The Gujarat (India) Seismic Network

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INTRODUCTION

The 26 January 2001 (*Mw* 7.7) Bhuj earthquake, in the Kachchh region of Gujarat, India, caused 13,819 deaths, U.S. $10 billion in economic losses and damaged more than 1 million houses (Gupta, Purnachandra Rao, *et al.* 2001, Gupta, Harinarayana, *et al.* 2001; Rastogi *et al.* 2001). The city of Bhuj and neighboring villages were most affected. The damage can be seen as far as Ahmedabad, 240 km from the epicenter, where 69 reinforced buildings collapsed (Department of Earthquake Engineering, University of Roorkee 2001). Gujarat and the adjoining region falls under all four seismic zones—V, IV, III, and II—of the seismic zoning map of India (Bureau of Indian Standards 2002), with likely earthquakes of magnitude 8, 7, 6, and 5, respectively. It is one of the most seismic-prone intracontinental regions in the world. It has experienced two large earthquakes of magnitude M_w 7.8 (Johnston and Kanter 1990) and 7.7, in 1819 and 2001, respectively, and seven earthquakes of magnitude **M** ≥ 6.0 (Figure 1) during the past two centuries (Quittmeyer and Jacob 1979; Rastogi 2001, 2004). The intense aftershock activity of the 2001 Bhuj earthquake is still continuing. Through March 2008, 14 aftershocks with **M** 5.0–5.8, about 200 aftershocks with **M** 4.0–4.9, about 1,600 aftershocks with **M** 3.0–3.9, and several thousand aftershocks with **M** < 3 have been recorded (Mandal and Johnston 2006; Mandal 2007). Regional seismicity has also increased with **M** ≤ 5 earthquakes and associated foreshock-aftershock sequences. At the time of the earthquake, the Kachchh region had only one seismic observatory at Bhuj operated by the India Meteorological Department (IMD), the primary agency in the country for routinely monitoring earthquakes through its national seismological network. In the past, a few analog seismic recorders and strong-motion accelerographs have been operated by irrigation projects in the northeastern, central, and southern parts of the state of Gujarat. A three-station network was operated around Kadana in the northeastern part of Gujarat, and one station each was operated at Vadodara, Kevadia, and Ukai in the central and southern part of Gujarat.

After the 2001 Bhuj earthquake, a network of stations (19 strong-motion accelerographs, 11 broadband seismographs, and one short-period seismograph) has been operated by the National Geophysical Research Institute (NGRI), Hyderabad, confined to the aftershock zone of the 2001 Bhuj earthquake. Even this network is not enough to enable more detailed studies needed to develop proper mitigation strategies, such as regional hazard assessment, microzonation of critical areas, early warning systems, and synthetic shake maps.

The Gujarat region is at the tri-junction of three failed rifts: Kachchh, Cambay, and Narmada, with several active faults (Biswas 1987, 2005; Talwani and Gangopadhyay 2001). These rifts were formed by rifting along major Precambrian trends. The rifting occurred at successive stages during the northward movement of the Indian plate after the breakup from Gondwanaland in the Late Triassic or Early Jurassic. The rifting developed around the Saurashtra horst. The Kachchh rifting took place in the Late Triassic–Early Jurassic, Cambay rifting in Early Cretaceous, and Narmada rifting in the Late Cretaceous (Biswas 1987). The rifting ceased in the Late Cretaceous era during the pre-collision stage of the Indian plate. The Kachchh rift basin became a shear zone during the post-collision compressive regime of the Indian plate, with strike-slip movements along subparallel rift faults. The Kachchh mainland fault along the rift axis became the active principal fault (Figure 1). The eastern part of this fault, where it overhangs the South Wagad fault, is the most strained region (Biswas 2005). The epicenter of the 2001 Bhuj earthquake and its aftershocks are located in this zone. Presently, this zone is most active. Yet in spite of its being a high seismic hazard zone, the Gujarat region has not been studied adequately from the point of view of seismic hazard and risk.

To rectify this situation, the Department of Science and Technology (DST), Government of Gujarat, India, established the Institute of Seismological Research (ISR) and a network of seismic stations with funding from the Asian Development Bank and World Bank through the Gujarat State Disaster Management Authority. In July 2006, the Gujarat Engineering Research Institute (GERI) and ISR installed a network of 22 broadband seismographs and 43 strong-motion accelerographs throughout the state of Gujarat to monitor earthquake activity. The network was further strengthened in April 2008 with the addition of 23 broadband seismographs and six strong-motion accelerographs. In this article, we describe the Gujarat Seismic

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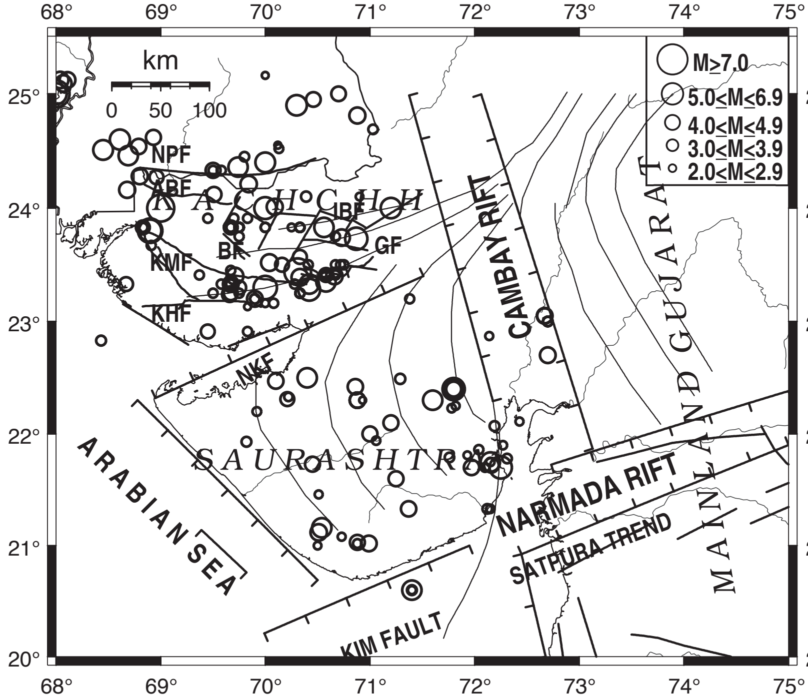


