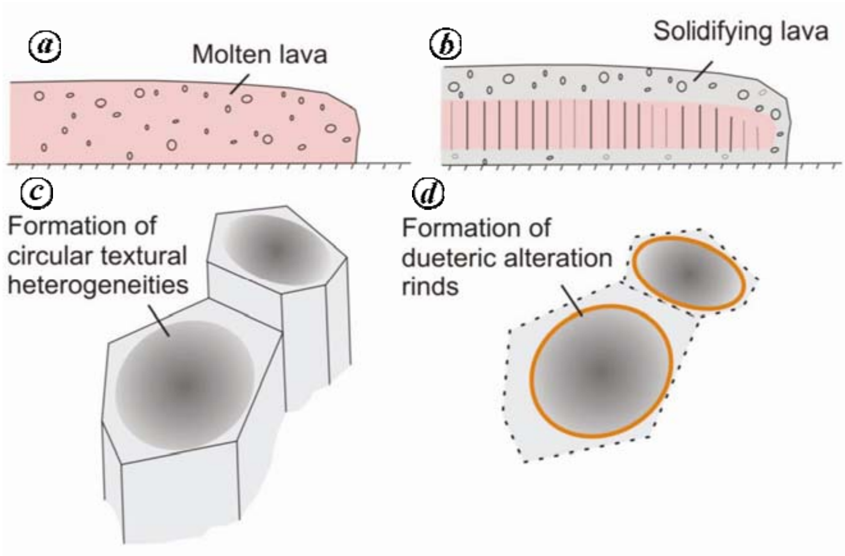

Figure 4. Cartoon depicting the stages in the emplacement of the Chincholi flow and the subsequent development of the enigmatic glassy rinds. ***a***, Eruption of lava and subsequent spread as lava flow. Note that almost all the lava is liquid and hence the vesicles are trapped within the liquid lava. ***b***, Solidification of lava flow into distinct vesicular crust, massive core and basal vesicular zone. Note that the flow solidified around the periphery, but is still molten within the core. ***c***, Compositional supercooling of lava flow with minor thermal contraction is responsible for the formation of prismatic columnar joints. Note that the liquid to solid or glass may have taken place during this phase. ***d***, Deuteric alteration occurs contemporaneous with prism formation in the presence of moisture/volatiles expelled from the solidifying liquid lava.

porting the non-homogeneous column hypothesis.

The deuterically altered basaltic columnar structures near Chincholi are a common feature in the simple flows in the Deccan Trap, as these structures are also seen at several localities in the Ahmednagar, Sholapur and Osmanabad districts. Similar structures have also been reported from basalts in Oregon, USA[9], Skaftafell Park, Iceland; Giant Causeway, Ireland; Saint Arcons d'Allier, Haute-Loire, France[10], etc. In columns or basalt prisms, circular or semicircular structures are ubiquitous features. Heterogeneities in columnar basalts are revealed by bubble circles or radiating structures within circular structures related to textural differences in size, shape, alignment of crystals, abundance of glass, etc. rather than compositional differences[10] that are attributed to melt migration driven by crystallization-induced pressure gradients[11].

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P. K. SARKAR[1,*]
RAYMOND DURAISWAMI[2]
R. N. MACHE[1]
DIYA CHOWDHARY[3]

[1]*Department of Geology,*
Fergusson College,
Pune 411 004, India
[2]*Department of Geology,*
University of Pune,
Pune 411 007, India
[3]*U-15/53, Pink Town Houses,*
DLF, Phase III,
Gurgaon 122 002, India
**For correspondence.*
e-mail: pksarkar123@yahoo.com

Causative fault of swarm activity in Nanded city, Maharashtra

Nanded city in Maharashtra is a part of the Godavari river basin and is located about 3 km north of the Godavari river. The Godavari river basin is bounded by the Manjira Tectonic Zone to the south and the Pranahita Godavari Graben to the north, both structures trending along the NW–SE direction. Further, the NW–SE trending Kadam fault lies to the north at a distance of 90 km and Latur lineament about 100 km south (Figure 1). The lineaments located within the study area are mostly oriented in the NW–SE, NE–SW, ENE–WSW and NNE–SSW directions[1]. A NW–SE trending minor lineament having a strike length of about 6 km passes between the Wadi and Jangamwadi areas, aligned along a rivulet, which meets the Godavari river at a distance of 2 km east of Hassapur. Basaltic flows belonging to the Ajanta Formation of Sahyadri group of upper Cretaceous to lower Palaeocene age are exposed in the area under study (Nanded). The upper portions of the traps are highly weathered as seen along a section of a dry tank whose depth is about 4 m. The traps are overlain by black cotton soil whose thickness varies from 1 to 5 m in different parts of the study area[2].

