kelia dam in early February-April 1986 migrated up to 18 km to its south and back again to the region around Kelia reservoir by September 1987 with depth of foci progressively becoming shallower towards north. The "*b*" value of 1.04 is higher than that of a few tectonic sequences of Peninsular India. The rate of decay of the activity was 0.52 which is rather slow compared to other sequences of the region. Hence, the reactivation of the existing fractures/lineaments might be responsible for the recent activity. The geomagnetic studies in this area have corroborated the existence of NW-SE to NNE-SSW trending conductive fractures. The earthquake activity during 1988 is quite low compared to earlier years.

## 1. Introduction

Some instances have been reported from various parts of the world where the initiation of micro to medium level seismicity occurred in areas around irrigation projects after impounding. However, the question whether the major irrigation projects of height 60 metres or more can initiate the activity or other factors are responsible for the activity is still a matter of debate and no specific set of parameters have been evolved so far to identify and distinguish the reservoir associated seismicity from normal tectonic sequences.

In order to ascertain the effect of the projects on the ambient/regional/local seismicity, the reactivation of the existing lineaments such as faults/fractures in the vicinity of these projects needs to be studied for at least 10 years from pre-impounding to post-impounding stages by installing 5 to 6 portable seismographs.

In the Peninsular India the instances of seismic activity around irrigation projects like Koyna, Idukki, Bhatsa and Kadana have raised a question whether the seismic activity is reservoir induced. Of late, the

*Department of Science & Technology, New Delhi

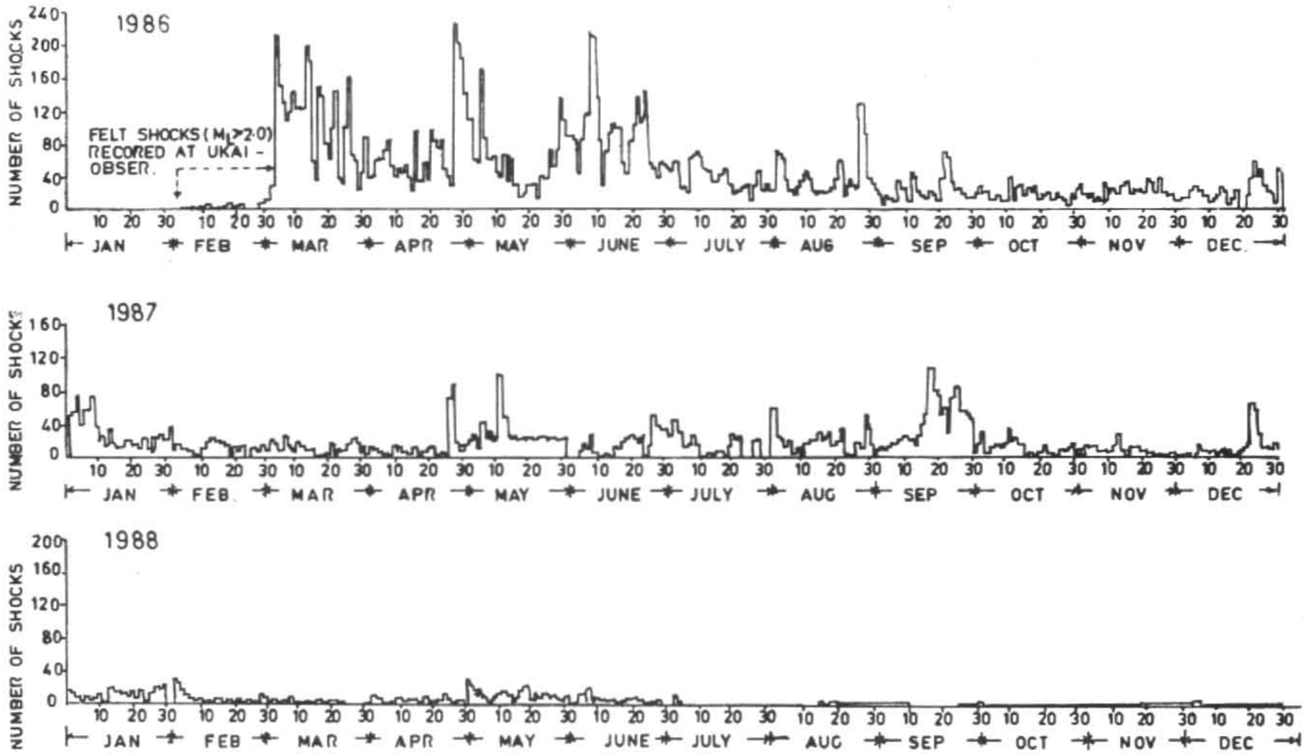


Fig. 1(a). Number of shocks recorded at Ukai during 1986, 1987 and 1988

occurrence of the swarm type of seismic activity in south Gujarat close to the Kelia reservoir having height of 18 metre with one event of $M_L=4.6$ on April 1986, necessitated to take up multi-disciplinary studies for understanding the physical processes involved. In this paper the details of the observations through seven high gain portable seismographs and results of the study up to 1988 are presented and discussed.

## 2. Geotectonic set up

### 2.1. *Geology*

The south Gujarat area around Kelia dam is occupied by flows and dykes of basaltic rocks. It forms the part of southwestern margin of the large Deccan trap formation, of cretaceous eocene occurring in Gujarat, Maharashtra and Madhya Pradesh. The Deccan traps are overlain by tertiary sediments in Mehasana, Sabarkantha, Ahmedabad, Kheda, Baroda, Bharuch and Surat districts of north, central and south Gujarat. These rocks are famous for their economic mineral deposits of oil, gas and lignite. The traps are overlain by older alluvium of late pleistocene age and subsequent holocene formations like newer alluvium blown sands and beach deposits.

### 2.2. *Tectonics*

The area is located near the west coast of India which is a fault formed in late pliocene (Krishnan 1982). This fault is a major geofracture zone related to the breaking away of the Indian plate from the Gondwanaland. This fault is responsible to give a straight western coast up to Gulf of Cambay in its north. The Cambay basin itself lies in a trough fault running N-S from *Banas* river north of Mehsana, southward through the alluvial plains of Gujarat to the Gulf of Cambay near Surat and further southwards into the Arabian Sea. Krishnan (1982) observes that this fault zone extends for some distances south of Bombay.