▲ **Figure 1.** Seismotectonic map of Gujarat and adjoining region showing the distribution of epicenters of earthquakes M≥2.0 that occurred in the region during the period 1668 to March 2008 (Oldham, 1883; Tandon and Srivastava, 1974; Chandra, 1977; Quittmeyer and Jacob, 1979; Malik *et al.*, 1999; India Meteorological Department; Geological Survey of India, NEIC, USGS; ISC; Gujarat Engineering Research Institute, Gujarat, India; National Geophysical Research Institute, India; Institute of Seismological Research, India). The epicenters shown are the locations of mainshocks with no associated sequences (*i.e.,* foreshocks and aftershocks). Thick black lines are major faults. Thin black lines shown in Kachchh, Mainland and Saurashtra are major lineaments adapted from Biswas (1987). NPF: Nagar Parkar fault, ABF: Allah Bund fault, IBF: Island Belt fault, GF: Gedi fault, KMF: Kachchh Mainland fault, KHF: Katrol Hill fault, NKF: North Kathiawar fault, SNF: Son Narmada fault, BSF: Barwani Sukta fault.

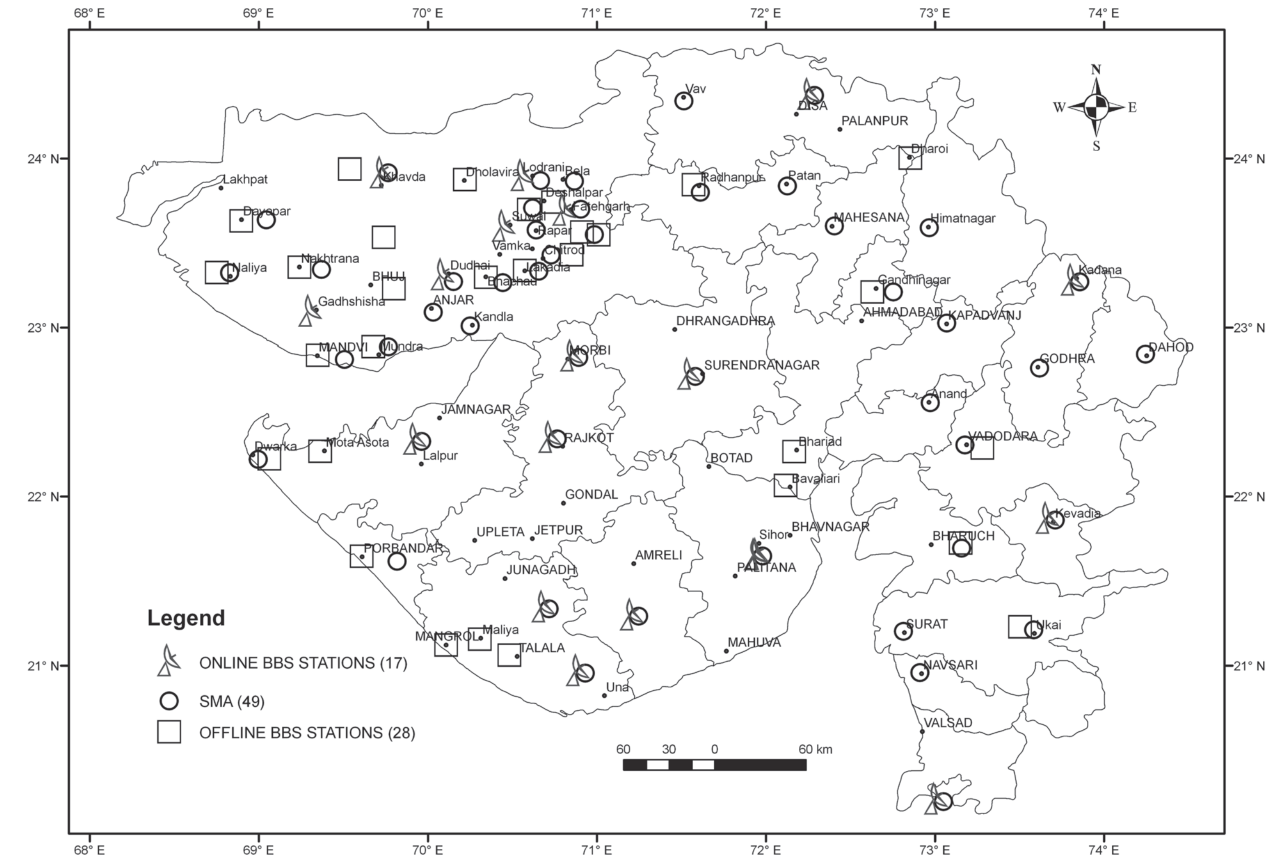
Network (GSNet), its instrumentation, and its detection and location capability during 2006, 2007, and 2008.

THE GUJARAT SEISMIC NETWORK (GSNet)

The GSNet covers an area of approximately 196,000 sq km (500 km × 400 km) involving three distinct geographical zones: Kachchh, Saurashtra, and the Gujarat mainland (tectonic provinces of Kachchh, Cambay, and Narmada rift basins; see Figure 1). The network consists of three main elements, namely, the seismic stations, the data communication channels, and the Seismic Data Analysis Centre. The network has 45 broadband seismographs (Figure 2) and 49 strong-motion accelerographs. Each of 30 sites has both an accelerograph and broadband seismograph installed, which enables these sites to record unclipped waveforms in case of a strong earthquake nearby. Eighteen stations have permanent buildings, where the sensors are installed in double-walled, thermally insulated vaults separate from the recording rooms. Of these, 14 are located on fresh, unweathered rock reached after a few meters of excavation, and four are located on hard soil.

