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# Profiling of late Tertiary–early Quaternary surface in the lower reaches of Narmada valley using microtremors

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ABSTRACT

In this paper, we propose the first approximation for thickness of Quaternary sediment and late Quaternary–early Tertiary topography for the part of lower reaches of Narmada valley in a systematic way using the shallow seismic method, that records both horizontal and vertical components of the microtremor (ambient noise) caused by natural processes. The measurements of microtremors were carried out at 31 sites spaced at a grid interval of 5 km s using Lennartz seismometer (5 s period) and City shark-II data acquisition system. The signals recorded were analysed for horizontal to the vertical (H/V) spectral ratio using GEOPSY software. For the present study, we concentrate on frequency range between 0.2 Hz and 10 Hz. The thickness of unconsolidated sediments at various sites is calculated based on non-linear regression equations proposed by Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002). The estimated thickness is used to plot digital elevation model and cross profiles correlating with geomorphology and geology of the study area.



## 1. Introduction

The frequency of seismic noise shows both temporal and regional variations depending on the influence of source and site. In case of thick unconsolidated sediment overlying the bedrock, the seismic waves give high mechanical contrast, where the upper unconsolidated sediment amplifies the seismic motion. The frequency of resonating waves in the unconsolidated upper layer is related to the velocity as well as the thickness of the sediment. Such site amplification can be estimated using an ambient noise method introduced by Kanai (1957). Several studies have shown that ambient seismic noise records reveal the fundamental resonant frequency of surface sediments (Ohta et al., 1978; Celebi et al., 1987; Lermo et al., 1988; Field et al., 1990; Hough et al., 1991; Konno and Ohmachi, 1998). To infer the site amplification characteristics from ambient noise, one however needs to remove source effect. Nakamura (1989) proposed a method to remove the source effect and estimate site response by dividing the horizontal component noise spectrum by the vertical component (H/V). Several modifications, shortcomings and applications of this method were studied thereafter (Ohta et al., 1978; Celebi et al., 1987; Lermo et al., 1988; Hough et al., 1991; Field and Jacob, 1993; Lermo and Chavez-Garcia, 1993, 1994; Konno and Ohmachi, 1998; Zhao et al., 2007). Several researchers have applied microtremor H/V spectrum for site investigation and measuring thickness of the top soil cover over the bedrock in Europe, China, Japan (Tertiary–Quaternary interphase: Yamanaka et al., 1994; Ibs-von Seht and Wohlenberg, 1999; Delgado et al., 2000; Parolai et al., 2002; Garcia-Jerez et al., 2006; Zhao et al., 2007) and mapping of regolith thickness over Archaeans (Dinesh et al., 2010). In both cases there is high mechanical contrast, however, in the former case the variation of Quaternary–Tertiary interphase in the basin is predictable, whereas regolith cover would have wide variation locally. Studies by Ibs-Von Seht and Wohlenberg (1999) and Parolai et al. (2002) proposed equations relating the fundamental resonant frequency to the thickness of soft sediment cover (Quaternary sediments) from the observed well data and theoretical calculations. Ibs-Von Seht and Wohlenberg (1999) investigated western Lower Rhine Embayment in Germany comprising a variable thickness of sediment belonging to Tertiary and Quaternary age. On the other hand, Parolai et al. (2002) investigated Cologne area in Germany comprising sediments of Quaternary and Tertiary age covering Devonian bedrock. In the recent work of Dinesh et al. (2010), they have derived an equation for the Archaean meta-sediments and the overlying sediment cover at Bangalore City, India.

The present investigation is the first attempt to map the thickness of the Quaternary sediments in the lower reaches of Narmada

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valley located at the southern margin of Jambusar–Bharuch Block of Cambay Basin, a potential hydrocarbon block in western India (Mukherjee, 1983) using microtremors (Fig. 1A). In the study area along the south eastern portion (Ankleshwer and Rajpardi segment) the Tertiary sediments occur at shallow depths and are enveloped by unconsolidated thin layer of Quaternary sediment, whereas towards the northwest portion of the study area (Bharuch and Nareshwar segment) the Tertiary sediments extend only in the subsurface (Rao, 1969; Agarwal, 1986; Ramanathan and Pandey, 1988). The only subsurface information regarding Quaternary–Tertiary contact in the lower reaches of Narmada Valley is estimated through cross profiles along Broach–Dadhal (Rao, 1969) as shown in Fig. 2. Further, the area has been investigated by different researchers in terms of mapping of the exposed sedimentary sequence, their depositional environment and neotectonic characteristics (Allchin and Hegde, 1969; Gadekar et al., 1973; Bedi and Vaidyanadhan, 1982; Sant and Karanth, 1993; Rajaguru et al., 1995; Bhandari et al., 2001; Chamyal et al., 2002; Bhandari, 2004; Bhandari et al., 2005; Raj, 2007, 2008; Raj and Yadava, 2009). However, the area still lacks information on the floor variation of Tertiary bedrock, thickness of Quaternary sediments and its relation with surface topography/landforms. The recent

