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Shallow surface shear wave velocity beneath the Godavari Rift using P wave seismograms of local earthquakes

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ABSTRACT

The prolonged micro to moderate sized earthquakes in the Indian peninsular shield over the past few decades have been linked with the rift zones and reactivation of pre-existing weak zones. The Godavari Rift is one such active rift situated in the southeastern part of the Indian shield. Moderate tectonic activity and presence of thick sedimentary deposits in this region accentuates the vulnerability due to earthquakes. Since the thick sedimentary layers and low shear wave velocities play a critical role in amplification of seismic waves even from small magnitude earthquakes, determination of shallow shear wave velocity (SSV) assumes importance. In the present study, shear wave velocities in the shallow subsurface are estimated adopting a latest technique that utilises the horizontal to vertical ratios of the local *P* waves. Our results indicate that the shallow subsurface structure is quite variable in the Godavari Rift, with the SSV values ranging between 3.22 km/s and 1.03 km/s. The SSV values obtained in the present study beneath different seismic stations are found to be in good agreement with the near surface velocities obtained from the receiver function technique using teleseismic *P* waves.

Key Words: Godavari Rift, Shallow surface shear wave velocity, Horizontal to vertical ratios, Local *P* waves.

INTRODUCTION

The Indian shield is a mosaic of cratonic blocks bounded by palaeo-rift valleys and mobile belts that localize most of the intraplate seismic activity. Intraplate stresses and seismicity in the Indian shield are strongly affected by the continued convergence between Indian and Eurasian plates. It is widely recognized that the plate boundary regions are vulnerable to large and great magnitude earthquakes and the shield regions within the plate interiors are seismically stable, being either devoid of any major seismic activity or characterized by very long time intervals of earthquake recurrence. However, due to the occurrence of micro and moderate earthquakes in the shield regions over the past few decades, these are now being considered as not so stable. Globally, the intraplate earthquakes are dominantly associated with palaeo-rift zones that are host to large population. Thus, a moderate earthquake in the plate interior can cause huge damage to property as well as life. It is found that the death toll due to intraplate earthquakes is almost double compared to those at plate boundaries (England and Jackson, 2011). Therefore, understanding and assessment of hazard associated with the intraplate earthquakes assumes importance.

The three palaeo-rift zones in the Indian shield namely the Kutch, Narmada and Godavari, have experienced major to moderate earthquakes in the past; the Godavari rift being hitherto less studied. The Godavari rift valley is a NW-SE trending linear belt, about 350 km long and 40 km wide, adjoining the Dharwar craton in the south-west and the Bastar craton in the north-east. The valley is characterized by a history of rifting, sedimentation and block adjustments including uplift and subsidence, since the Archaean times. The basin evolution began with sedimentation during the Archaean and Proterozoic times (Pakhal super group) followed by deposition of the upper Paleozoic Gondwana sediments along a distinctly fault-controlled rift valley zone (Rao et al., 1977). The northern portion of the Godavari valley, the main basin, is connected to the southern segment by a narrow link, which hosts the tri-junction of the Dharwar craton, Bastar craton and the Eastern Ghats mobile belt. Landsat images of the Godavari valley region revealed 110 lineaments ranging in length from 10 to 200 km (Ramana Murthy et al., 1988). The lineaments, mostly of the Archaean period, form two distinct sets: a NW-SE trend predominantly found in the main basin with a transition to the NE-SW trend in the south-eastern part, in the vicinity of the Mailaram high. Evidence from recent seismicity and neotectonic activity in the study region indicated four major faults (Venkat Raju et al., 2003) namely the Kaddam fault (KF), Kinnerasani-Godavari fault (KGF), Godavari Valley fault (GVF) and the Kolleru-Lake fault (KLF) (Figure 1).