At other sites, instruments are installed in free field (that is, directly on the ground and without any pier) in government buildings away from cultural noise. Because of this, station buildings are not required at these sites. The details of seismic stations, their locations, sensors, digitizers, and local geology are listed in Table 1. These stations are located on a variety of geological formations from Mesozoic to Quaternary age.

The seismic data collected from 17 stations (one site is still under construction) are transmitted through very small aperture terminals (VSAT) at Gandhinagar, Gujarat. The data from seismic stations is transmitted at 50 sps. In addition, the triggered data are also transmitted at 100 sps. The strong-motion accelerographs operate stand-alone instruments. The VSAT uses TDMA (time-domain multiple access) technology on the Ku band. Data are transmitted from remote stations to a master station (HUB) located at Noida, near New Delhi, and then transmitted to Gandhinagar with backhaul connectivity. The Ku band is susceptible to rain fade in the monsoon season, which may happen for a few hours a day over a period of 15 to 30 days. The communication is in duplex mode, allowing data recovery and remote configuration. The allocated bandwidth is 160 kbps from remote sites to HUB and 140 kbps from HUB to Gandhinagar. For data recovery, state of health, and sensor calibration, 20 kbps is allotted. The bandwidth for the link between the stations and the service provider is shared bandwidth of 160 kbps with a maximum of 160 kbps when using one link and 7 kbps when all links are used. Transfer delay is approximately 0.7 seconds. The data of temporary stand-alone stations are collected periodically and incorporated in the database for detail analysis.



▲ **Figure 2.** Map showing the permanent and temporary broadband seismographs and strong motion Accelerographs of Gujarat Seismic Network (GSNet).

Instrumentation

The VSAT-connected seismograph stations have Güralp CMG 3T 120-s triaxial broadband sensors and Güralp CMG-DM24 24-bit digitizers with external GPS (Figure 3A). The VSAT system consists of a DW-6000 IDU (DIRECWAY indoor unit), a Hughes RFT (radio frequency transceiver) and a 1.2-m Ku band dish antenna. Digitizers are provided with a 40-GB storage disk. The link is provided by a private service provider through its hub. The data are recorded and transmitted in two streams, continuous and trigger, from each station. The continuous data is recorded at 50 sps and triggered at 100 sps. Triggering is based on STA/LTA ratio, enabling recording of earthquakes of **M** > 2.5. The triggered data is recorded at 100 sps. The triggered data is displayed alongside continuous data at the central station. All the seismic stations have continuous AC power supply.

Most of the strong-motion accelerographs consist of internal AC-63 GeoSIG triaxial forced balance accelerometers and GSR-18 GeoSIG 18-bit digitizers with external GPS (Figure 3B). Four strong-motion accelerographs are Etna (Kinemetrics) with internal accelerometer (model episensor) and 18-bit digitizer. The recording is in trigger mode at 200 sps with threshold set at 0.002 g. The recording is done on a 32-MB GeoSIG and 1-GB Kinemetrics compact flash card.

Each seismic station is powered by external 12-volt batteries with regular charging through a 230 volts alternating current (VAC) line. The VSAT system has a 30-minute uninterrupted power supply (UPS) backup. A generator set is installed at those sites with permanent buildings to compensate for any data loss due to a power failure.

The offline broadband seismograph stations are equipped with Güralp 120-s triaxial CMG-3T broadband sensors and Reftek 24-bit 130-01 digitizers with external GPS. Data are recorded in continuous mode at 100 sps. The data are saved on a 4-GB flash disk. The system is powered by external batteries with AC charging.

The central recording station at the IRC receives seismic data from all 17 seismic stations (51 channels). There are two HP servers to receive the data streams (Figure 4), one of which is a reserve server. The server retains the past 24 hours of data in a buffer. The data from each station are saved at four-hour intervals. In addition to the two servers, two HP workstations with 42-inch monitors continuously monitor the data streams and display event information.

Noise Level

The seismic stations of the network are located on varied geological formations including sandstone, basalt, shale, limestone, and hard soil of Mesozoic to Quaternary age. All the stations are 5 to 15 km from main cities and 1 to 2 km away from highways, railway lines, and industries. The background noise levels of all the stations are checked by calculating power spectrum

TABLE 1
Details of Seismic Stations, Types of Instrumentation, and Local Geology

Station	Latitude °(N)	Longitude °(E)	Foundation Geology
Morbi #•	22.84	70.89	Basalt
Lalpur #•	22.35	69.96	Basalt
Rajkot #•	22.36	70.76	Basalt
Gadsisa #•	23.10	69.34	Sandstone
Khavda #•	23.92	69.77	Sandstone
Suvai #▪	23.61	70.49	Sandstone
Kevadia #•	21.88	73.71	Basalt
Kadana #•	23.29	73.85	Basalt
Dudai #▪	23.32	70.13	Sandstone
Lodrani #•	23.89	70.62	Shale
Una #•	20.98	70.93	Basalt
Sipu(Deesa) #•	24.39	72.29	Granite
Amreli #•	21.31	71.24	Basalt
Fatehgadh # •	23.69	70.84	Sandstone
Valsad #•	20.22	73.45	Basalt
Junagarh #•	21.35	70.72	Basalt
Surendranagar #•	22.73	71.58	Sandstone
Naliya #•	23.33	68.83	Limestone
Bhachau *•	23.28	70.34	Sandstone
Bhutakia *•	23.55	70.80	Sandstone
Porbandar *•	21.64	69.61	Limestone
Nakhatrana *•	23.34	69.27	Sandstone
Dayapar *•	23.65	68.87	Sandstone
Mandvi *•	22.83	69.36	Hard soil
Gandhinagar *•	23.20	72.65	Hard soil
Radhanpur *•	23.82	71.62	Hard soil
Vadodara *•	22.31	73.13	Hard soil
Jhagadia *•	21.72	73.15	Hard soil
Ukai *•	21.22	73.58	Basalt
Lakadia *▪	23.34	70.57	Hard soil
Mota-Asota *	22.25	69.35	Hard soil
Mangrol *	21.12	70.12	Limestone