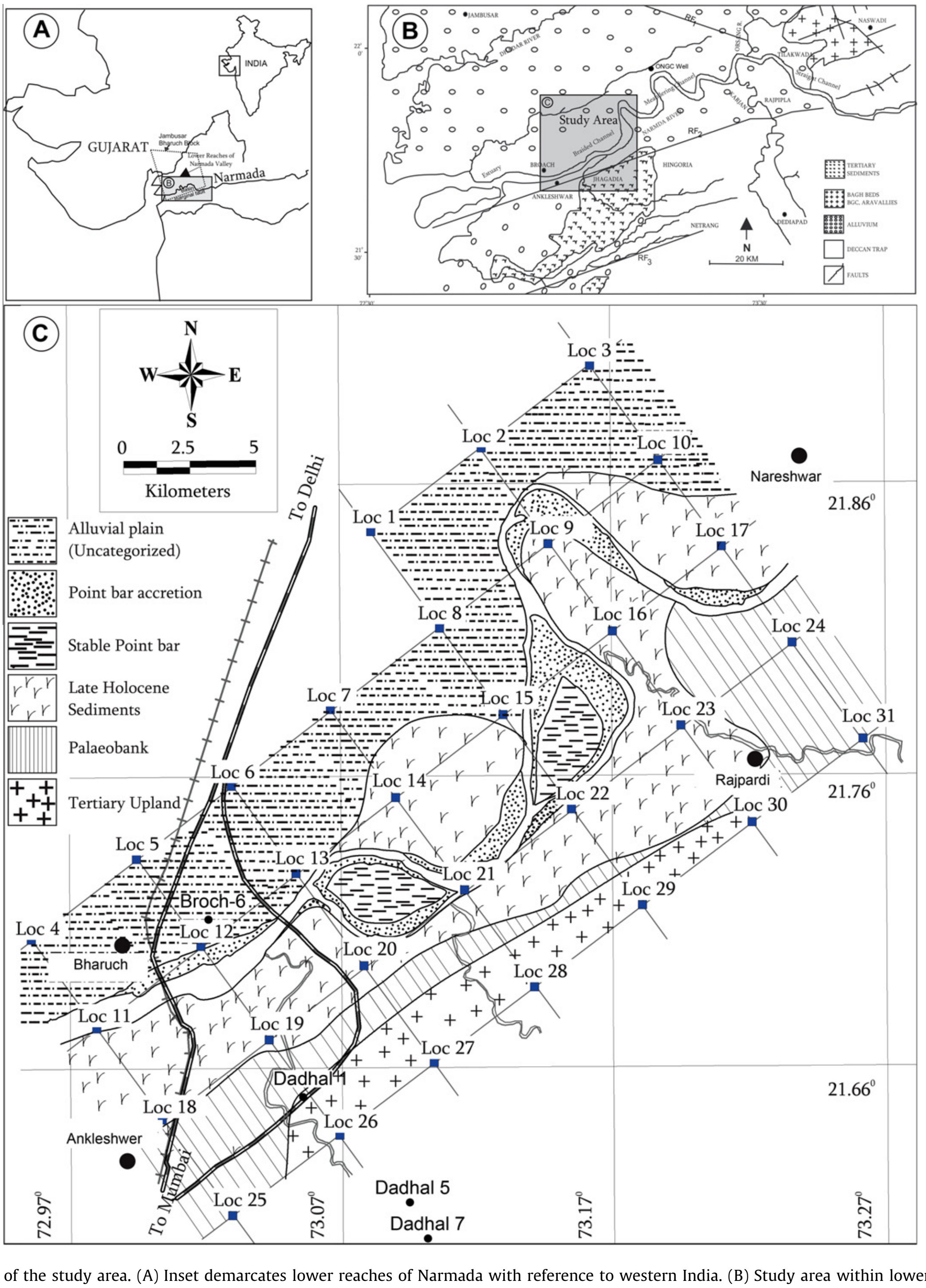


**Fig. 1.** Location map of the study area. (A) Inset demarcates lower reaches of Narmada with reference to western India. (B) Study area within lower reaches of Narmada valley. (C) Geology and geomorphology of the study area (modified after Bedi and Vaidyanadhan (1982). Loc 1–Loc 31 represents locations for microtremor recording.

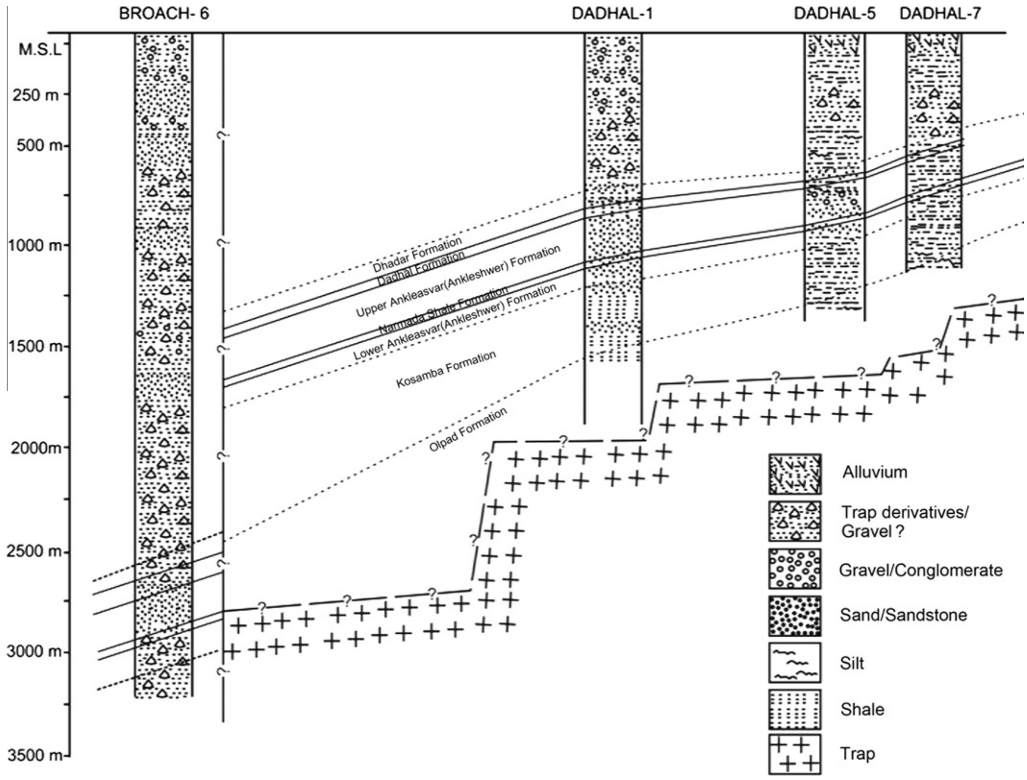


**Fig. 2.** Image showing borehole correlations from the available boreholes in the present study area (adopted from Rao (1969), Fig. 2, p. 27). See Fig. 1 for location of boreholes. Broach 6 shows a thick sediment accumulation compared to the SE portion is well correspond with the present finding.

discovery of hydrocarbon occurrence at a shallow depth (total depth of 540 m; occurrence of hydrocarbons is reported from 328–325 m, 315–313 m and 309–305 m, 293–290 m levels) immediate outside the study area would further open avenues for exploring shallow hydrocarbon traps and 3D geometry of landforms (ONGC Report, 2010).