The previous gravity, magnetic, active and passive seismological studies in the Godavari basin clearly indicate the presence of a thick pile of sediments (Kaila et al., 1989, Sarma and Rao, 2005, Sushini et al., 2014). Also, recent results of crustal deformation from GPS measurements have indicated high rates of localized deformation, coinciding with pockets of moderate seismicity along the

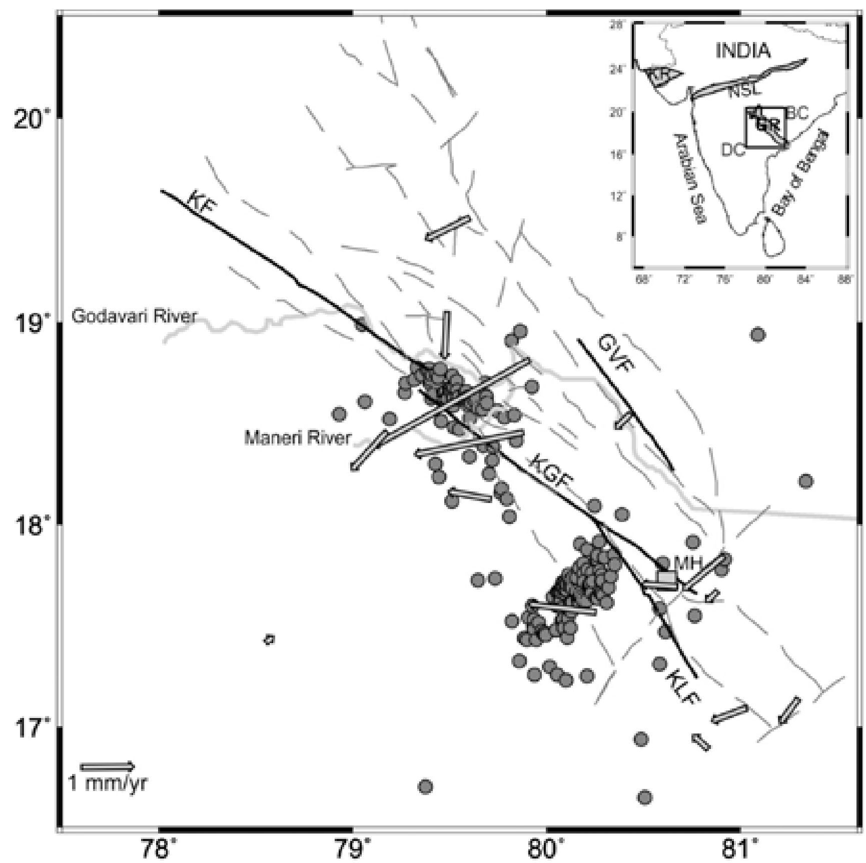

Figure 1. Tectonic map of the Godavari rift zone superimposed with the local seismicity (gray circles, Sushini, 2015) and GPS velocities in the Indian reference frame (Mahesh et al., 2012). Inset: Map of India showing the three major rifts in the peninsular shield and the study region (square). The Godavari fault system is indicated by dashed lines (gray) and major faults are indicated by solid lines (black), MH: Mailaram High (Gupta et al., 2014), KR: Kutch Rift, NSL: Narmada Son Lineament and GR: Godavari Rift, DC: Dharwar Craton, BC: Bastar Craton.

Godavari rift (Mahesh et al., 2012). It is a well recognized fact that thick sedimentary layers and low shear wave velocities play a critical role in amplifying the seismic waves even from small magnitude earthquakes and can lead to vast destruction. Thus, shear wave velocity is considered as one of the essential parameters for evaluating the dynamic behaviour of the soils/sediments in the shallow layers of the earth. In most of the earthquake engineering and various earth science applications, determination of shallow surface shear wave velocity (SSV) is an important task. Although, seismic wave propagation is controlled by the deeper structure of the earth, variations in the elastic properties within the top ten to hundreds of meters often influence the ground motions to a large extent. In the present study, three component waveforms of local earthquakes are utilised to estimate the shear wave velocity of the top sedimentary layer. The shear wave velocities in the shallow subsurface are estimated adopting a latest technique that utilises the horizontal to vertical ratios of the local *P* waves (Ni et al., 2014).

