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Challenges in Processing of Multi Azimuthal, Multi component Offset VSP data in a deviated well of Kuthalam area of Cauvery Basin, India.

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Summary:

Multi azimuthal offset VSP surveys are popular choices for instantly generating cost effective seismic images around the borehole which are very effective in mapping the lateral extension of the pay sands. The processing of a fixed offset three component VSP data in a deviated well is a difficult task due to various reasons like, absence of gimble mounted well geophone, rotation of well geophones (tool spin), inconsistent coupling between formation geophone sensors, inadequate energy sources & survey geometries, low foldage besides lack of adequate processing software. Three component offset VSP surveys oriented along different directions, recorded P & S waves in a deviated well in Kuthalam field which were processed to generate sections /images around the well.

The present study deals with the processing of multi component VSP data providing deliverables of P & S wave sections/images besides P & S wave velocity attributes. The scope of applications of VSP deliverables is also addressed. The integrated use of petro physical data, (well logs) & VSP corridor/bin stack has immense importance in precise calibration of 3D seismic data. The shear wave velocity and Vp/Vs ratio are additional attributes to predict lithological information and simple anisotropic models along the survey directions.

Introduction:

Cauvery basin is pull apart Basin situated in the east Coast of India. It produces hydrocarbon (oil & gas) from sediments of early Cretaceous to Oligocene age Kuthalam Field is located in the flanks of Kumbakonam-Madanam ridge. The sands within Andimadan Formation are gas producers in this field. The deviated well "L" was drilled to probe the oil and gas prospects within Andimadan Formation. Multi azimuthal fixed offset VSP surveys were conducted (Fig-1a) to find out the lateral extension of the Oil & Gas bearing sand encountered within Andimadan little above the basement.

The data was acquired using explosive as energy source without validating the survey direction by any pre-survey modeling. The absence of data especially sensed by geophone sonde within deviation trajectory, witnessed obstruction to transmitted beam causing drastic foldage gap was evidenced at various segments along some profiles. The presence of mode converted shear waves at different depths, the inadequate receiver intervals and the greater source-well offset distances, also posed serious problems. In fact, these factors complicated the important jobs of VSP data processing e.g., wave field separation, HODOGRAM analysis for tool spin correction etc.

Source generated shear waves could be identified with confidence in rotated radial component of VSP data, derived after tool spin correction. The First break pick of shear waves could be validated using FD modeling program. The P-wave & shear wave velocity attributes were computed and VSP-CDP sections/ images were generated to derive subsurface structural information around the well in various directions. The integrated display of well logs, synthetic seismogram & VSP-CDP stack were displayed. Anisotropic velocities were computed after applying the slant path correction to First Break times (F-B) for each Offset directions. This modifies the actual source offset F B time to projected zero offset F B times for P waves & S waves for anisotropic velocity computation along survey directions. The simple anisotropic variations (models) along three major survey directions are illustrated.

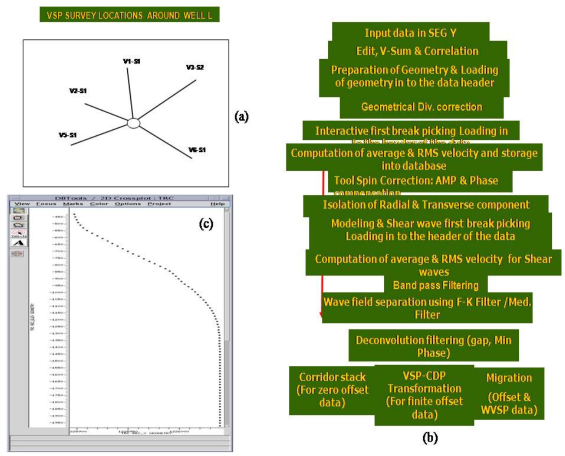


Fig-1 Scheme of VSP surveys around well "L", Deviation Trajectory after loading geometry & Standard Processing Flow.

Methodology:

The processing of vertical component data (P-wave) was carried out using a standard work flow (Fig-1b) usually practiced in Industry. The various attributes of the deviation data (supplied by the drilling crew) was coded in the spread sheet and CDP binning was performed and after saving in data base, the geometry was loaded in the header of each data sets. The well trajectory derived from database is shown in figure- 1c. The different velocity attributes namely average velocity; RMS velocity and Interval velocity (Fig-2) were computed. The amplitude recovery, wave field separation & VSP-CDP transformation followed in sequence. The corridor stack & VSP CDP stack of Zero offset VSP data & correlation with surface seismic is shown in Fig-3.