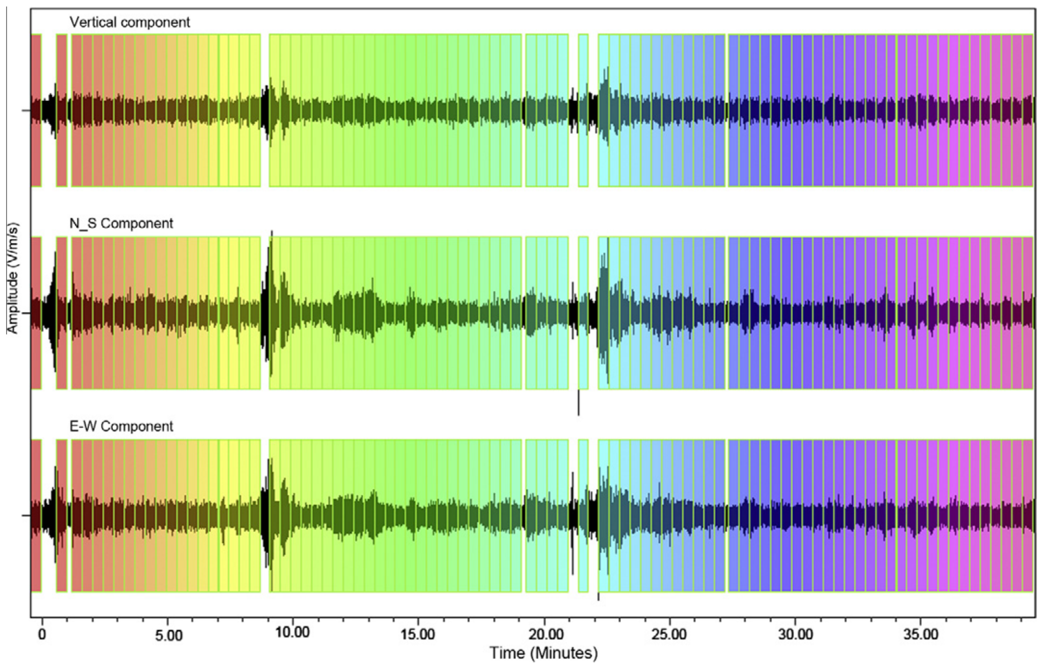


**Fig. 3.** An example of waveform recorded (Location 13) by Lennartz seismometer (5 s period) with City shark-II data acquisition system. *X* axis shows the time and *Y* axis shows the different components of amplitude viz. NS, EW and vertical.