DATA

Data accrued from an array of six broadband seismic stations traversing the Godavari rift in the NE–SW direction and two stations located to the northwest and northeast of this profile, operated by the National Geophysical Research Institute are used in the present study (Figure 2). Except for the permanent station KGD, the other seven stations have been operated for a period of 2 years (2007 and 2008). A total of 230 local earthquakes were recorded during the study period and it is observed that the seismicity is spread over a 200 km^2 area (Figure 1). In the present study, local earthquake waveform data from all the eight broadband seismic stations is utilised to estimate the shallow shear wave velocity. The pre-processing involves the following steps:

a. The seismograms having a clear *P* phase and recorded by all the three components are selected.
b. The selected waveforms are associated with the complete information about the hypocentral and station parameters.
c. The associated waveforms are cut to have a uniform

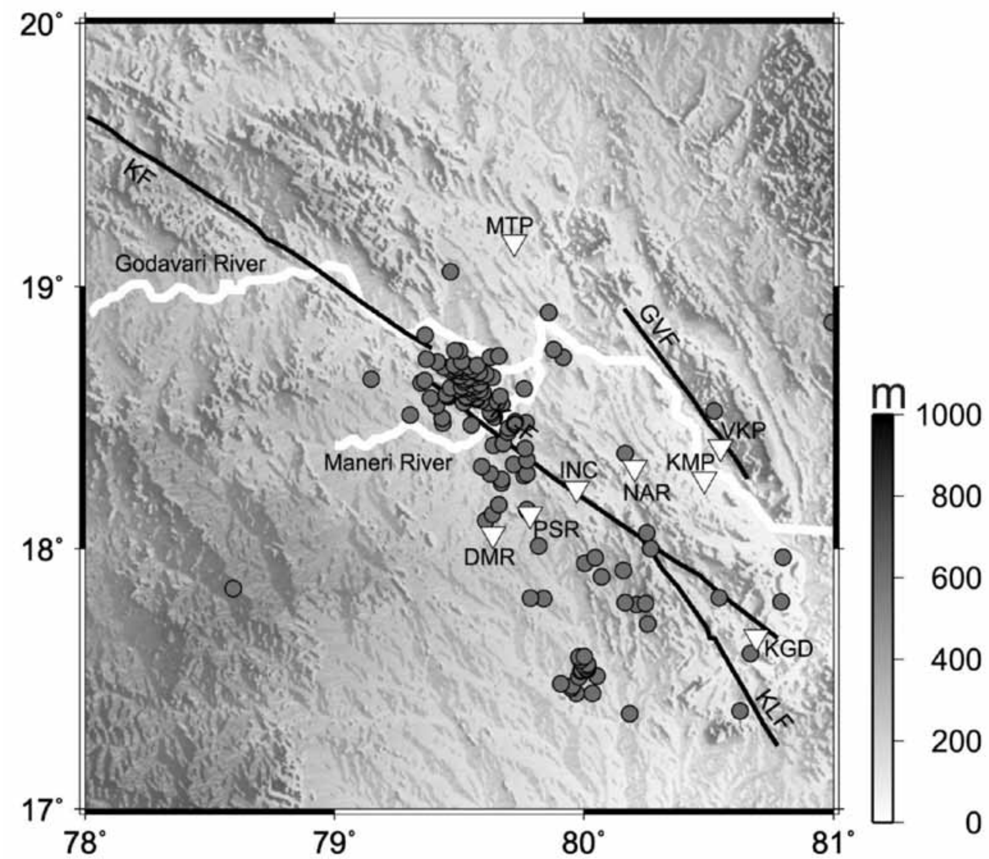

Figure 2. Topographic map of the Godavari Rift and adjoining regions showing the seismological stations (white inverted triangles) operated by NGRI along with the major tectonic features as in Figure 1. Dark gray circles indicate the local earthquakes selected to estimate SSV.

length of 5 seconds starting 2 seconds before the *P* wave onset that is manually picked (Figure 3).

d. The ZNE components of the waveforms are rotated to the ZRT coordinate system using the event back azimuth.

e. Only the waveforms that have good Signal to Noise Ratios (SNR>2) in both the Z and R components are used to estimate the SSV. The SNR is estimated by considering a time window of 2 s after the observed *P* arrival time as signal and 2 s before it as noise on the vertical and radial components. The corresponding SNR is obtained by dividing the mean envelope amplitude of the selected time window of the signal to noise for the vertical and radial components respectively.