On 12 November 2007, a tremor of magnitude *M* 2.9 with its epicentral location at 19.173°N, 77.309°E and origin time at 14 : 48 GMT (source IMD) was widely felt by people in Nanded city. After this earthquake, NGRI personnel visited the epicentral area of the micro-tremor in Nanded immediately and installed four digital seismographs, three of which are equipped with state-of-the-art high-resolution 24-bit, three-channel broadband equipment, while one seismograph unit had a short-period sensor. The earthquake data were recorded at 100 samples/s with GPS time tagging. The seismic stations are located at sites having low cultural noise in locales of earthquake-felt regions. The locations of three seismic stations together with the already existing broadband station at Swamy Ramananda Teerth Marathwada University (SRTMU) Nanded are shown in Figure 2 (the fourth station installed at Ardhapur is not covered in the figure) and the coordinates of these stations are given in Table 1.

The earthquake waveform data originally recorded in mini seed format were converted to Seisan format for analysis. The Seisan software[3] (version 8.1.3) was used to pick arrival times of different phases and the earthquakes were located using the Hypo71 software. This exercise resulted in locating a total of 122 micro-tremors using the micro earthquake network of stations. Figure 3 shows that the swarm activity in Nanded area occurs in a 10 sq. km area with the activity beginning at 1.5 km depth and extending up to a depth of 4 km. Most of the tremors are confined to the depth range 2–3 km with depth errors less than 400 m.

Earlier to this activity in the proximity of Nanded town at a distance of about 150 km, a devastating earthquake of magnitude 6.3 struck the Killari region on 30 September 1993. This earthquake occurred along a hidden fault under the Deccan Trap cover with its epicentre at 18.07°N, 76.45°E. The occurrence of this earthquake prompted several geophysical studies, which included aftershock monitoring[1], damage assessment[4], magnetotelluric[5,6] and helium measurements[6,7] and drilling of a 600 m deep bore hole[7,8]. These studies enabled better constraints

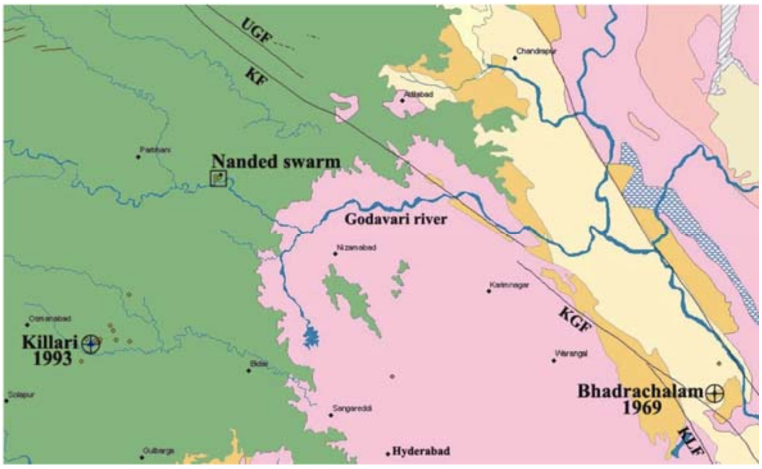

Figure 1. Tectonic map of Godavari basin and southwestern part of the Deccan Volcanic Province (adapted from Geological Survey of India). KF, Kadam Fault; UGF, Upper Godavari Fault; KGF, Kinnerasani Godavari Fault; KLF, Kolleru Lake Fault. Locations of Bhadrachalam earthquake (1969), Killari earthquake (1993) and Nanded swarm (2007) are shown.

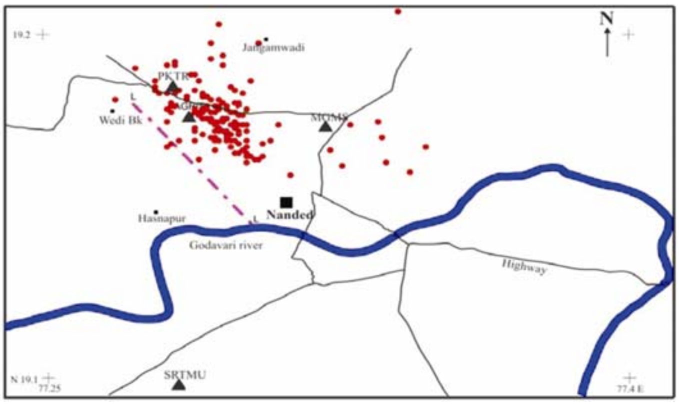

Figure 2. Pink dashed line is the lineament inferred by Geological Survey of India, filled red circles are the epicentres located by NGRI and filled black triangles are seismograph locations.