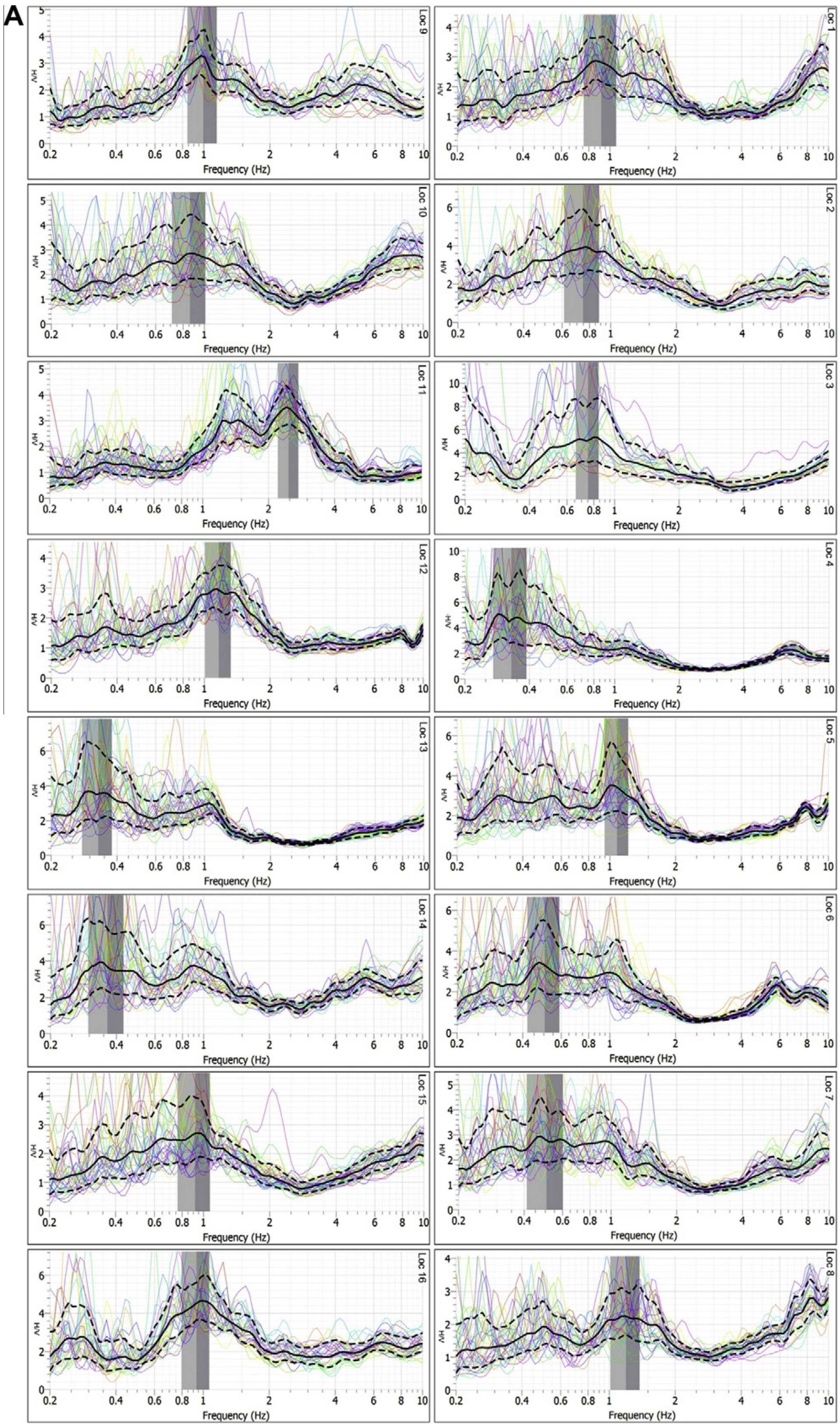


**Fig. 4.** (A and B) H/V spectral ratio for 31 for frequency range 0.2–10 Hz. The coloured thin lines are H/V spectral ratio for different windows, black solid line is the average value and black dashed lines are ±standard deviation. The bar shows the fundamental frequency with two grey shades representing ±standard deviation.

## 2. Field observations and methodology

The lower reaches of Narmada exemplify various palaeo and neolandforms well preserved within the flood plain of River Narmada. In general, the southern portion of the study area forms three surfaces, viz. Late Holocene surface, Palaeo bank and exposed Tertiary uplands, whereas the northern portion remains an uncategorised alluvial plain surface (Bedi and

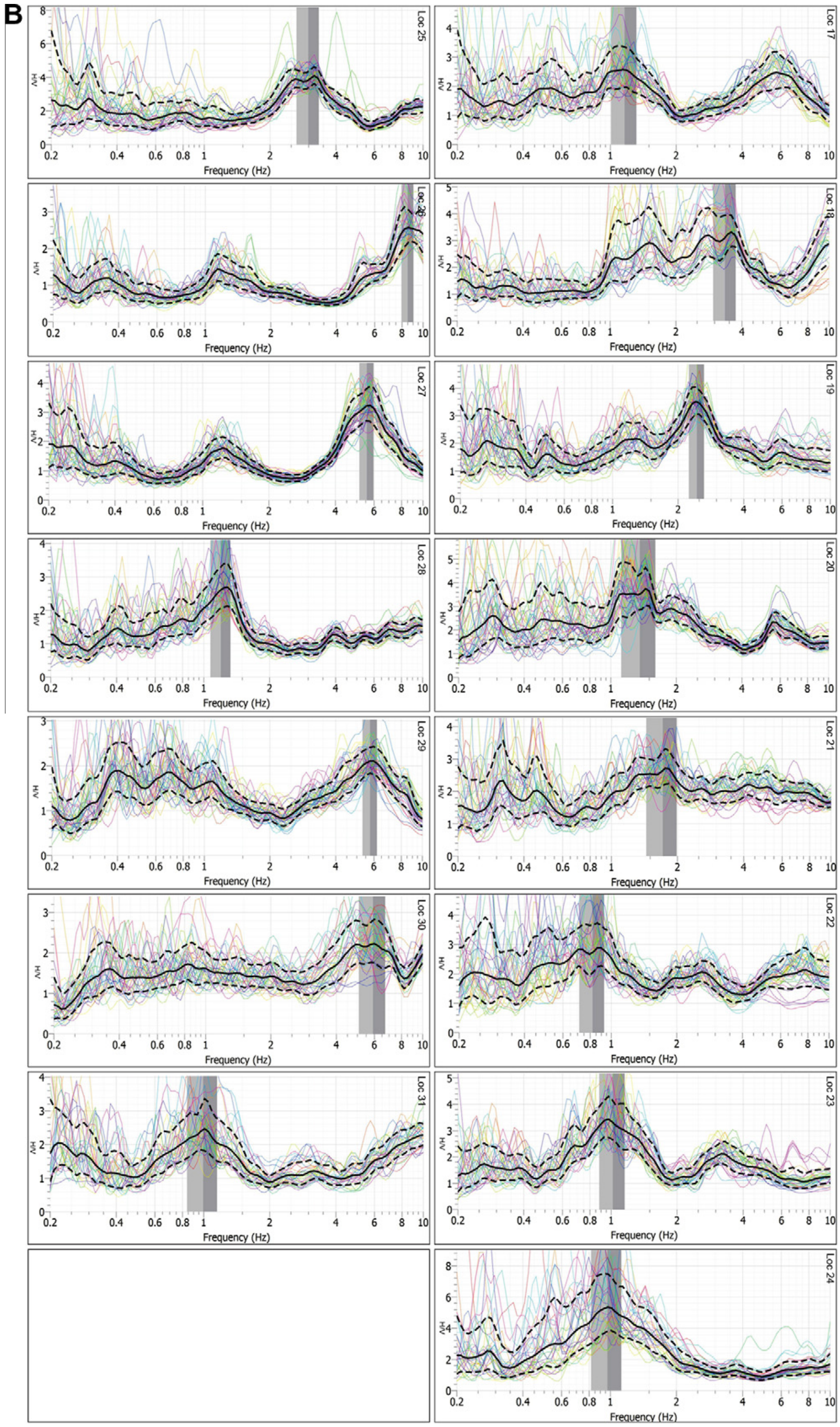


**Fig. 4** (*continued*)

Vaidyanadhan, 1982: Fig. 1C). The area poses flat to rolling topography with Palaeo bank and neobank as a paired landform which runs ENE–WSW direction from Jhagadia in east to Ankleshwer in west with a length of more than 30 km (Allchin and Hegde, 1969; Bedi and Vaidyanadhan, 1982; Mukherjee, 1983; Sant and Karanth, 1993). The incised river channels have exposed a few metres to 40 m of Quaternary sediments in the study area.