A total of 242 radial (R) and the corresponding vertical (Z) component waveforms from 144 earthquakes recorded at different stations constitutes the final database for the present study (Figure 2). The pioneering studies using the R/Z ratios have clearly demonstrated that the vertical *P* waveforms are less sensitive to the subsurface structure (Ni et al., 2014). Therefore, resolving the shallow structure from local waveforms is akin to resolving crustal structure from teleseismic P-receiver functions (Langston, 1989), where the propagation of the vertical *P* wave is assumed to be simple. The shallow subsurface velocity structure from local earthquakes can be resolved with a high resolution since the frequency content of the *P* waves in the local earthquake waveforms is higher (>10 Hz), whereas the teleseismic *P* waves contain frequencies below 2 Hz owing to attenuation in the mantle and scattering due to 3D crustal heterogeneities. Further, the estimation of SSV of top ten to hundreds of meters in the region beneath the station is much simpler and devoid of the interferences or complexities like 3D crustal heterogeneities.

Estimation of shallow shear wave velocity from local *P* waveforms

The crystalline basement of the study area is overlain by unconsolidated sediments. Thus, various seismic phases including the *P-to-S (Ps)* and *S-to-P (Sp)* converted waves are expected to be present in the local earthquake seismograms (Figure 4) (Chen et al., 1996; Langston, 2003). Thus, these converted phases contained in the *P* coda of local earthquakes can be used to estimate the near-surface