For horizontal component data, the matter was not so straight forward. The rotation of down hole tool causes distortion of amplitude & phase in X & Y component data (Fig-4). The down hole tools used in recording the data did not have the facility of measuring the orientations while recording. Application of "Tool Spin" correction is mandatory.

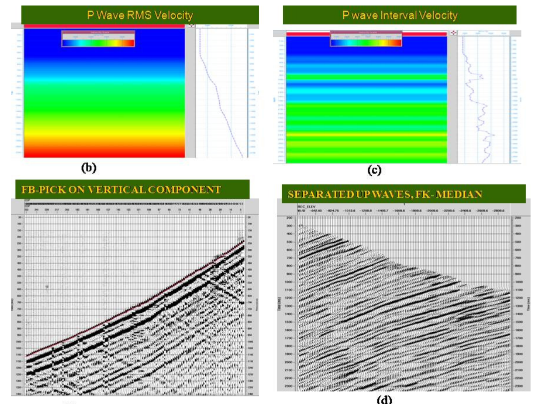


Fig-2 RMS & Interval Velocity Input & separated up waves

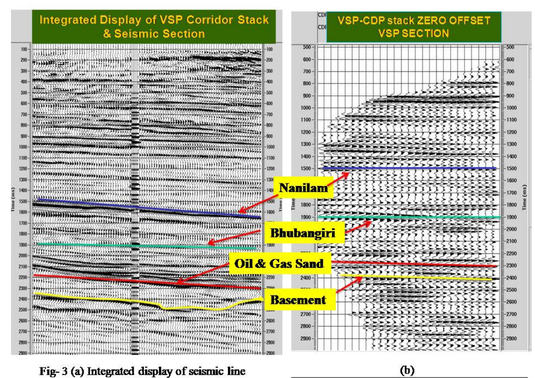


Fig- 3 (a) Integrated display of seismic line through well & VSP Corridor stack

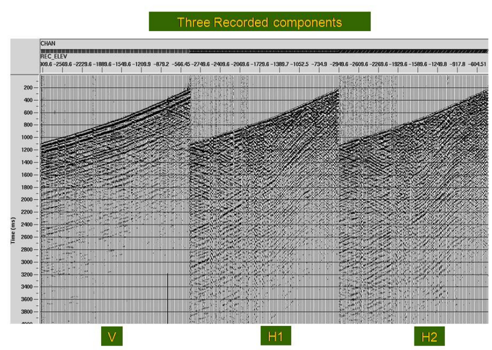


Fig- 4 Three recorded components : Input for Tool Spin correction

Tool Spin Correction:

The X & Y directions of the sensors, are not uniform, at each receiver depths due to rotation of the sonde; but may occupy different positions in horizontal planes distorting the recorded signals. Hodogram analysis of two horizontal components (H1 & H2) using the horizontal projections of the direct arrival along a survey direction provides the polarization angle at each depth along which the energy maximized (Fig-5). The analysis ensures the reconstruction of the Radial H Hθ (in source –receiver plane) and Transverse component Hμ (orthogonal to source- receiver plane) data sets preserving the amplitude and phases of the of P & S wavelets (Fig-6a). Later, rotation in vertical plane, using Vertical component & Radial component as inputs which gives Rotated vertical Vφ & Rotated Radial components Hθφ (Fig-6b). The P & S wave energy are more focused in these two components Vφ & Hθφ which are used in subsequent phases of work flow to derive final products VSP-CDP trans formed sections and Migrated sections (images).