An ENE–WSW trending reverse basin marginal fault, traverse through the southern boundary of the study area (Kaila et al., 1981). As a result, the basin marginal fault exposes Tertiary sequence immediately along the southern periphery. The structural studies on exposed Tertiary rocks suggest that they have undergone last deformation during Plio–Pleistocene time, resulting in development of several anticlines–syncline structures (Agarwal, 1986). Towards the north of the fault, the late Tertiary rocks form the bedrock for unconsolidated Quaternary sediments whose thickness varies depending on the late Tertiary–early Quaternary topography.

We apply the seismic method using ambient noise to decode a two-layered model demarcating unconsolidated Quaternary sediment and the bedrock belonging to Tertiary age. The measurements using ambient noise were carried out using the Lennartz seismometer (5 s period) with City shark-II data acquisition system for 31 sites located on different landforms (Fig. 1C). The data acquisition was done in a gridded pattern at a resolution of 5 km covering an area of 470 km$^2$ that includes Tertiary high land surface in the south east to a flat flood plain towards North West (Fig. 1). We have acquired the microtremor data at 100 samples/s for each site. However, the frequency range between 0.2 Hz and 10 Hz has been analysed in the present study. The acquisition system records frequencies as three components viz. EW, NS and vertical vibration directions for a time duration of 40 min (Fig. 3).The noise recordings were processed using GEOPSY freeware (http://www.geopsy.org/) to determine the fundamental resonant frequency after generating the H/V spectral ratio for each station (Fig. 4A and B).

## 3. Theoretical calculation

Theoretical estimation of the thickness ($h$) of the soil layer over the bedrock can be related to the fundamental resonant frequency ($f_r$) of H/V spectral ratio by a allometric function as given by Eq. (1) (Ibs-von Seht and Wohlenberg, 1999),

$$h = af_r^b \tag{1}$$

where '$a$' and '$b$' are the standard errors of the correlation coefficients.

The estimated terrain specific equation was justified studying Quaternary–Tertiary inter phase at western Lower Rhine Embayment (Ibs-von Seht and Wohlenberg, 1999; based on 34 boreholes ranging in depth from 15 m to 1257 m and data from 102 seismic stations: Eq. (2A)) and the Cologne area in Germany (Parolai et al., 2002; based on 32 boreholes having a depth of <402 m and 337 data from seismic stations: Eq. (2B)) simulating the thickness of soil cover (Quaternary sediments) above bedrock (Tertiary rocks). Dinesh et al. (2010) derived terrain specific equation (Eq. (2C)) for the distinctly different terrain around Bangalore in India (inter phase of soil and regolith with metamorphic rock and granites).

$$h = 96f_r^{-1.388} \tag{2A}$$

$$h = 108f_r^{-1.551} \tag{2B}$$

$$h = (58 \pm 8.8)f_r^{(-0.95\pm0.1)} \tag{2C}$$

To map Quaternary–Tertiary interphase in the lower reaches of Narmada valley, we adopt terrain specific equations by Ibs-von Seht and Wohlenberg (1999), Parolai et al. (2002) and Dinesh et al. (2010). A theoretical thickness for the unconsolidated Quaternary sediment is calculated using the fundamental frequency ($f_r$) values of each station (Table 1). The underlying assumption to the present calculation is that the H/V spectral ratio depends primarily on the source/site characteristics rather the geographical location. Comparing the data estimated using

**Table 1**
Calculated thickness of unconsolidated sediments over Tertiary bedrock using Ibs-von Seht and Wohlenberg (1999), Parolai et al. (2002) and Dinesh et al. (2010) equations for 31 stations in lower reaches of Narmada River.

| Loc. on map | $F$ (H/V) (Hz) | Thickness (m) (Ibs-von Seht and Wohlenberg, 1999) $h = 96f_r^{-1.388}$ | Thickness (m) (Parolai et al., 2002) $h = 108f_r^{-1.551}$ | Thickness (m) (Dinesh et al., 2010) $h = (58 \pm 8.8)f_r^{(-0.95\pm0.1)}$ |
|---|---|---|---|---|
| Loc 01 | 0.9 | 111.1175 | 127.1726 | 67.13352 |
| Loc 02 | 0.747 | 143.9137 | 169.7866 | 86.94788 |
| Loc 03 | 0.754 | 142.0626 | 167.3481 | 85.8295 |
| Loc 04 | 0.333 | 441.6911 | 594.4465 | 266.855 |
| Loc 05 | 1.085 | 85.72249 | 95.1639 | 51.79067 |
| Loc 06 | 0.499 | 251.9461 | 317.446 | 152.2174 |
| Loc 07 | 0.504 | 248.4836 | 312.5748 | 150.1255 |
| Loc 08 | 1.185 | 75.84905 | 83.00162 | 45.82547 |
| Loc 09 | 0.973 | 99.71732 | 112.6836 | 60.24588 |
| Loc 10 | 0.865 | 117.4067 | 135.2421 | 70.93321 |
| Loc 11 | 2.476 | 27.27378 | 26.46772 | 16.47791 |
| Loc 12 | 1.173 | 76.9282 | 84.32232 | 46.47746 |
| Loc 13 | 0.324 | 458.812 | 620.2524 | 277.1989 |
| Loc 14 | 0.361 | 394.8674 | 524.4814 | 238.5657 |
| Loc 15 | 0.918 | 108.105 | 123.326 | 65.31341 |
| Loc 16 | 0.936 | 105.2302 | 119.6671 | 63.57657 |
| Loc 17 | 1.15 | 79.07198 | 86.95237 | 47.77266 |
| Loc 18 | 3.326 | 18.10686 | 16.74643 | 10.93956 |
| Loc 19 | 2.428 | 28.02503 | 27.28369 | 16.93179 |
| Loc 20 | 1.36 | 62.64973 | 67.03551 | 37.85088 |
| Loc 21 | 1.721 | 45.18636 | 46.52942 | 27.30009 |
| Loc 22 | 0.832 | 123.9196 | 143.6523 | 74.8681 |
| Loc 23 | 1.012 | 94.42363 | 106.0202 | 57.04761 |
| Loc 24 | 0.973 | 99.71732 | 112.6836 | 60.24588 |
| Loc 25 | 2.985 | 21.04013 | 19.80547 | 12.71175 |
| Loc 26 | 8.585 | 4.855564 | 3.847623 | 2.93357 |
| Loc 27 | 5.545 | 8.907091 | 7.579359 | 5.381367 |
| Loc 28 | 1.208 | 73.85201 | 80.56343 | 44.61892 |
| Loc 29 | 5.767 | 8.434759 | 7.131656 | 5.096 |
| Loc 30 | 5.998 | 7.987268 | 6.710204 | 4.825641 |
| Loc 31 | 0.993 | 96.94059 | 109.1831 | 58.56828 |