The Deccan traps dip into the Arabian Sea at an angle of 7° to 10° as a monocline, the axis of which turns through Panvel and Kalyan to south of Surat. This monoclinal feature is termed the Panvel flexure. Along its axis, which is fractured, there are several hot springs. The present area is near this flexure and it is marked by many hot springs, *viz.*, Unai, Mola-Amba, Arnai and others. Another major fault is a ENE-WSW along *Narmada* river. The *Tapi* river also runs along a fault. Another parallel fault passes near Billimora.

There are various fracture patterns in Deccan trap, the prominent being NE-SE (Das and Ray 1976, 1977). The south Gujarat area has major trends of N-S and NW-SE. The trap dykes are very common which follow the trends of fractures and faults. Misra (1980) notes that the Cambay basin is a graben with deep-seated N-S fractures extending into the mantle. There is a gravity high to the axial part of this basin with a high temperature gradient.

### 2.3. *Hot springs*

It may be noted that the study area lies in the same west coast tectonic environment in the Ratnagiri-Surat hot spring zone. The Unai hot spring is about 30 km from the recent earthquake affected area. Arnai and Mola-Amba hot springs are within this area. However,

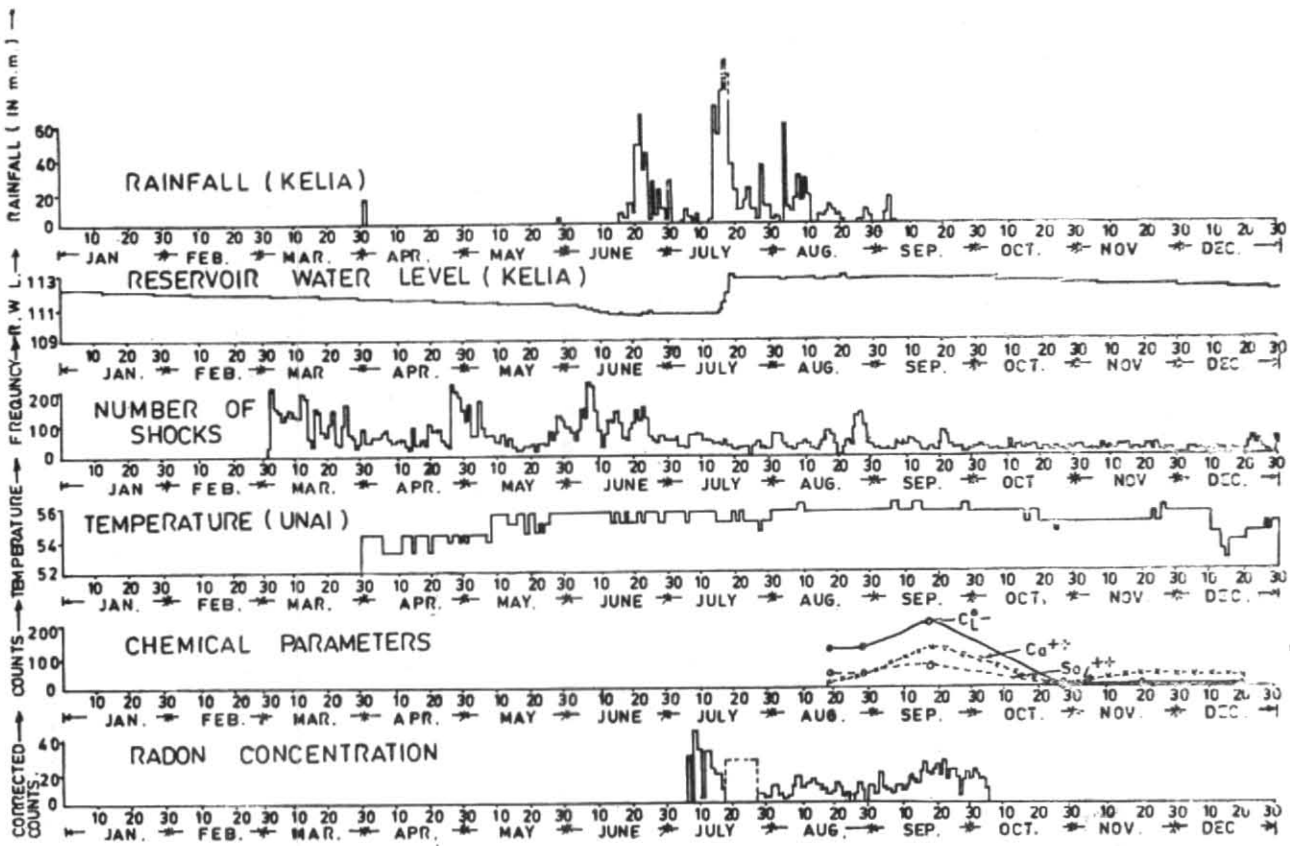


Fig. 1(b). Variation of rainfall, reservoir water level, temperature, chemical parameters and radon concentration

**TABLE 1**

| Station | Location Lat. (°N) | Long. (°E) | Instrument type | Date of Installation (1986) | Gain (dB) | Filter (Hz) |
|---|---|---|---|---|---|---|
| Kelia | 20°41.92′ | 73°16.78′ | MEQ-8008 | 28 Feb | 66 | 5-30 |
| Umberthane | 20°34.6′ | 73°29.2′ | Portacorder | 28 Apr | 84 | 5-12.5 |
| Makadban | 20°26.40′ | 73°13.10′ | Portacorder | 03 May | 84 | 5-12.5 |
| Vadichonda | 20°41.95′ | 73°17.85′ | Portacorder | 12 May | 84 | 5-12.5 |
| Nirpan | 20°38.00′ | 73°26.5′ | MEQ-8008 | 17 May | 78 | 5-30 |
| Sidumber | 20°31.00′ | 73°15.65′ | MEQ-8006 | 18 May | 78 | 5-30 |
| Jamanpada | 20°36.6′ | 73°09.8′ | MEQ-8008 | 20 May | 78 | 5-30 |
| Anklachh | 20°36.66′ | 73°16.35′ | Portacorder | 19 Dec | 78 | 5-12.5 |

their temperatures and discharges are much less compared to Unai. The temperature of Unai is about 54°C to 57°C. During the recent earthquake activity 2° to 5° change in temperature was observed in Unai. The presence of 33 hot springs along the N-S Surat-Ratnagiri trend strongly supports the existence of a fault.