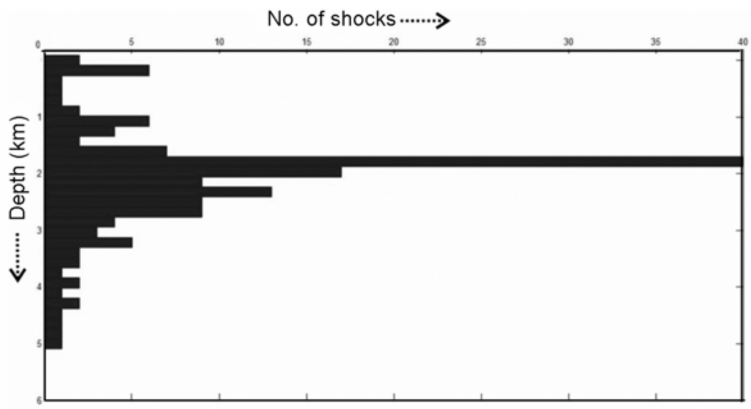

Figure 3. Histogram depicting the number of earthquakes with depth.

Table 1. Location of seismological stations with respective station coordinates

Station	Station code	Latitude (N)	Longitude (E)
Panchayat Office, Ardhapur	ARTH	19°17.09′	77°22.32′
Mahatma Gandhi Memorial Engineering College, Nanded	MGMS	19°10.76′	77°19.43′
Parna Kutir, Purna Road, Nanded	PKTR	19°11.50′	77°17.14′
SRTMU, Nanded	SRTMU	19°05.85′	77°17.22′
Agricultural School, Nanded	AGRIS	19°10.93′	77°17.38′

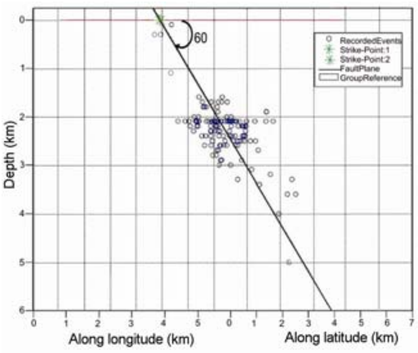

Figure 4. The best-fit fault plane of the hypocentres.

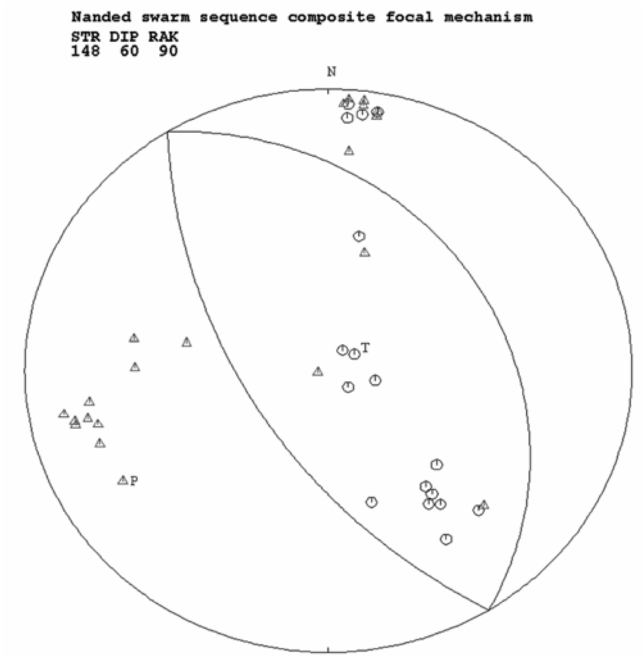

Figure 5. Composite focal mechanism of the Nanded swarm sequence.

on the source zone and inferring the approximate rupture size of the earthquake. Based on the epicentres of well-located aftershocks using digital data for the 1993 Killari earthquake for the first time in India[9], the orientation and dimensions of the causative hidden fault were established[10].

In order to characterize the nature of the fault zone responsible for the occurrence of the swarm activity, spatial distribution of well-located events during 2007–2009 was examined in conjunction with the lineament (marked *L–L* in Figure 2) identified by the Geological Survey of India from satellite imageries. The strike of the best-fit fault plane obtained by least squares technique coincides with two end-points of the lineament, whereas the dip of the plane explains the orientation of hypocentres in depth.