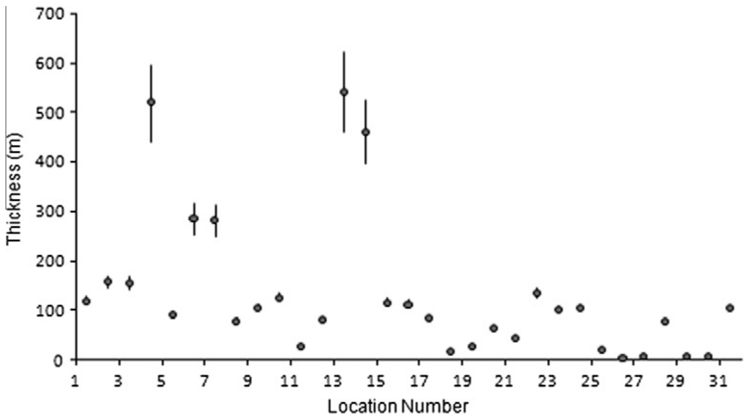


**Fig. 5.** Comparison between depths calculated using Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) relationships (Eqs. (2A) and (2B)). The circle indicates the average value whereas the length of the line suggests deviation from the average.

the three equations; it has been observed that the variation of estimated depth is more in the case of Dinesh et al. (2010). The large deviation in the depths could be inferred due to the high mechanical contrast between Archaean meta-sediments and the overlying soil cover. While, the depths calculated using Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) show significantly smaller variations in the thickness due to the comparable geotechnical characteristics of geological formation. Further, the values of thickness obtained from Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) were more compatible with each other (Fig. 5). This analysis clearly brings out that the thickness calculated for H/V spectral frequency >0.5 Hz (26 data points) show an averaged standard deviation of 8 m in thickness, whereas, the H/V spectra frequency <0.5 Hz (5 data points) show averaged standard deviation of 114 m in thickness. In other words, there is not much difference between results obtained using the above two equations.

We further averaged the values derived using Eqs. (2A) and (2B) giving a best fit equation for the lower reaches of the Narmada valley (Eq. (3)). This is further used for deriving primary information on the relative depth variation of the interface between the two mechanically contrasting layers of Quaternary sediment (soft sediment) and Tertiary rock (bedrock) in the study area (Table 2).

$$\bar{h} = 102.1 f_r^{-1.47} \quad (3)$$

**Table 2**
Relative variation of the thickness of Quaternary sediment cover at 31 locations which is further used for the elevation models.

| Loc. on map | Latitude | Longitude | Elevation (m) | $F$ (H/V) (Hz) | Relative variation of average thickness (m) Present work Represents the equation $\bar{h} = 102.1 f_r^{-1.47}$ |
|---|---|---|---|---|---|
| Loc 01 | 21.84895° | 73.08142° | 25 | 0.9 | 119.1451 |
| Loc 02 | 21.8773° | 73.12202° | 22 | 0.747 | 156.8502 |
| Loc 03 | 21.90541° | 73.1619° | 25 | 0.754 | 154.7054 |
| Loc 04 | 21.71003° | 72.95635° | 28 | 0.333 | 518.0688 |
| Loc 05 | 21.73744° | 72.99498° | 24 | 1.085 | 90.44319 |
| Loc 06 | 21.7622° | 73.02984° | 18 | 0.499 | 284.696 |
| Loc 07 | 21.78819° | 73.0663° | 20 | 0.504 | 280.5292 |
| Loc 08 | 21.81587° | 73.1064° | 36 | 1.185 | 79.42534 |
| Loc 09 | 21.84444° | 73.14631° | 23 | 0.973 | 106.2005 |
| Loc 10 | 21.87292° | 73.18669° | 34 | 0.865 | 126.3244 |
| Loc 11 | 21.67962° | 72.98013° | 19 | 2.476 | 26.87075 |
| Loc 12 | 21.70752° | 73.01841° | 19 | 1.173 | 80.62526 |
| Loc 13 | 21.7323° | 73.05333° | 23 | 0.324 | 539.5322 |
| Loc 14 | 21.75803° | 73.09002° | 15 | 0.361 | 459.6744 |
| Loc 15 | 21.78613° | 73.12948° | 23 | 0.918 | 115.7155 |
| Loc 16 | 21.81451° | 73.16965° | 20 | 0.936 | 112.4487 |
| Loc 17 | 21.84339° | 73.20974° | 20 | 1.15 | 83.01217 |
| Loc 18 | 21.64826° | 73.00391° | 11 | 3.326 | 17.42665 |
| Loc 19 | 21.67547° | 73.04317° | 17 | 2.428 | 27.65436 |
| Loc 20 | 21.70058° | 73.07807° | 14 | 1.36 | 64.84262 |
| Loc 21 | 21.72634° | 73.11506° | 12 | 1.721 | 45.85789 |
| Loc 22 | 21.75382° | 73.15429° | 17 | 0.832 | 133.7859 |
| Loc 23 | 21.78227° | 73.19457° | 14 | 1.012 | 100.2219 |
| Loc 24 | 21.8104° | 73.23541° | 33 | 0.973 | 106.2005 |
| Loc 25 | 21.61547° | 73.0295° | 29 | 2.985 | 20.4228 |
| Loc 26 | 21.64276° | 73.06886° | 25 | 8.585 | 4.351594 |
| Loc 27 | 21.6674° | 73.10354° | 39 | 5.545 | 8.243225 |
| Loc 28 | 21.69308° | 73.14048° | 22 | 1.208 | 77.20772 |
| Loc 29 | 21.72093° | 73.18014° | 29 | 5.767 | 7.783208 |
| Loc 30 | 21.74903° | 73.22044° | 48 | 5.998 | 7.348736 |
| Loc 31 | 21.77744° | 73.26117° | 19 | 0.993 | 103.0619 |