### 3. Seismic activity

The earthquake activity started in the first week of February 1986. Many shocks were felt in the villages around Kelia dam almost every day. In February itself more than 50 shocks with magnitude$\geqslant$2.5 were felt. This earthquake activity which is the first of its kind in the Gujarat State in recent years created considerable panic and widespread fear in people particularly in the tribal public. The Water Resources Department, Government of Gujarat convened a meeting of experts from various National Organisations like National Geophysical Research Institute (NGRI), India Meteorological Department (IMD), Geological Survey of India (GSI), Survey of India (SOI), Central Water Power and Research Station (CWPRS), Indian Institute of Geomagnetism (IIG) and University of Roorkee. Based on their recommendations, multi-disciplinary investigations were initiated covering, (a) Seismological and isoseismal studies for identifying the sources of the activity, (b) Identifying and studying the earthquake precursors such

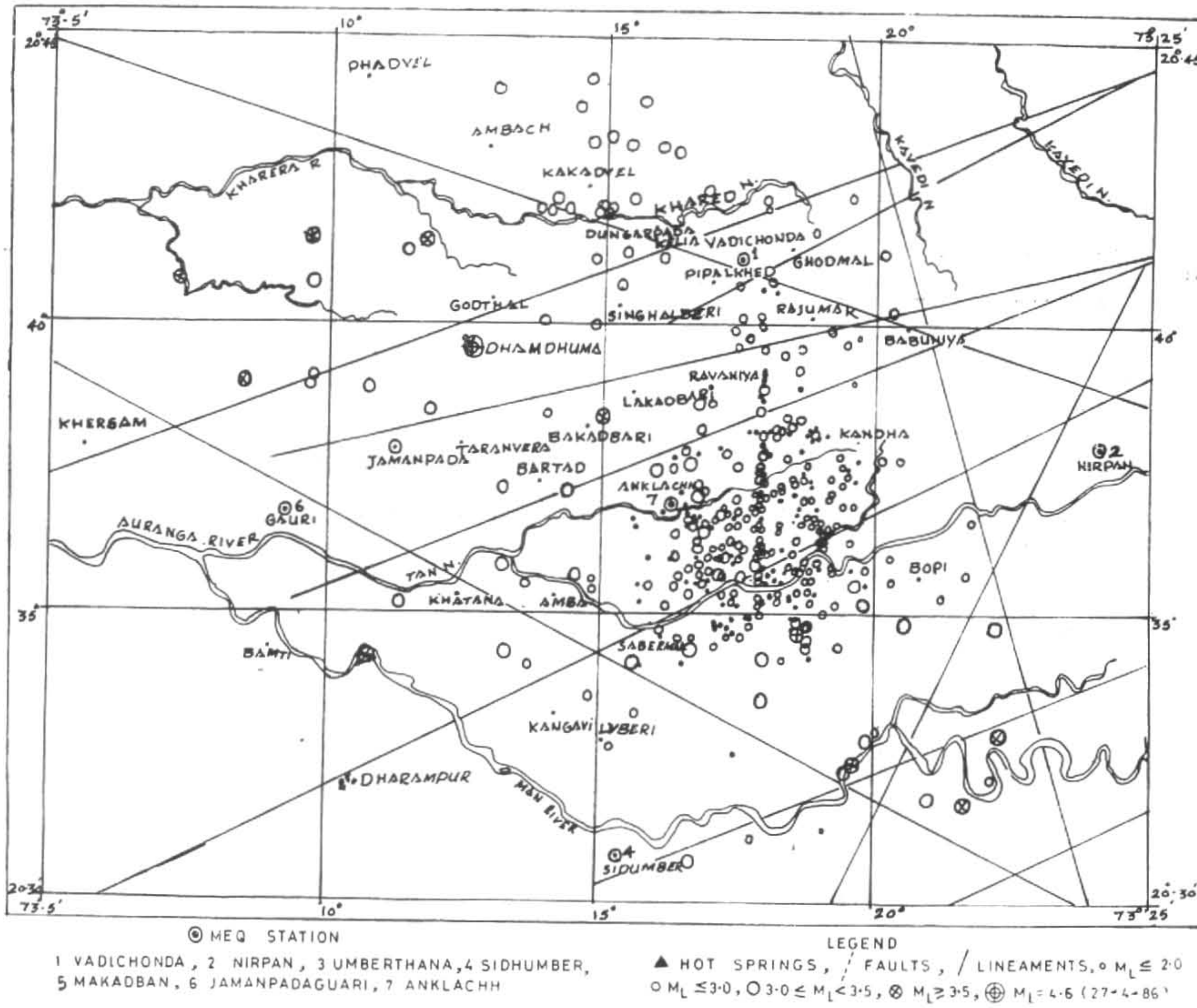


Fig. 2. Epicentres of Swarms near Valsad (Gujarat) occurred during June 1986 to December 1986

as radon gas, geochemical and geomagnetic effects and to attempt prediction of the bigger event, if possible, (c) Geodetic studies for identifying the ground uplift/subsidence if any due to earthquake activity and (d) To determine the *in situ* tectonic stress conditions in the region for assessment of the critical state of the region by carrying out hydrofracturing studies. This is yet to be taken up.

**4. Seismological studies**

Immediately after the occurrence of the felt earthquake in the region, a network of 6 to 7 portable high gain microearthquake recording (MEQ) stations were planned around the area. The design of this network was based on the analysis of the data recorded by the permanent seismological observatories operating around Kadana project (Chattarpur, Arthuna, Bakor and Sanjeli), Ukai project, Sardar Sarovar project (Kevadia) and Bhuj and other regional observatories of IMD which located relatively larger events of which the epicentres of 16 and 17 February ($M_L$=3.6) earthquakes were determined by India Met. Dep. (IMD).