\# Broadband stations with CMG-3T sensor (Guralp) and CMG-24 digitizer (Guralp)
* Broadband stations with CMG-3T sensor and 130-01 digitizer (Reftek)
• Stations with GSR-18 (GeoSIG) strong motion accelerographs
▪ Stations with Etna (Kinemetrics) strong motion accelerographs

TABLE 1 (Continued)
Details of Seismic Stations, Types of Instrumentation, and Local Geology

Station	Latitude °(N)	Longitude °(E)	Foundation Geology
Khirdhar *	21.07	70.49	Basalt
Maliya *	21.16	70.29	Basalt
Modpar *	23.22	70.59	Hard soil
Badargadh *	23.47	70.62	Sandstone
Chobari *	23.51	70.34	Hard soil
Bandhadi *	23.39	70.31	Sandstone
Bhimasar *	23.19	70.16	Sandstone
Kodki *	23.24	69.55	Sandstone
Lodai *	23.39	69.89	Sandstone
Nagalpar *	23.11	69.98	Basalt
Traya(Lakod) *	23.27	69.77	Sandstone
Dholavira *	23.87	70.22	Sandstone
Sihor *	21.65	71.97	Basalt
Anjar •	23.11	70.03	Basalt
Kandla •	23.03	70.22	Hard soil
Chitrod •	23.41	70.67	Sandstone
Vamka •	23.42	70.42	Sandstone
Desalpar •	23.55	70.80	Sandstone
Bela •	23.87	70.80	Sandstone
Rapar •	23.56	70.66	Sandstone
Vav •	24.36	71.51	Hard soil
Patan •	23.85	72.13	Hard soil
Dharoi •	24.00	72.85	Granite
Mehsana •	23.60	72.39	Hard soil
Himmatnagar •	23.59	72.96	Sandstone
Anand •	22.52	72.98	Hard soil
Kapadvanj •	23.04	73.07	laterite
Surat •	21.17	72.80	Hard soil
Dahod •	22.84	74.25	Granite
Godhra •	22.77	73.62	Granite
Hirenval ▪	21.14	70.61	Basalt
Chitravad •	21.11	70.53	Basalt

\# Broadband stations with CMG-3T sensor (Guralp) and CMG-24 digitizer (Guralp)
* Broadband stations with CMG-3T sensor and 130-01 digitizer (Reftek)
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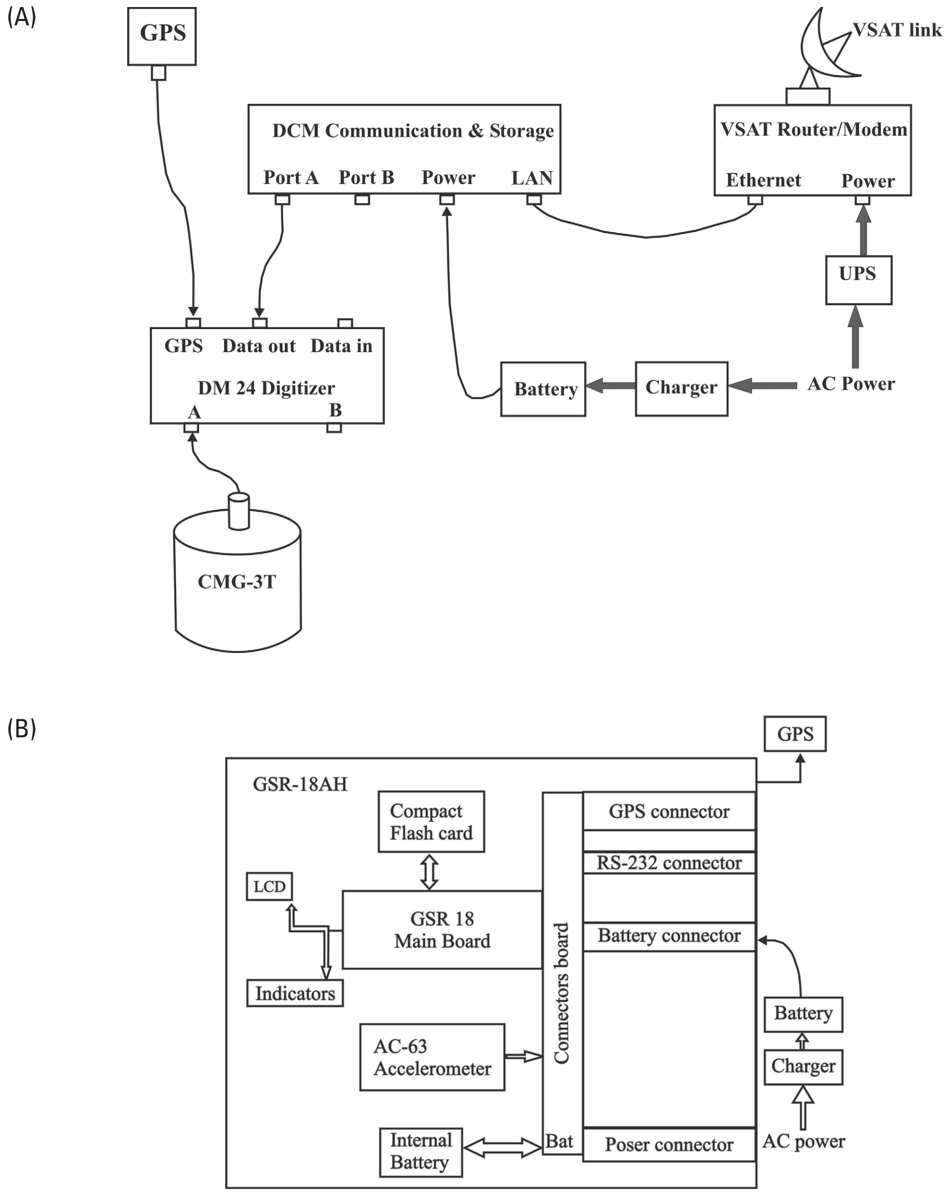
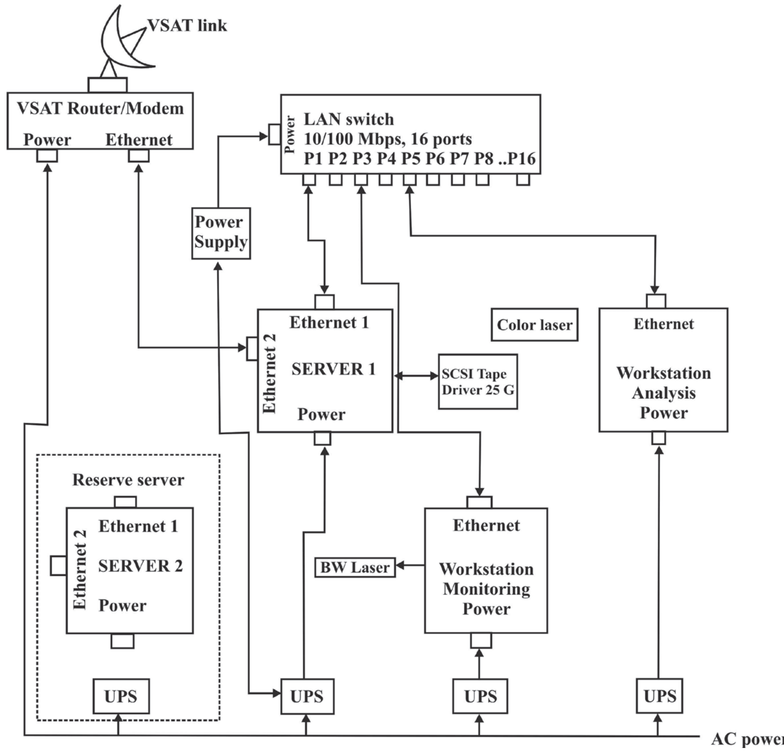