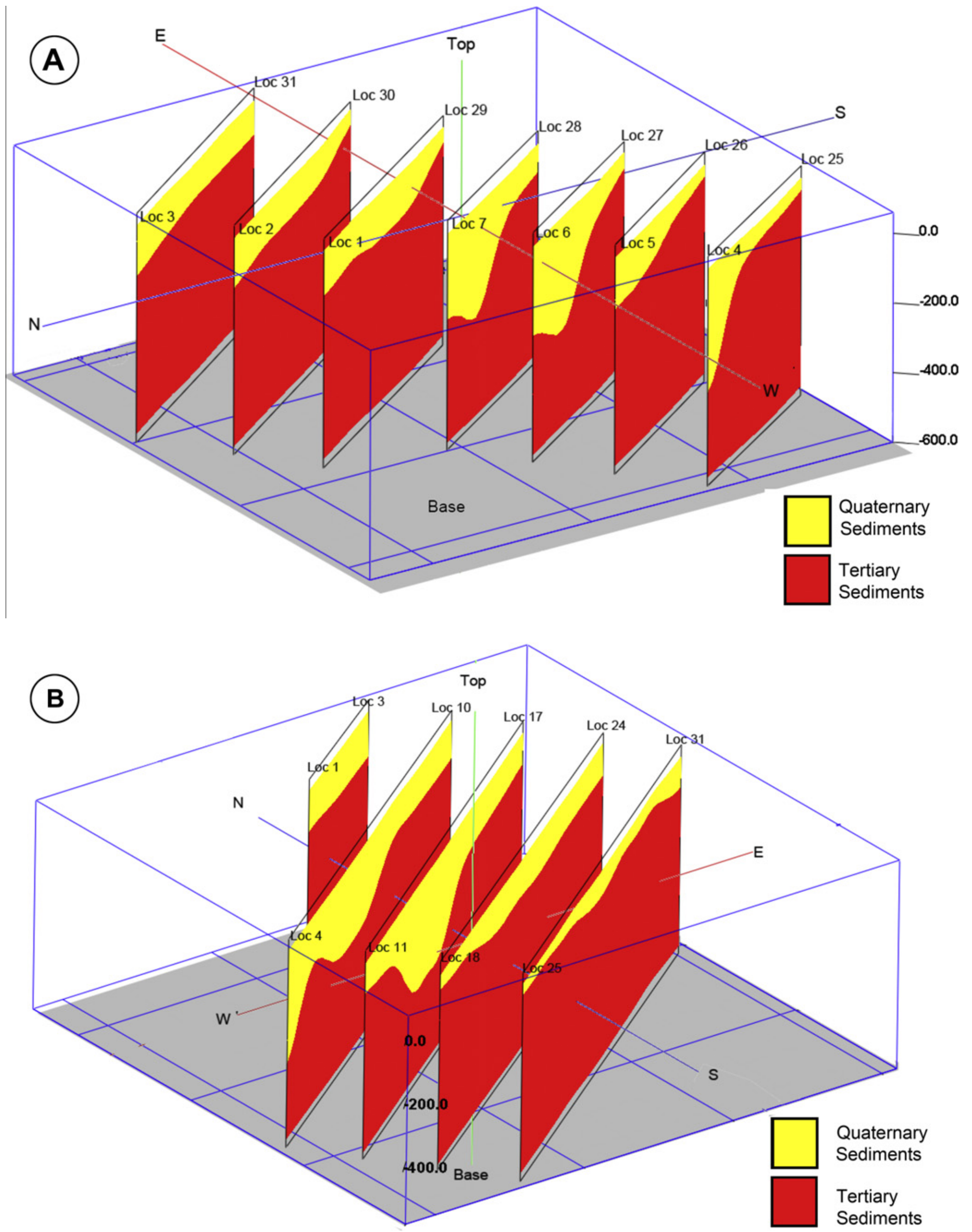


**Fig. 6.** Cross profiles showing the contact of unconsolidated soft sediment and consolidated bedrock variations of Quaternary sediments. (A) NW–SE profile and (B) NE–SW profiles.

The calculated values give a shallow interface of Quaternary and Tertiary sediments in the Ankleshwer and Rajpardi segment and deep in the Bharuch and Nareshwar segment. This observation is validated by correlation of wells across Narmada River (Fig. 2). The correlation profile shows a thick sediment cover at the Broach well. A thin cover of sediment inferred from the locations Loc 26, Loc 27, Loc 29 and Loc 30 validates the occurrence of Tertiary rocks at observed shallower depth. However, the observed depth of 77 m at Loc 28 within the Tertiary bedrock indicates a local depression.