The MEQ stations were jointly operated by IMD, New Delhi and Gujarat Engineering Research Institute, Vadodara. The recording started with effect from 22 May 1986. The details of the instrumental set-up and their locations are given in Table 1. Before starting the 7 station network, 3 RV-320B-portacorders were operated at, (a) Ukai (24 Feb 86), (b) Damanganga and (c) Kelia from end of February 1986. The Ukai project seismological observatory is equipped with 3 sets of short period seismographs-one vertical component Benioff seismograph and a single component Wood Anderson seismograph. The local magnitudes are determined from the W. A. seismographs. All the shocks of $M_L$=2.0 are well recorded at Ukai. The magnitude of the shocks thus determined from Ukai observatory are found to be within $\pm 0.2$ from the magnitudes reported by IMD. The Ukai instruments and the portable seismographs at Damanganga and Kelia recorded more than 2300 shocks up to the end of December 1988 with their magnitude between —0.6 and 4.6. Number of shocks recorded during 1986, 1987 and 1988 are shown in Fig. 1(a). For 1986 same data has been shown in Fig. 1 (b) in conjunction with rainfall, reservoir water

TABLE 2

**Crustal velocity models used for Valsad region**

| Layer | I | | II | | III | | IV | | V | | VI | | VII | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Vel. (km/sec) | Depth (km) | Vel. (km/sec) | Dep. (km) | Vel. (km/sec) | Dep. (km) | Vel. (km/sec) | Dep (km) | Vel. (km/sec) | Dep. (km) | Vel. (km/sec) | Dep. (km) | Vel. (km/sec) | Dep. (km) |
| I | 4.80 | 0.0 | 4.50 | 0.0 | 4.0 | 0.0 | 4.80 | 0.0 | 4.80 | 0.0 | 4.80 | 0.0 | 4.85 | 0.0 |
| II | 5.82 | 1.2 | 5.82 | 1.5 | 5.82 | 2.0 | 5.82 | 2.0 | 5.80 | 1.5 | 5.80 | 2.0 | 5.85 | 2.0 |
| III | 6.61 | 17.5 | 6.61 | 17.5 | 6.61 | 17.5 | 6.61 | 17.5 | 6.61 | 18.5 | 6.61 | 18.00 | 6.61 | 18.5 |
| IV | 8.23 | 26.3 | 8.23 | 36.3 | 8.23 | 36.3 | 8.23 | 36.3 | 8.23 | 38.0 | 8.23 | 38.0 | 8.23 | 37.0 |
| RMS | 0.281 | | 0.309 | | 0.313 | | 0.301 | | 0.281 | | 0.299 | | 0.310 | |
| ERZ | 10.94 | | 10.31 | | 7.13 | | 14.15 | | 8.64 | | 12.12 | | 11.75 | |

level, temperature, chemical parameters and radon concentration.

The epicentres determined by GERI using the data from regional observatories of Gujarat are scattered over a wide zone trending NW-SE. However, better control and accuracy in epicentral determination was possible through the 7 MEQ stations whose locations are shown in Fig. 2. One station was set up in the epicentral region itself at Anklachh for better control over the depth of focus of these events. These stations have recorded every day hundreds of shocks within the period May-December 1986.

The magnitude of the bigger shock, *i. e.,* $M_L \geqslant 3.0$ were determined directly from Wood Anderson records and the magnitude of shocks $M_L$ less than 3.0 were determined from the coda length (signal duration) using the relationship (Gupta and Rastogi 1967) for Koyna region. The signal duration magnitude $M_D$ is given by

$$M_D = -2.44 + 2.61 \log T$$

where, $T$ is the signal duration in seconds.

The events which are well recorded with clear onset of *P* and *S* waves, and recorded at least by 3 or more stations, with $M_L = 1.0$ were analysed and located using Hypo-71 computer program (Lee and Lahr 1975) using the various velocity models developed for Koyna region from DSS data (Srivastava *et al.* 1984). The velocity model II with $V_P/V_S$ ratio 1.65 as shown in Table 2 was found to give less errors in the epicentre as well as focal depths (Rao *et al.* 1986). The epicentres of the events recorded from June 1986 to December 1986 are presented in Fig. 2. It may be noticed that the seismic activity is concentrated in a zone between the rivers *Tan* and *Nirpan* lying between Long. 73° 15′ to 73° 30′ E and Lat 20°30′ to 20° 45′ N approximately. The activity is more concentrated in a narrow strip of about 10 km along N-S direction.

In order to have idea about the behaviour of the activity, association with any of the existing lineaments, the length of the faulting involved and migration of seismic activity, the epicentres and foci of the events are plotted depthwise for each month. Such plotting for September 1986 and September 1987 are shown in Figs. 3 (a) and 3 (b) respectively. These figures show that (*i*) the seismic activity during the period of study has been concentrated in the area of about 7×10 km² (*ii*) the focal depths of shocks vary between 1&15 km, (*iii*) the migration of the activity occurs mostly along N-S direction, (*iv*) the N-S trending faults indicate dip towards E, (*v*) the concentration of seismic activity during September 1986 between 5 and 12 km focal depths along and E-W cross-section (latitudinal) has been found to break into two groups, one migrating to a shallow layer from 1 to 8 km eastwards and the other between 6 and 10 km westward and (*vi*) the comparison of the seismicity between September 1986 and September 1987 clearly reveals the migratory nature of the activity.