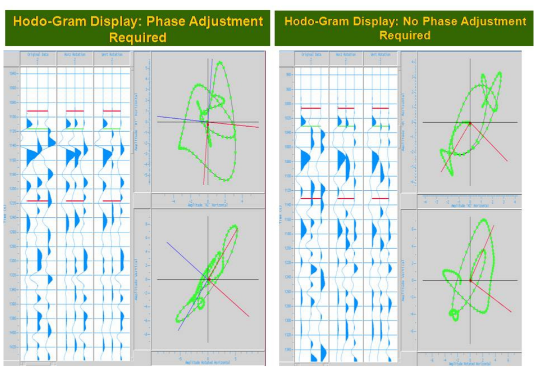


Fig-5: Hodo Gram Display for Energy maximization Technique: Tool SPIN correction

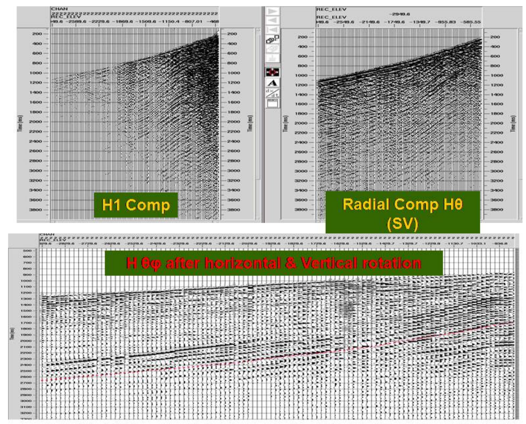


Fig-6 Enhancement of shear wave signal after tool Spin Correction
Input H θφ after horizontal & Vertical rotation : Uncertainty in FB Picking

True Shear Wave First Breaks:

The wave field in rotated Radial comp. data in Zero offset VSP data, exhibits focused shear wave energy appearing from various depth besides source generated shear waves. The interpolation (Gradient) of one "Shear Wave" cycle from zero VSP data meets almost zero depth (well head-Kelly Bush) as shown in figure-7. This is first indication of the presence of source generated Shear down wave energy (First break) in the recorded data. However, non availability of Shear wave well log (Dipole sonic/ Array seismic imager) is a constraint for cross checking the shear wave velocity estimated from VSP data in this case. The presence of down going multiples of Shear waves in the closer vicinity of the first down wave arrival complicates the identification of true first break pick which is very crucial for further processing, especially for distant fixed Offset survey.

To validate First Breaks of shear waves in case of zero VSP data and to identify the genuine First breaks of shear waves, in Offset VSP survey, the Finite Difference modeling was attempted and synthetic shear waves (primary) were generated using the shear wave interval velocity derived from zero VSP data. The first break times of synthetic data were used for identifying the real First arrival of Shear down waves in radial component data (Fig-8). The noises present in shear wave data of radial component were cleaned by applying FK filter and focusing down wave energy. This technique of identification of First shear wave arrival, is an important QC and followed for each offset profiles, immediately after tool spin correction (Fig-8). Shear wave velocity field (RMS and Interval velocity) were recomputed with refined genuine first breaks (Fig-7). The SV (Shear wave) RMS velocity was used to apply the geometrical divergence correction.

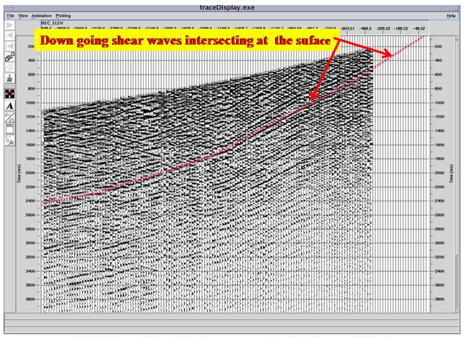


Fig-7: Source Generated Shear wave originating from well Head

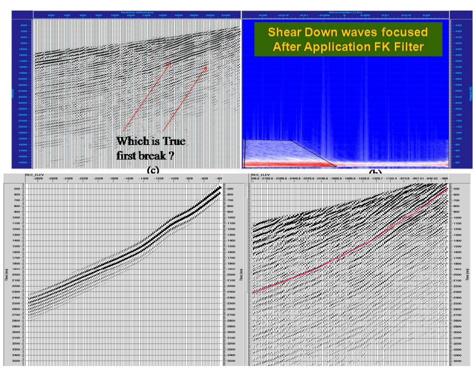


Fig.-8 Shear Wave First Braek Picking taking the help of FD Model (Synthetic response)