▲ **Figure 3.** Block diagram of (A) permanent broadband and (B) strong-motion seismograph stations.

density. This is calculated using the spectral analysis module of SEISAN, where new high noise models (NHNM) and new low noise models (NLNM) (Peterson 1993) are superimposed on the observed spectrum for comparison. A two-minute window is selected for calculating power spectrum density in terms of dB relative to $((1\ m/sec^2)^2)/Hz)$. Calculations show that the level of noise does not vary with time of day. This is to be expected, since the stations are away from main cities, at sites where cultural noise is less. The noise levels of stations in Saurashtra are lower than in Kachchh. The rocks in Saurashtra are more compact (Deccan basalt) in comparison to Kachchh, which is a sedimentary basin with soft rocks (Figure 5). Also, the stations on hard soil show relatively high noise levels at higher frequencies (above 1.0 Hz). This may be due to the fact that predominant frequencies at these stations are between 2 and 4 Hz. These stations are good for recording teleseismic earthquakes as compared to local earthquakes. We also looked at the long-period ambient noise levels in the stations situated on varied geology, and found that in all stations, the long-period noise levels were less than the short-period noise levels.

Data Processing

Presently, all data processing is carried out in offline mode on SEISAN software (Havskov and Ottemöller 2000). The online data are viewed on a 42-inch LCD monitor using the SCREAM (seismometer configuration, real-time acquisition and monitoring) application of Güralp. Whenever an event is detected, the operator captures the data from the continuous streams viewed on the monitor and saves the file to a separate directory and folder on a workstation. This file is called a SCREAM file, which is in GCF (Güralp Compressed Format). The SCREAM file is converted into SEISAN format through the SCREAM2SEI utility. Phases are read as per distance of the earthquake. The station locations and velocity model for



▲ **Figure 4.** Block diagram of Seismic Data Analysis Centre, located at ISR in Gandhinagar, Gujarat (India).

TABLE 2
Velocity Model for Locating Earthquakes in Kachchh Region (Mandal 2007)