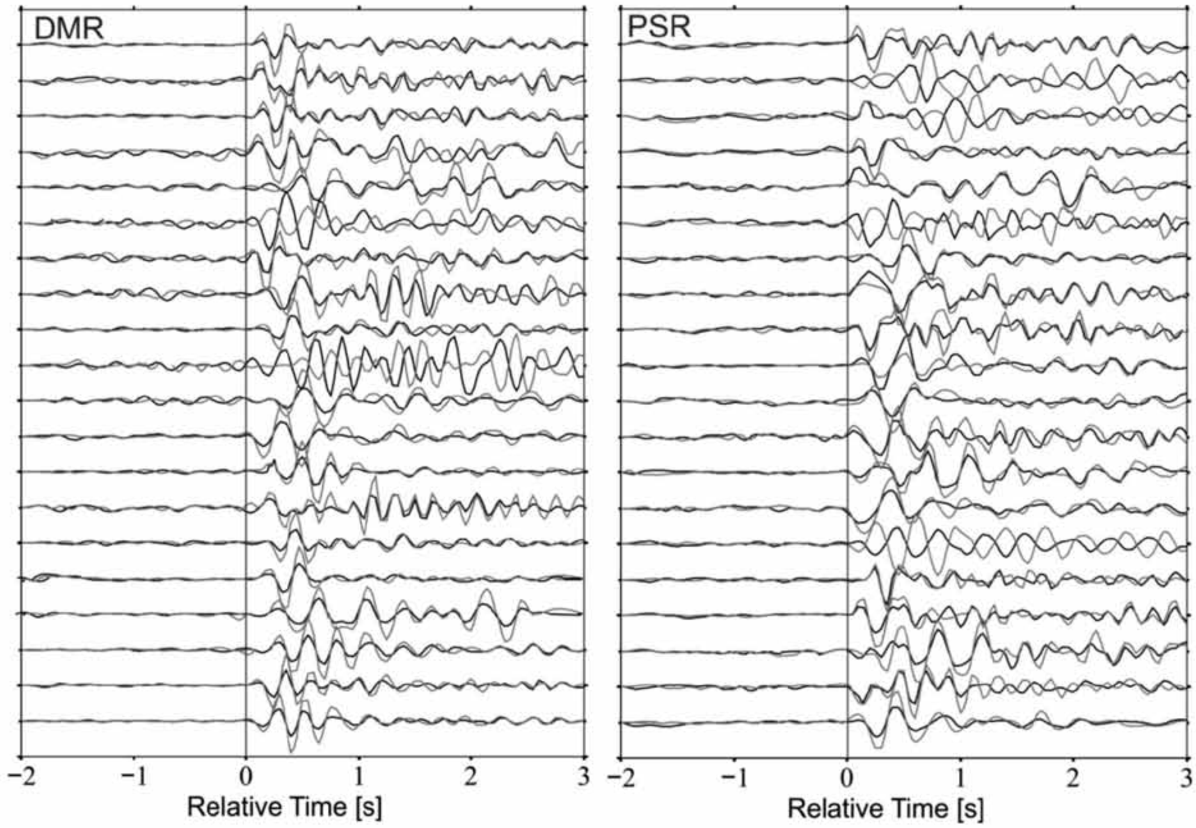

Figure 3. Examples of vertical (black) and radial (gray) waveforms form station DMR (left) and PSR (right). Vertical lines at zero time correspond to the arrival time of the P phase picked manually.

shear velocities beneath the stations. Generally, most of the earthquakes occur in the crystalline basement or the bed rock, where seismic velocities are high. However, in regions like the Godavari rift, the stations that record the seismic waves are situated on sedimentary rocks whose velocities are much lower compared to those in the basement. The incidence angles of the direct *P* and *P-to-S* converted phases near the seismic station are typically much smaller than the takeoff angle at the earthquake source. Due to the steeper ray path, the *P* wave is weaker on the radial component than on the vertical component, and the Ps is stronger on the radial component because its polarization is perpendicular to the ray path and almost horizontal.

For the incoming *P* wave, the ratio of radial to vertical component of the particle motion depends mostly on the shear wave velocity of the medium in which the wave travels and the ray parameter (horizontal slowness). Therefore, the subsurface shear wave velocity, which is directly proportional to the ratio of the R to Z can be measured when the ray parameter "*p*" is known. The particle motion of incoming *P* wave on the R, T, Z components is defined by the following equation (Aki and Richards, 2002).

$$U_R, U_T, U_Z = \frac{\left[\frac{4\alpha p}{\beta^2}\frac{\cos i}{\alpha}\frac{\cos j}{\beta}, 0, \frac{-2\alpha}{\beta^2}\frac{\cos i}{\alpha}\left(\frac{1}{\beta^2}-2p^2\right)\right]}{\left(\frac{1}{\beta^2}-2p^2\right)^2+4p^2\frac{\cos i}{\alpha}\frac{\cos j}{\beta}} \tag{I}$$

Where, U_R, U_T, U_Z are the radial, tangential, and vertical components of the particle velocity at the free surface; α is the subsurface compressional wave velocity; β is the subsurface shear wave velocity; *p* is the ray parameter ; *i* and *j* are the incidence angles of the *P* and *S* waves respectively. The R/Z amplitude ratio at the free surface can be represented as

$$\frac{U_R}{U_Z} = \frac{-2\beta p\cos j}{1-2p^2\beta^2} \tag{II}$$

From equation II it is clearly evident that the ratio U_R/U_Z is proportional to the subsurface shear wave velocity, ray parameter and the angle of incidence of the *S* wave (Li et al., 2014). Further, the term *cos j* that can be expressed as

$$\cos j = \sqrt{1-p^2\beta^2} \tag{III}$$

is close to unity, due to low shear wave velocity near the free surface. The amplitude ratio (R/Z) and the ray parameter (*p*) can be determined from the local *P* waves.