The plane that best describes the 112 well-located hypocentres (with an rms error of 0.36 km) has a dip angle of 60° (Figure 4). The dip of the causative (*L–L* Figure 2) fault agrees well with the dip angle of the composite focal mechanism determined using the sequence of the Nanded swarm. The causative fault parameters inferred from this study can be used for deterministic hazard assessment, which provides valuable inputs for planning developmental activities or design of prominent structures of economic importance, since, most of the city is located over the fault plane deduced from seismicity patterns.

Determination of fault plane solution from observations of seismic waves is important as it characterizes the source or nature of faulting. Usually fault plane solutions are determined for individual earthquakes. In case of a sparse local seismic network, *P*-wave first motion data may not be enough to determine reliable solutions. In such a case, data from a number of earthquakes, which occurred closely in space and time, are combined for obtaining the composite focal mechanism. This procedure assumes that the focal mechanisms for earthquakes are identical. As the number of stations (5) operated to monitor earthquake swam activity is less, the composite focal mechanism is considered the most appropriate in the present case. Clear *P*-wave first motion polarities, their respective angles of incidence and azimuths form the input in the determination of the focal mechanism. The composite focal mechanism represents thrust faulting (Figure 5); strike angle of the NW–SE nodal plane is 148° and dip 60°. The marked regional lineament (*L–L* in Figure 2) is aligned along the same direction of the constrained nodal plane.

It has been recognized for a long time that earthquake damage is generally larger over soft sediments due to the amplification of ground motion than on rigid outcrops. This is particularly important because most of the urban settlements have occurred along river valleys, which are comprised of soft sediments. The amplification depends on several factors, including layer thickness, degree of compaction and age. These factors also influence the shear-wave velocity, density and damping characteristics of the soil. The technique of ambient noise measurement and analysis has been successful for site characterization of various regions

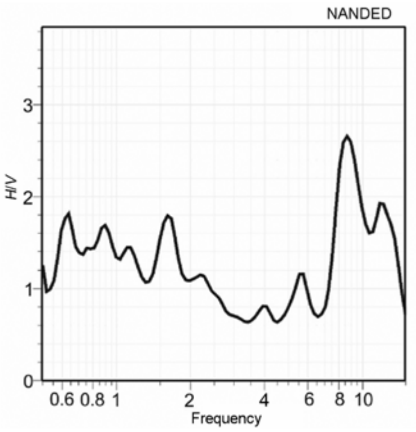

Figure 6. Site-response at the Nanded seismological station.

around the world. In this study, we investigate site response associated with the Nanded seismological station located within the city using the ratio of the horizontal-to-vertical (*H*/*V*) component of the Fourier spectrum of ground motions.

Lermo and Chavez-Garcia[2] found that it is possible to estimate the dominant period of the site response and the overall amplification factor based on the *H*/*V* ratio, for varied geology. They observed that the method gives a good estimate of frequency and amplitude for the first resonant mode of the site, though the higher modes do not appear.

The ambient noise data recorded at Nanded seismological station are used for estimating the dominant frequencies and amplifications. The predominant frequencies with clear amplification levels more than two units are observed at 8–10 Hz at Nanded site. Hence for any input signal in the 8–10 Hz frequency range, the site at Nanded can amplify it 2–3 times. Other frequencies seen with low levels of amplification in Figure 6 indicate response from multiple layers present beneath the seismic station.

The 112 well-located hypocentres are aligned along the NW–SE direction and can be correlated with the lineament *L*–*L* shown in Figure 2. The seismogenic plane is about 2.5 km in length and the depth extends up to 4 km. However, the maximum earthquakes are confined to 2–3 km range. The fault parameters obtained indicate that the strike of the fault (148°) and the dip (60°) correlates well with the strike of the marked lineament (*L*–*L*) and dip obtained through least square fit. Site response study indicates that for any input seismic signal in the 8–10 Hz frequency range, the site at Nanded can amplify the signal by 2–3 times. Further, as the micro earthquakes have been occurring at regular intervals till date in Nanded, this area needs to be closely studied. The seismic microzonation studies are being carried out in this area.

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D. SRINAGESH[1]
T. V. N. SRINIVAS[1]
P. SOLOMON RAJU[1]
G. SURESH[1]
Y. V. V. B. S. N. MURTHY[1]
SATISH SAHA[1]
A. N. S. SARMA[1]
T. VIJAY KUMAR[2]

[1]*National Geophysical Research Institute,*
Hyderabad 500 007, India
[2]*SRTM University,*
Nanded 431 606, India
**For correspondence.*
e-mail: srinagesh@ngri.res.in