**5. Iso-seismal studies**

The earthquake activity which started during first week of February 1986 was felt in several villages like Kelia, Ghodmal, Pipalkhed, Vadichonda, Vansda and Dharampur. In the month of February itself more than 100 shocks with rumbling noise were felt. There was no damage to the houses in those areas. However, cases with the rattling of windows, and falling of utensils and other

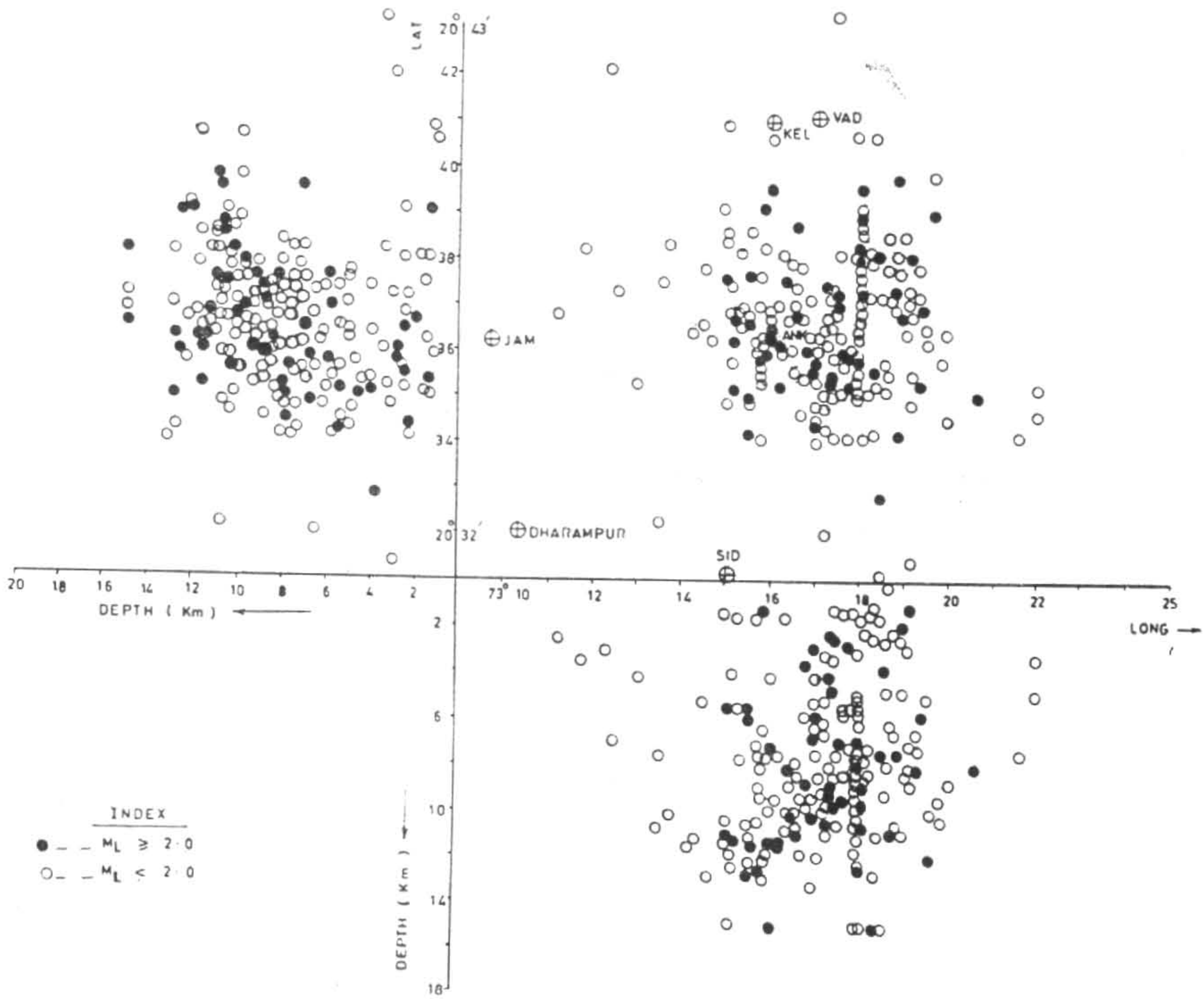


Fig. 3 (a). Projection of foci depthwise on various planes for September 1986

object were reported. The intensity on the MM scale was around IV in the epicentral area.

The shocks continued to be felt till March 1986 also with the burst of activity every 10-15 days. The number of felt shocks along with the microearthquakes started increasing in the month of April 1986. The main shock of magnitude $M_L=4.6$ occurred on 27 April 1986 during the early hours, which was felt over an area up to 100 km radius. This was followed by numerous aftershocks and caused considerable damage to the buildings at Anklachh, Ghodmal, Pipalkhed, Rumia. About 70% of the newly constructed government buildings developed horizontal and vertical cracks with traces of ground settlement near Anklachh. However, typically the houses of the interior tribal village have not suffered any damage due to their light roof with bamboos etc.

The villagers round the effected area were interviewed and based on their experience the intensity was assigned in the MM scale. It was observed that the maximum intensity was around Anklachh, Satimal, Kelia, Ghodmal Pipalkhed villages. It was noted that the iso-seismals were elongated roughly along NNE-SSW direction. (Rao *et al.* 1986). The iso-seismals on the eastern part envelop larger areas compared to western part, indicating dipping of the fault towards the eastern side. This is in agreement with results obtained from the depth cross-sections from the epicentral data.

## 6. *b*-value

Gutenberg and Richter's frequency-magnitude relationship for earthquake is given by