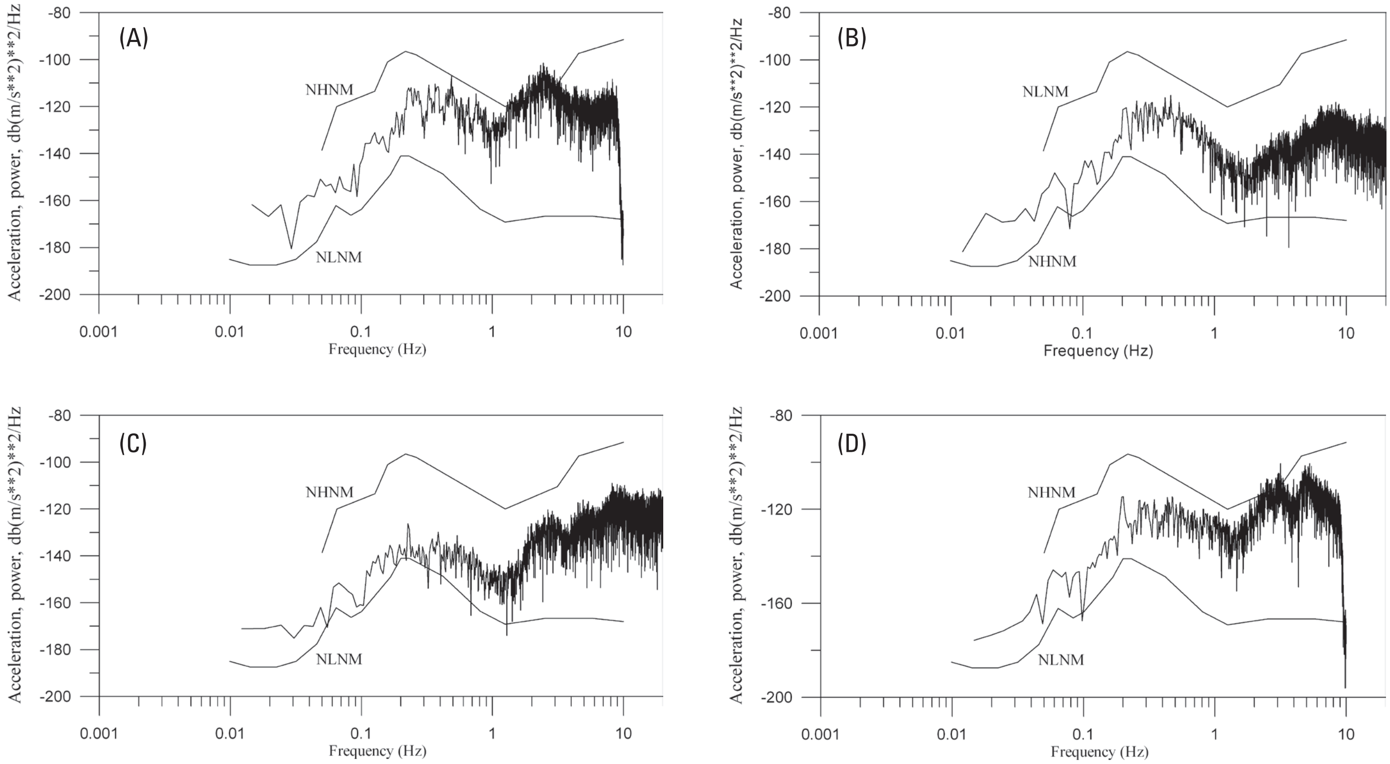
Depth to the top of layer (km)	Velocity of *P* wave (km/sec)
0.0	2.92
2.0	5.99
5.0	5.90
10.0	6.18
16.0	6.07
22.0	6.59
29.0	7.20
34.0	6.78
40.0	8.20

local and regional earthquakes are inserted in the input file. The velocity model estimated by Mandal (2007) from 1-D inversion is used for locating earthquakes in the Kachchh region (Table 2). For locating regional earthquakes, the network uses Koyna model, constrained by deep seismic sounding profiles (Kaila *et al.* 1981) (Table 3). The amplitudes are also read for all earthquakes. The earthquakes are located with HYPOCENTRE utility and $M_L/m_b/M_S$ are calculated on the basis of distances. The preliminary analysis is completed within 10 minutes of the arrival of seismic waves. The components of individual stations are rotated, and spectral analysis is carried out for estimation of M_W and source parameters like seismic moment, fault radius, corner frequency, and stress drop. The seismic data from

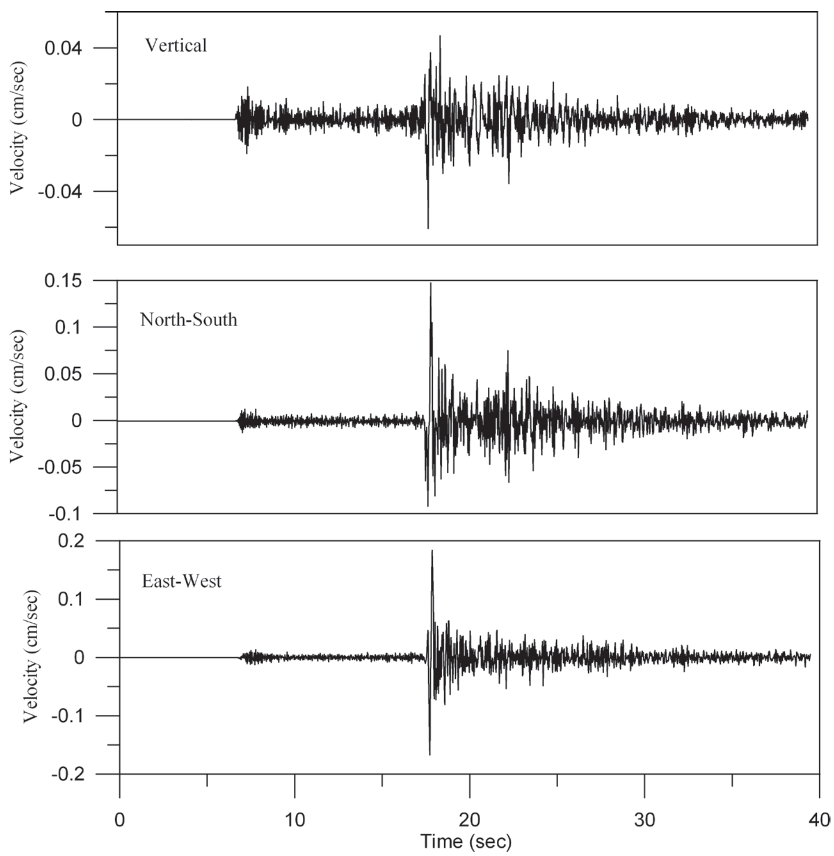
TABLE 3
Velocity Model for Locating Regional Earthquakes (Kaila *et al.* 1981).