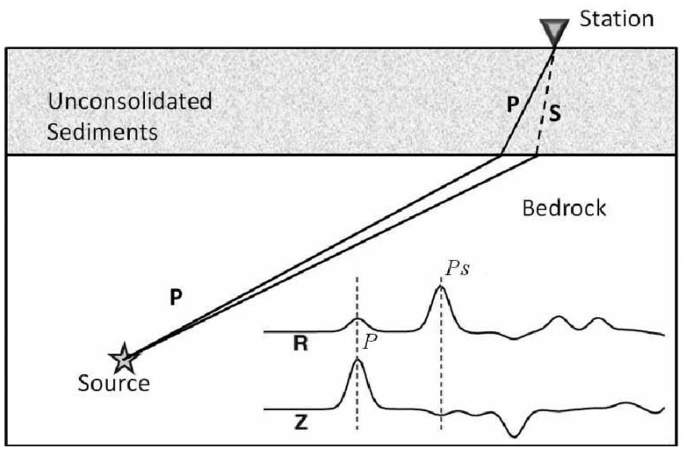

Figure 4. Schematic representation of the travel path of the *P* wave and the *P-to-S* converted phase (*Ps*) from the interface between the unconsolidated sediment and bedrock. These phases on the radial (upper trace) and vertical (lower trace) components are also indicated (modified after Ni et al., 2014).

These form the input to estimate the shallow shear wave velocity (β) after incorporating equation (III) in (II) and writing

$$\beta = \frac{1}{p}\sqrt{\frac{1-\sqrt{\frac{1}{1+(\frac{U_R}{U_Z})^2}}}{2}} \tag{IV}$$

Equation II demonstrates that the ratio of radial to vertical (*P*) amplitudes is sensitive to the subsurface shear wave velocity, so this ratio (R/Z) can be estimated individually from each selected earthquake record (Figure 3) to calculate the SSV using equation (IV). It is evident from equation IV that the estimation of SSV is directly influenced by both the ray parameter (p) and the R/Z ratio equally. Since the ray parameter is calculated using the station and earthquake location, errors in the estimation of location and the bias due to the local crustal velocity model directly affect the errors in estimates of SSV. However, it is observed that small errors in the earthquake location do not greatly influence the slowness parameter (p). It has been observed that a 10 km error in location causes a variation of only 1% in the calculated p (Li et al., 2014). Therefore, the error in the R/Z ratios has a dominant influence on the reliability of SSV estimates. Thus a good SNR on both the R and Z components is essential. Further, synthetic tests reveal that the shear wave velocity is mostly dependent on the subsurface structure and is not very sensitive to the location and depth of the earthquake (Ni et al., 2014). The shear wave velocities are usually dependent on the dynamic properties of soil and rock [soil density, void ratios, soil type, depositional environment, cementation and stress history] (Hardin and Drnevich, 1972). The depth of investigation is the product of the source duration (s) and shear wave velocity (km/s) (Ni et al., 2014). For a local earthquake whose source duration is 0.1 s (typically for an earthquake of magnitude 3), the shear wave velocity estimated from R/Z of *P* is actually the average velocity (β) from the free surface to a depth $h = 0.1 \times \beta$.

RESULTS

The average SSV of the uppermost surface beneath the stations in the Godavari rift estimated from the R/Z ratios of local *P* wave amplitudes vary from 1.03 km/s to 3.22 km/s. The scatter in the obtained SSV values at each station with respect to epicentral distance (Figure 5) indicates a broad variation in the elastic properties of the subsurface geological formations. The shear wave velocities beneath the stations VKP, KMP, MTP, KGD and NAR situated on the Gondwana sediments vary from 1.03 to 2.60 km/s. The SSV value obtained at the solitary station (INC) sampling the Proterozoic sediments is 2.27 km/s. Large values of SSV observed beneath stations DMR and PSR (2.99 and 3.18 km/s respectively) conform to the gneissic basement at the flanks of the Godavari rift, on which these stations are sited. The SSV values obtained truly reflect the subsurface geology as the stations sampling the centre of the rift that are predominantly occupied by sediments are characterized by low shear wave velocities in contrast to the stations sampling the gneissic basement that have high shear wave velocities (light gray colour in Figure 6). A distinct variation in the shallow surface velocity estimates is observed below each station (Table 1), with the depth of investigation varying from 122 m to 322 m.

The previous studies indicated a large variation in the sedimentary thickness values beneath the five stations sited on Gneissic to Gondwana sediments (Sushini et al., 2014). Although our shear wave velocity estimates are representative of very shallow surface layers, it is generally observed that the velocity increases with decrease in

Table 1. Average shallow shear wave velocities at each station, near surface velocities from teleseismic receiver function studies (Singh et al., 2013), their standard deviations, number of earthquakes used and surface geology.