$$\log N = a - bM$$

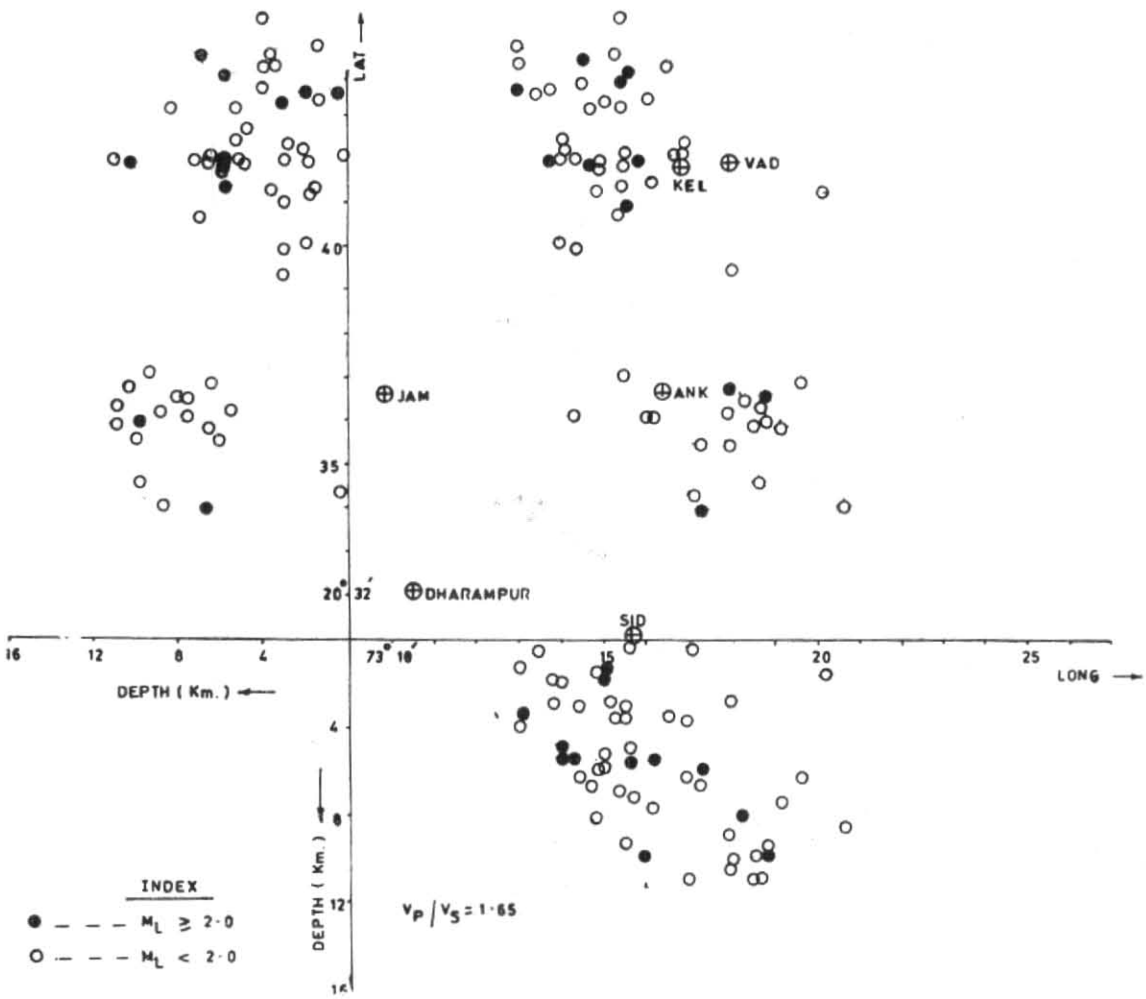


Fig. 3(b). Projection of foci depthwise on various planes for September 1987

where, $a$ and $b$ are constants, $M$ is the magnitude of shocks, $N$ is the number of shocks of $M \pm \triangle M$. It was found that the constants $a$ and $b$ vary significantly from region to region and with the mechanical properties and stress conditions. The parameter $a$ has been found to be varying significantly but $b$ does not vary much. Mogi (1963) studied the variation of $b$ while working on brittle fracture of rock samples in the laboratory and found that it increases with heterogeneity of the medium. Scholz (1968) found that $b$ depends upon the percentage of existing stress to the final breaking stress within the faults.

In the recent earthquake sequence in south Gujarat which started in February 1986, the main shock of 27 April 1986 had many foreshocks and aftershocks. The data from the earthquakes in south Gujarat from April 1986 to December 1986 gave the $b$ value ranging between 0.78 and 1.03. (Fig. 4). This value is higher as compared to the Koyna earthquake of 1967. The $b$ value for foreshocks was found to be 0.88 while it was 0.75 for aftershocks of the main earthquake of April 1986.

The constant $b$ in the frequency magnitude relation given by $\log N = a - bM$ can also be studied by adopting the least squares method and Utsu's empirical formula. The standard statistical method gave the lowest of $b$ as 0.38 to 0.78. This is because every data point in the set is considered and each point has equal weightage. Hence, it can be expected to give minimum possible $b$ value. The Utsu's method which is empirical depends upon the lowest magnitude of the shocks. This method gave $b$ values between 0.55 and 1.45.

**7. Decay trend of activity**

Utsu (1969) found that the time distribution of aftershock activity is given by inverse power $n(t) = C - h \log t$ where, $C$ and $h$ are constants, $n(t)$ is frequency of shocks per unit time. The value $h$ is a decay constant which can be used to infer the physical and stress state of the aftershock zone. Various sequences both reservoir associated and normal sequences had different rates of decay. The values of $h$ are relatively slower for reservoir associated shocks which decayed at a slower rate (Gupta and Rastogi 1967). The aftershock activity for mainshock