Depth to the top of layer (km)	Velocity of *P* wave (km/sec)
0.0	4.90
1.0	5.33
2.0	5.76
4.0	5.89
6.0	6.02
8.0	6.15
10.0	6.38
13.0	6.47
16.0	6.56
19.0	6.60
25.0	6.80
28.0	6.89
31.0	6.98
34.0	7.10
38.0	8.10

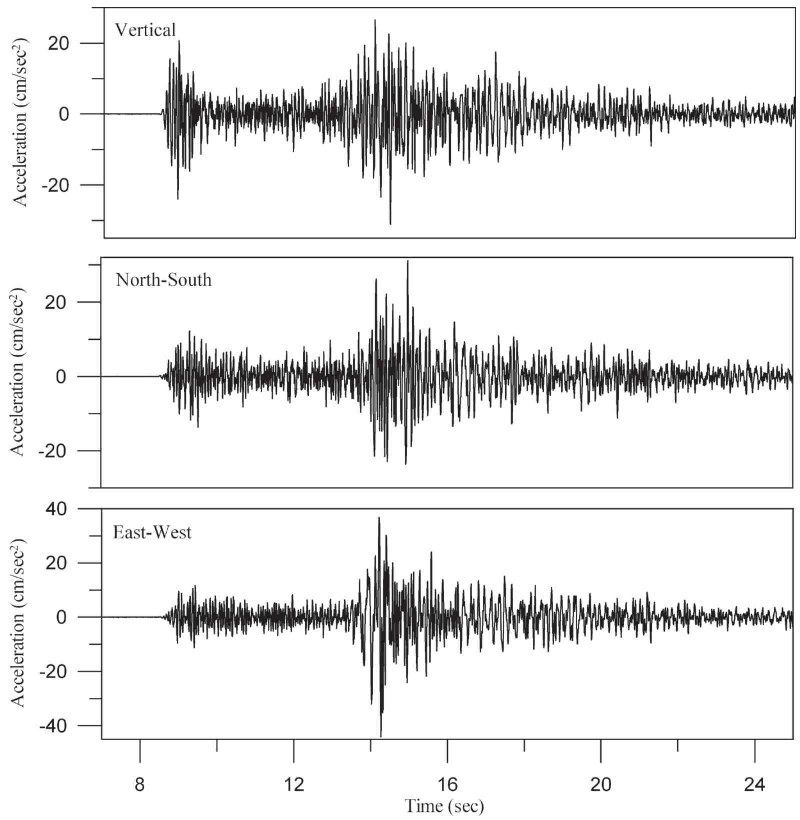
stand-alone temporary stations are added regularly to the database, thereupon improving the locations and depths. Figures 6 and 7 show examples of broadband seismographs and strong-motion accelerograph records of *Mw* 4.7 and m_b 5.0 Kachchh earthquakes that occurred on 13 May 2007 and 9 March 2008, respectively. Figure 8 shows an example of a teleseismic earth-



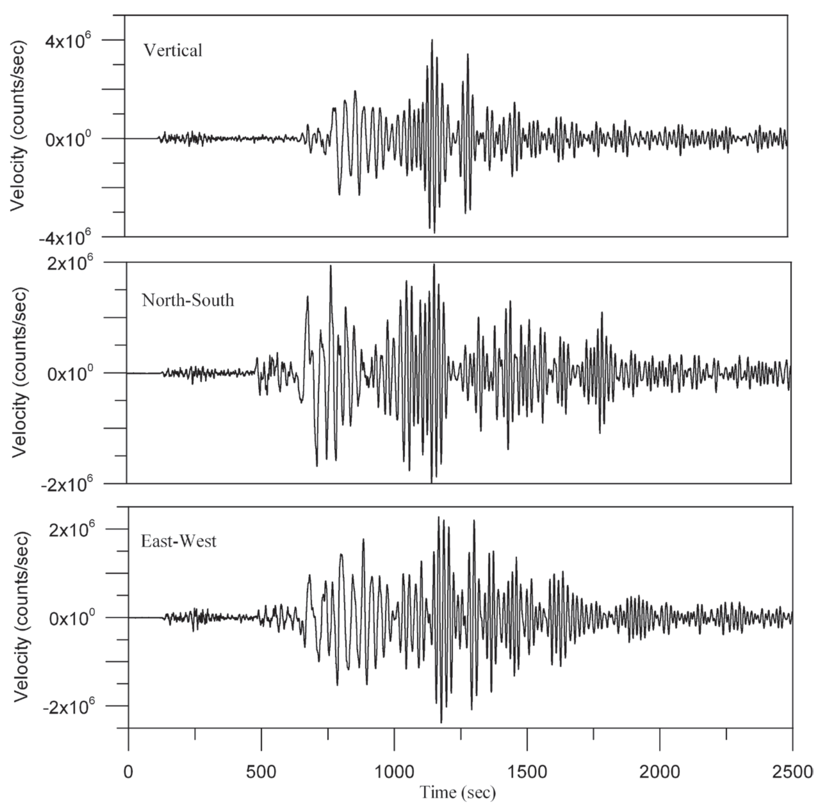
▲ **Figure 5.** Noise spectra of four GSNet stations located on (A) hard soil (Jhagadia), (B) basalt (Rajkot), (C) sandstone (Khavda), and (D) limestone (Naliya).



▲ **Figure 6.** A sample broadband record of an Mw 4.7 earthquake in the Kachchh region of Gujarat recorded at the Khavda (KAV0) station (epicentral distance 88 km) on 13 May 2007.



▲ **Figure 7.** A sample strong-motion (accelerograph) record of an mb 5.0 earthquake from the Kachchh region of Gujarat recorded at the Suvai (SUV0) station (epicentral distance 28 km) on 9 March 2008.



▲ **Figure 8.** A sample broadband record of an Ms 8.3 earthquake on 12 September 2007 in southern Sumatra, Indonesia, and recorded at the Kadana (KAD0) station (epicentral distance 5,024 km).