Station Code	Latitude (°N)	Longitude (°E)	SSV (km/s)	NSV (km/s) Singh et al. (2013)	Number of events used	Surface Geology
DMR	18.0548	79.6357	3.22±0.57	3.58±0.44	68	Gneissic complex
PSR	18.1324	79.7835	2.99±0.73	3.56±0.26	120	Gneissic complex
INC	18.2283	79.9713	2.27±0.75	3.27±0.48	4	Proterozoic Sediments
KGD	17.6600	80.6900	1.34±0.27	2.74±0.5	4	Gondwana Sediments
MTP	19.1691	79.7205	1.21±0.21	1.52±0.71	13	Gondwana Sediments
NAR	18.3109	80.2031	1.03±0.31	1.69±0.47	26	Gondwana Sediments
KMP	18.2657	80.4827	1.24±0.22	1.87±0.4	5	Gondwana Sediments
VKP	18.3882	80.5471	2.60±0.19	3.24±0.52	2	Gondwana Sediments

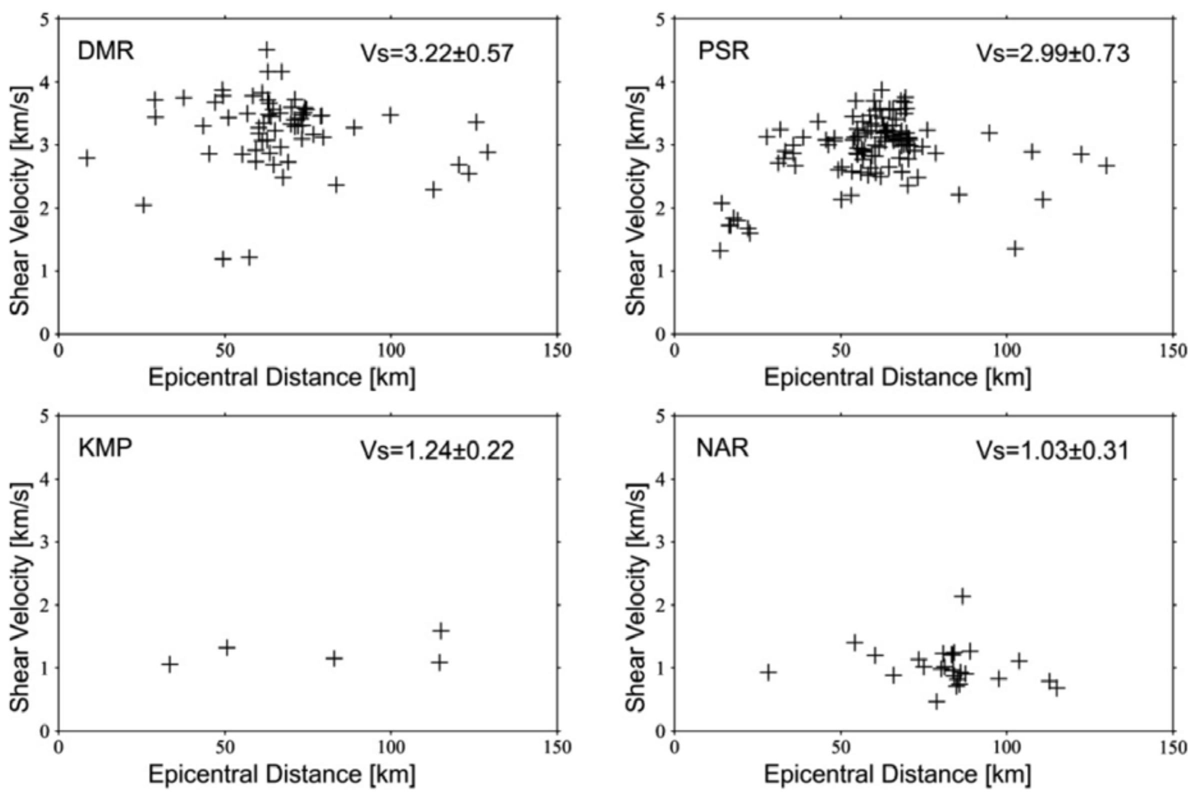

Figure 5. Examples of the estimated SSV values with respect to epicentral distance for stations DMR, PSR, KMP and NAR. The mean and corresponding standard deviation values (in km/s) at each station are indicated at the top right.