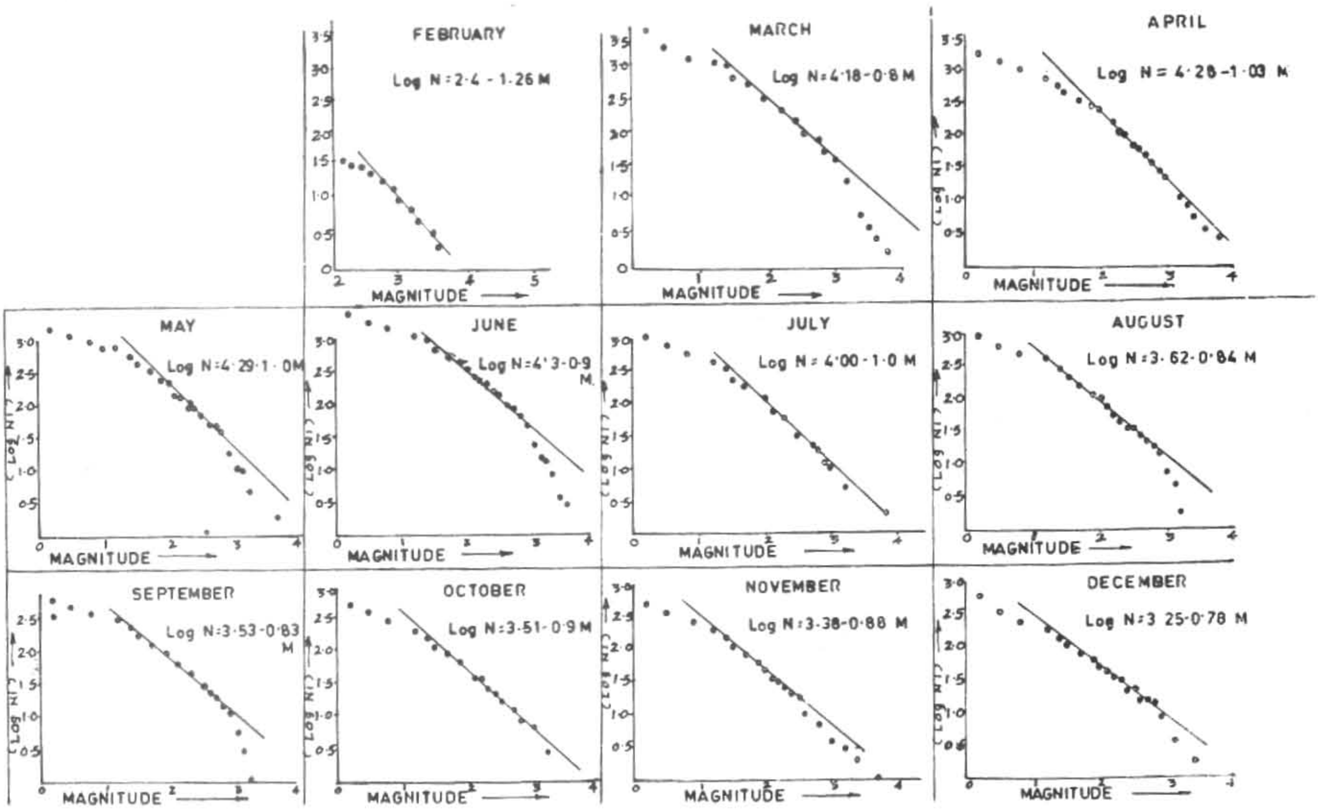


Fig. 4. Frequency magnitude plots of tremors (1986)

of 27 April 1986 in south Gujarat was found to follow the above. The unit of time was taken as one day and the relationship was as follows

$$n(t) = 354.81\ t^{-h}$$

The decay rate $h$ is found to be 0.53 which is much less. As compared to other tectonic sequences this was also slower than the other reservoir associated sequence like Kariba (1.0), Karemesta (0.78), Koyna (0.7) and Kurobe (0.67)

## 8. Tectonic significance of the seismic activity

Mogi (1963) based upon the experimental studies classified the natural earthquake sequence into 3 categories. It can be seen from the pattern of the seismicity in south Gujarat that with the exception of the event of 27 April 1986 ($M_L$=4.6) the entire sequence fits to type III of Mogi's model which is characteristic of highly heterogeneous regions and highly concentrated applied stresses. Due to this, the block between each heterogeneity cannot hold much strain and the energy is released in the form of many low magnitude shocks periodically which is attributed to redistribution of stresses in the adjacent blocks. The activation of the adjoining blocks depends upon the direction of the weak fractures and of the orientation of the applied stresses.

## 9. Radon gas studies

The formation and propagation of cracks and fissures in the dilatancy zone increases the surface area of the zone and consequent increase of flow of groundwater into these newly created cracks dissolve various substances and gases in the water. The Radon-222 is an inert radioactive gas (which is abundantly soluble in groundwater) has been used in many cases for identification of cracks and fissures in the rocks. In the earthquake studies, the episodic changes in the radon content of soil gas and ground water prior to earthquakes are explained by the dilatancy model.

The radon gas studies were initiated in the south Gujarat region to study the correlation between the earthquakes and radon variations. The studies were undertaken jointly by NGRI and GERI. For this purpose a few monitoring sites were located in the affected area near seismological stations shown in Fig. 2. At these sites both soil gas and groundwater samples were collected every fortnight and analysed by NGRI and GERI. Five radon gas stations at Jamanpada, Sidumber, Makadban, Vadichonda and Anklachh were set up for soil gas observations and ten wells in the area were set up to monitor radon gas in ground water. Track etch method in which cellulose nitrate film sensitive to radiations was put in shallow holes and exposed for one week. This film was chemically etched and the tracks were counted under a projection microscope. Groundwater samples were degassed using degassing instrument (RDU-200) and then counted in a Radon detector (RDA-200) to get the radon counts per minute at NGRI, Hyderabad.

The radon concentration in soil gas and water was monitored from July 1986 to February 1987. The results of NGRI have shown a precursory period of one week prior to earthquake swarms of 31 July, 27 August, 20 September 1986 (NGRI report 1987). The results of radon gas in water samples from shallow wells and land soil were studied at GERI. The results are shown in Fig. 1 (b). A good correlation was observed between radon variation in this area and the earthquake activity.

**10. Geomagnetic/geoelectric studies**

The geomagnetic field variations before and during major earthquake sequences have been reported in many cases. The geomagnetic studies were taken up in the earthquake affected area jointly by the IIG and GERI, to determine the major conductive zones such as faults, fractures and fissures. An array of 12 fluxgate magnetometers was operated simultaneously at 12 sites including those of MEQ stations in the affected area and also a few sites outside the seismic zone. These observations were continued for 30 days to evaluate the pattern of the induced currents utilising the natural magnetic disturbances. Some anomalous pattern of the currents was observed during the period of study.

This study suggested three distinct conductive zones in the area. The first one is north of survey area and probably associated with Tapi-Narmada rift. The second one is aligned with continental margin of west coast related to the west coast fault. The third and the important one is a chain of conductive zones aligned roughly along NNE-SSW which may either represent elongated dykes or fractures saturated with saline water. These zones may be deep fractures through which dykes might have intruded. The presence of hot springs in the area suggests the high conductivity of these fractures as observed in the geomagnetic studies. Further studies for the determination of size, shape, and the orientation of these features are under progress.