## 4. Results and discussion

Calculated depth of the interface between the two layers (using Eq. (3)) is used to plot cross-profiles and digital elevation model (DEM) for lower reaches of Narmada valley. Fig. 6A and B shows NW–SE and NE–SW cross-sections respectively. The NW–SE profile shows a gentle northerly slope of the consolidated bedrock viz. Loc 1–Loc 29, Loc 2–Loc 30 and Loc 3–Loc 31 profiles, whereas the profiles along Loc 4–Loc 25, Loc 6–Loc 27 and Loc 7–Loc 28 show steeper slope and increase in the unconsolidated sediment thickness. The profile Loc 5–Loc 26 appears to form a ridge dividing depressions into two (Loc 4 and Loc 6). The variation in the depth of consolidated bedrock in the SW portion of the study area can better be appreciated along NE–SW profiles (Fig. 6B). The study of cross profiles implies linkages between the depocentres and the source in the different direction. The DEM for the bedrock further reveals late Tertiary–early Quaternary palaeo-depressions (I) between Loc 6, Loc 7, Loc 13 and Loc 14 showing relative depth variations of 284 m, 280 m, 539 m, 459 m respectively and depression (II)

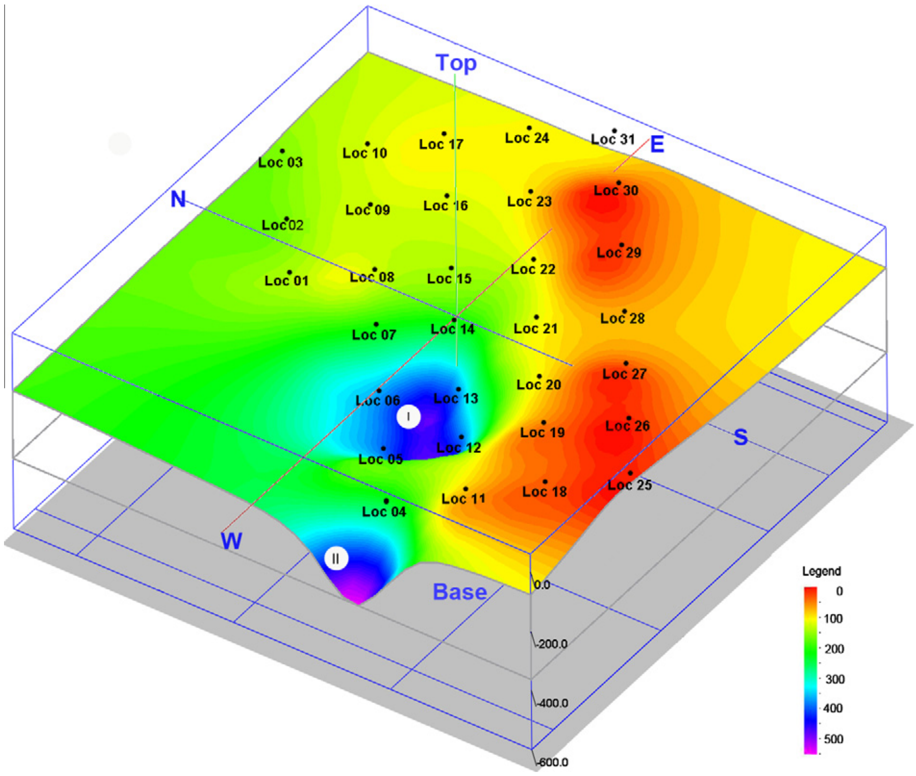


**Fig. 7.** Late Tertiary–early Quaternary palaeo-topography of area under study in the lower reaches of Narmada valley. I and II are the depressions carved over late Tertiary–early Quaternary surface forming the sites of thickest Quaternary sediment in the study area.

Loc 4 reaching a depth of 518 m (Fig. 7). Comparing the geomorphology with digital elevation model of the bedrock raises two possible explanations for the variation in the bedrock profile (Fig. 7). Firstly, the steeply dipping Tertiary rock between Loc 18 and Loc 23 is correlating with the surface expression of Palaeo bank. While the region connecting Loc 18, Loc 19, Loc 20, Loc 21, Loc 22, Loc 15 and Loc 14 shows control of shallow Tertiary rocks to the present braided channel of River Narmada. The profile connecting Loc 15 and Loc 12 suggest a steep channel gradient of River Narmada during late Tertiary–early Quaternary. The ridge formed between Loc 4, 5, 11 and 12 that differentiate depressions I and II may be correlated with the thick gravel lobe exposed along the southern bank of Narmada (within locations 19–21 and 25–27) brought by transverse River system in to the depression. Secondly, both the Quaternary depressions appear to be structural control as they lie adjacent to ENE–WSW Cambay basin block fault identified along DSS profile (Kaila et al., 1981).

The studies using high resolution H/V spectral records from the region using area specific shear wave velocity model and borehole records would capture further local details enhancing the surface topography of Tertiary top as the topography captures relative differences instead of absolute values. The deviation in the new values would fall within its standard deviation (Fig. 5 explains the present case). Such records would give better opportunity to access role of climate and/or tectonics in sculpturing the palaeo surface.

## 5. Conclusion

The present study evaluates the usefulness of the H/V spectral ratio of microtremor investigations. This is a relatively quick, easy and economic method for estimating the thickness of unconsolidated sediments for a given terrain. An equation for a geologically comparable terrain can be recalculated using the average values of Ibs-von Seht and Wohlenberg (1999) and Parolai et al. (2002) and records of H/V measured from the terrain.

The lower reaches of Narmada valley where estimation of pre-Quaternary topography has been difficult due to its wide variation has now been profiled using a non-linear regression equation ($\bar{h} = 102.1 f_r^{-1.47}$). Two significant Quaternary depocentres have been outlined in the lower reaches of Narmada valley. The present discovery is significant as it lies adjacent to ENE–WSW Jambusar–Bharuch margin fault where the presence of shallow gas reservoirs is being exploited.

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