the sedimentary thickness. However, station VKP that overlies thick sediments and reveals high shear wave velocities similar to observations from teleseismic studies (Singh et al., 2013), is an exception. Singh et al. (2013) utilised teleseismic *P* waveforms from the same stations to calculate the near surface shear wave velocities (NSV). This provides an opportunity to compare the results obtained from the present study using the local *P* waveforms with those from teleseismic waveforms. The SSV values at each station obtained in the present study are comparable with the NSV values obtained by Singh et al. (2013), thereby lending credence to the results obtained (Table 1). Also the

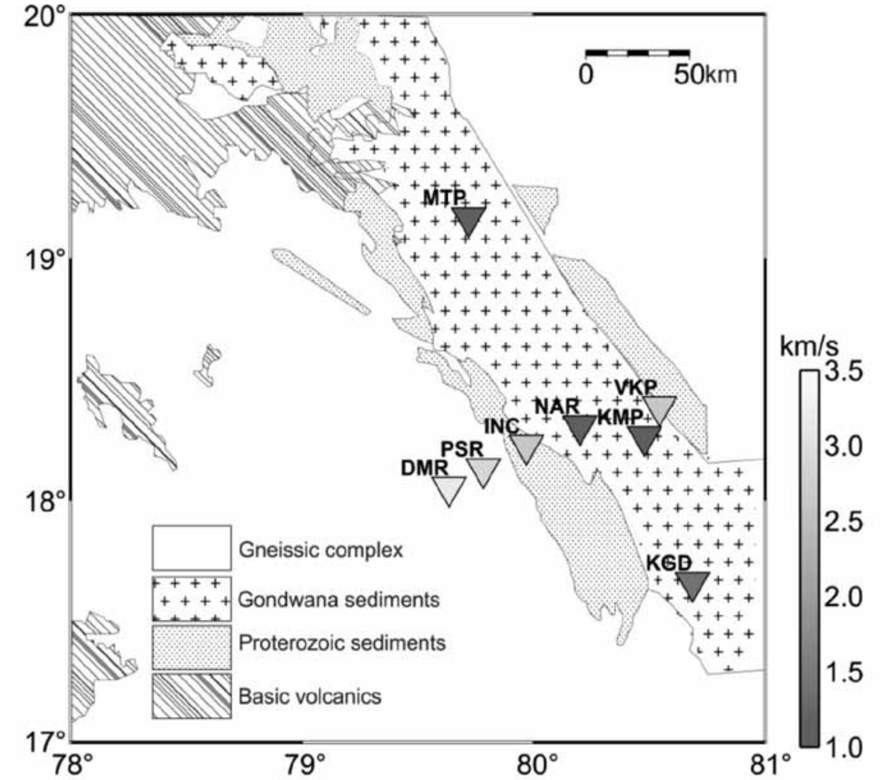

Figure 6. The estimated average shallow shear wave velocities (in km/s) at each station colour coded according to the values, superimposed on the surface geology.

obtained SSV values correlate with the shallow subsurface geology of the region.

CONCLUSIONS

Estimates of SSV using the ratio of Radial and Vertical components of local *P* wave seismograms provide constraints on the subsurface structure. Results from this study reveal that:

i. the shallow subsurface structure is quite variable in the Godavari region, indicated by the variation of SSV values between 3.22 km/s and 1.03 km/s.
ii. the SSV values are much larger beneath the stations on the Gneissic complex compared to those sampling the Proterozoic and Gondwana sediments (Figure 6).
iii. the SSV values obtained in the present study beneath different seismic stations are in good agreement with the near surface velocities obtained from receiver function technique using teleseismic *P* waves (Singh et al., 2013) (Table 1).

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