**11. Geochemical studies**

The water samples from shallow wells in the seismic region were collected periodically for 20-25 days every month before the burst of earthquake activity and sent for chemical analysis to Bhabha Atomic Research Centre (BARC) Bombay, so as to ascertain the probable change in the quality of ground water. The analysis indicated variations in chloride, sulphate, sodium, magnesium and calcium contents. The results of the study are shown in Fig. 1(b). Some variations are observed during the sequence of September 1986. However, the duration of the study and frequency of water sample collection is insufficient to ascertain the correlation with earthquake sequences.

**12. Geodetic studies**

With a view to study the possible land deformation taking place, if any, during the recent earthquake activity in the area around Kelia reservoir, geodetic studies were planned and about 50 bench marks have been established by the Survey of India during September–December 1987. The bench marks were selected taking into consideration, (a) The epicentral zone of $7\times10$ km$^2$ around villlage Anklachh and (b) The lineaments mapped from satellite data in form of thematic maps. The lineaments are generally trending along N-S and NW-SE directions. The subsequent ground truthing has indicated mostly the presence of the dykes along these lineaments. These bench marks are planned to be reoccupied once in every 2 years.

**13. Discussion**

The seismic activity of the south Gujarat which started in the first week of February 1986 and continued throughout the year with the main shock on 27 April 1986, had some similarities with the seismic activities in other parts of the Peninsular India. Many earthquakes of magnitude ($M_L$=4.0 to 5.0) have been reported in these shield regions. The characteristic feature of the activity concentrated along the west coast is the occurrence of numerous foreshocks as well as aftershocks except for the Broach earthquake sequence of 1970 which had a few aftershocks only. Many hot springs aligned roughly along N-S trend following the west coast clearly indicate the existence of a deep seated active fault. Many fractures with N-S, NW-SE trends have been found to be existing in the trap terrain with N-S trend prominent in the northern part of Bhatsa and south Gujarat area. Many dykes having the above trends seems to be the intrusions through the fractures. The existence of 33 hot springs along these fractures confirm these trends.

In all the three cases namely Koyna, Bhatsa and Valsad in this western shield area in the traps, long periods of microearthquake activity with concentration of activity in a very limited area have been observed. The epicentral plot of the area has indicated the concentration of the activity in an area of $7\times10$ km$^2$ with the extension of the region roughly along N-S with many epicentral aligning along 73° 17.95′N longitude and some of them oriented along NW-SE and NE-SW with the entire zone activity confining to Longitudes 73° 15′-73° 20′E and Latitudes 20° 30′-20° 45′ N during May-December 1986. The depth of the activity is mainly concentrated down to 15 km with clustering of the activity between 1 and 5 km and 8 and 12 km. The activity is confined to the upper granitic layer of the crust. The time distribution of depth cross-sections through September 1986 to December 1986 have clearly indicated the migration of the activity roughly along N-S to NNE-SSW trend with depth of activity progressively increasing towards south. The field investigations have indicated that the activity around February 1986 concentrated to the regions around Kelia and Pipalkhed (near Kelia) and surrounding area of 27 April 1986 main-shock. The activity started migrating towards south. The earthquake sequence has been studied for its association with various tectonic features of the area. The *b*-value of the activity during April to December was found to be varying between 0.78 and 1.03 with high *b*-value during April 1986. This *b*-value is found to be high compared to other natural tectonic sequences of the Peninsular India like Broach sequence (0.4), Bhatsa (0.6) but is generally comparable to that of Koyna (0.8) earthquake. The *b*-value for aftershock was slighly higher than the foreshock value as in other sequences. The decay of the aftershock activity was found to be 0.53 which is very low compared to other tectonic sequence.

The composite iso-seismal map prepared has shown the elongated elliptical pattern trending roughly NNE-SSW and the enveloping of larger area between the iso-seismals on the eastern side suggests the source to be trending along NNE-SSW and dipping towards east. The geomagnetic studies in the epicentral zone have indicated the presence of electrically conductive zones in the area-one on the northern part corresponding to

Narmada-Tapi-Son lineament, the second in the western part of the area along west coast faults and the third and most important is the conductive zone trending NE-SE mainly due to the major lineaments in the area. However, the NNE-SSW/NS trend observed in the seismological studies have not been reflected in the geomagnetic study. This may be due to the fact that these fractures are believed to be due to recent activity and may not be of sufficient dimension to generate any detectable anomaly in the magnetic map. Secondly, it may be due to the compatively dry fractures with insufficient conducting pore fluids or minerals to make these fractures visible in magnetic map.

The radon gas and geochemical studies have shown anomalous changes in the concentration in the samples and well collected from the epicentral area. The change is some what pronounced in the zone trending north-south with time gap of a few days. The temperature of Unai has indicated a rise of 3° to 4°C from its normal temperature (54°C) after a few earthquake sequences. However, further studies are needed.

**14. Conclusions**

(*i*) The swarm type of seismic activity which started during February 1986 and continued for more than 2 years with the main shock of 4.6 on 27 April 1986 appeared to be a typical case with similar characteristics as observed for other earthquakes in the west coast region.

(*ii*) The seismic activity is found to be concentrated in an area of $7\times10$ km$^2$ south of the Kelia dam within a 15 km distance, with the depth of activity mainly concentrated from 1 to 15 km with much of the activity within 8-12 km. The epicentres are mainly clustered along all the 3 sets of lineaments along NNE-SW with much of the activity along N-S to NNE-SSW trends.

(*iii*) The basaltic dyke which have been found in the area during the field check of the lineament and faults inferred from the thematic map data and serial photos (GSI) indicated the association of these dykes with the existing deep seated fractures. These conform to the NNE-SSW and NW-SE and NE-SW trends, which have been confirmed by geomagnetic studies and indicate highly conductive features in the area. The rise in the temperature of Unai hot spring in the present activity and during Broach earthquake also shows possible relationship with the active status of the west coast fault.

(*iv*) Radon gas and geochemical studies have indicated the possibility of creation of many interconnected cracks and fractures in the epicentral source region. More observations are needed to correlate earthquake occurrence with the changes in the radon gas.

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