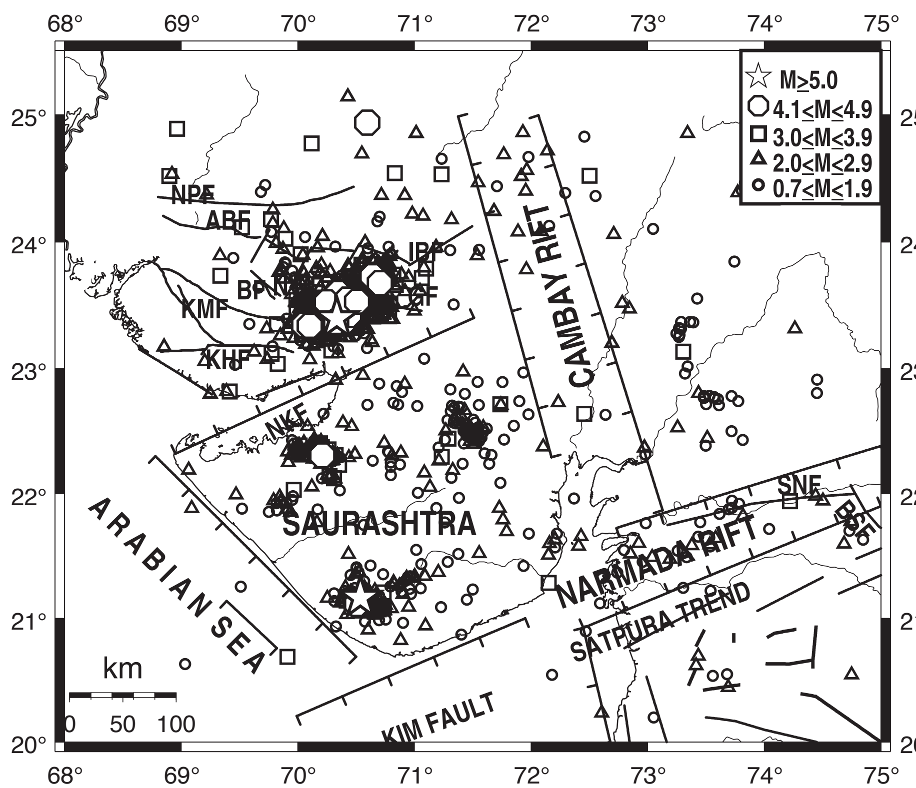
quake of M_S 8.3 that occurred on 12 September 2007 at southern Sumatra, Indonesia.

Detection Capability

Earthquakes of **M** ≥ 3 are well-recorded up to 200-km distance. Such earthquakes in Gujarat are invariably recorded on three or four stations, which means that the detection capability is **M** 3 in the mainland. **M** ≥ 2 earthquakes are well-recorded up to 75-km distance; such earthquakes in most parts of Kachchh are recorded on four or more stations. Therefore **M** 2 is the detection capability in most parts of Kachchh. Average station spacing in Kachchh is 25 km, in Saurashtra 60 km, and in mainland Gujarat 100 km. In the most active area of Kachchh, 23 broadband seismograph stations and 20 strong-motion accelerograph stations are deployed, and the station spacing is 15 km. The network recorded and located about 2,000 local earthquakes from July 2006 to March 2008 with magnitudes in the range of 0.7 to 5.0, as shown in Figure 9. Most of the seismic activity is concentrated in the 2001 Bhuj aftershock region in Kachchh, with the rest in Saurashtra (Chopra *et al.* 2008). Events from all azimuths are well-recorded in most of the stations, except those stations which are in soil, where background noise is much higher. Local earthquakes are located with an error of 2–3 km in latitude and longitude and 4–5 km in depth. All major teleseismic earthquakes are recorded in the network as far away as Peru, Kuril Islands, Solomon Islands, Fiji, and Aleutian Islands; in all, 353 regional and teleseismic earthquakes were recorded and located during this period. Based on this, the network can record earthquakes of **M** ≥ 4 within about 1,000 km, **M** ≥ 5 within about 2,000 km, **M** ≥ 5.5 within about 5,000 km, and **M** ≥ 6 within about 10,000 km. The teleseismic earthquakes in the 2,000–5,000-km range are located with an error of about 1 degree in latitude. The error decreases for earthquakes occurring within 2,000 km and increases for earthquakes occurring beyond 5,000 km. This is expected as the network stations are concentrated in a small area. Though the mandate of the network is to locate and report local earthquakes as soon as possible, the network also locates teleseismic events to detect tsunamigenic earthquakes. There are a few tsunamigenic sources in the Arabian Sea, such as Makran, which are capable of generating tsunamis. The ISR plans to carry out near real-time rupture modeling of such earthquakes.

DISCUSSION AND CONCLUSIONS

The GSNet is equipped with all the latest seismic instruments, and quality seismic data are being produced that will be very helpful in seismological research. The GSNet is planning to connect more stations, particularly strong-motion accelerograph stations, to the online network, so that a reliable early warning system can be developed. In this system earthquake magnitude will be estimated from the first few seconds' arrival, and the information will be transmitted to far-off cities like Ahmedabad (270 km) where a lead time of 30 seconds is avail-



▲ **Figure 9.** Distribution of epicenters of earthquakes recorded and located by GSNet during the period January 2007 to March 2008 for earthquakes of magnitude ML ≥ 0.7 that occurred in Gujarat and adjoining region. The epicenters shown are the locations of mainshocks and associated sequences (*i.e.*, foreshocks and aftershocks).

able from any damaging earthquake from the Kachchh region. Presently, the network is limited only by the unavailability of auto-location software. The GSNet is planning to procure a standard auto-location software module in the current year. The ISR has also procured 32 permanent geodetic-grade GPS receivers, which will be networked with the GSNet to study the coseismic crustal deformation of the area in near real time.

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