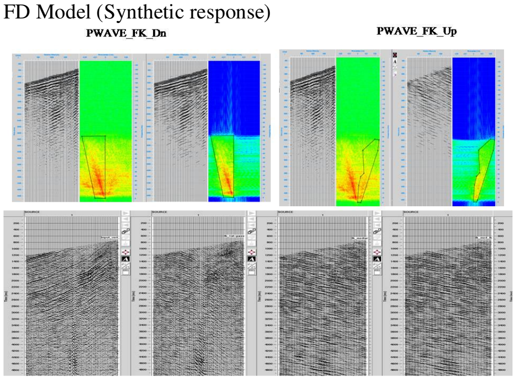


Fig-9: Scheme of separation FK-MED_FK

Wave Field Separation:

Wave field separation is the process of isolating one of the two interfering wave fields (up waves & down waves) in VSP data which always occur at equal & opposite dips. Usual tools are FK filter as dip & wave number filter (polygon), Tau-p filter, Median filter and linear subtraction filter. The key issues for any separating process are prevention rather minimizing of the spatial aliasing and the non distortion of the wavelet shape preserving the true amplitude. In this case of deviated well and multi component data the problems are not straight forward. Four wave types namely P down, P up, S down and S up waves are the events to be separated and one type is noise to the other type. FK filters (polygon method) in accept and reject mode along with median filters (two pass) were judiciously used for separation of P and SV reflected waves. Extensive QCs were done to ensure separation free from aliasing & distortion (Fig-9).

Vsp-Cdp Mapping & Migration:

VSP CDP transformation gives us the CDP equivalent stack sections in x-t domain using conditioned up waves recorded in z-t domain. Since the reflectors around the well have gentle dip, the simple interval velocity model derived from zero VSP data was used in VSP CDP mapping. The bin interval was kept 15-20 M, ray trace interval kept 10 M. The process gives mapped NMO corrected events corresponding to every bins falling at the respective receiver trajectories. Common ensemble stacking was performed to get VSP-CDP section which was further cleaned using FX de-convolution and median filter. The P & S wave sections VSP-CDP stack and images Migrated output in depth scale are shown in Fig-10. The sections show the reflections corresponding to different stratigraphic horizons and the oil & gas bearing sand.The attitude (structural trend) of the reflections match reasonably well with their counter parts in seismic sections along the survey directions (Fig-11). Because of the higher temporal and spatial resolution minor faults are very clearly visible in VSP sections which are very important in reservoir studies. The data loss (Foldage gap) was noticed in sections of offset profiles OV-2, OV-6 and OV-5 which is expected due to non uniform well trajectory caused by the drilling process in a deviated well (Fig-12).

Kirchhoff, Migration was applied in 2D sense, to derive depth images along the survey directions on conditioned up-going wave fields of P and S waves using the same interval velocity The Eiquonal equation option was chosen for travel time computation during migration execution. Migrated images were also cleaned following post stack conditioning. The migrated images were not affected by data gaps because of inherent nature of data interpolation available with the migration algorithm (Fig-10 c, d).

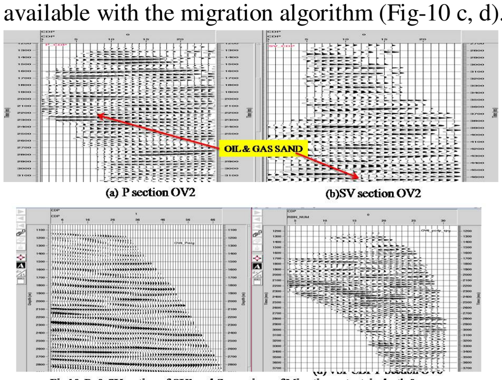


Fig 10: P & SV section of OV1 and Comparison of Migration output in depth & VSP CDP stack (P wave) OV6.

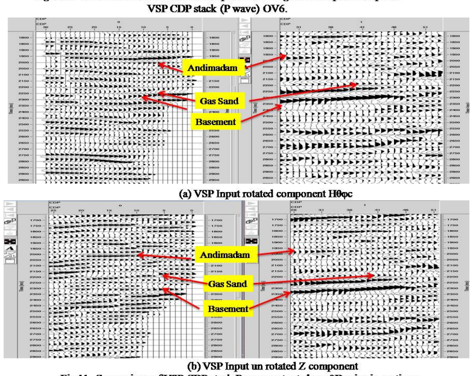


Fig 11- Comparison of VSP CDP stack P wave output along 3D seismic sections

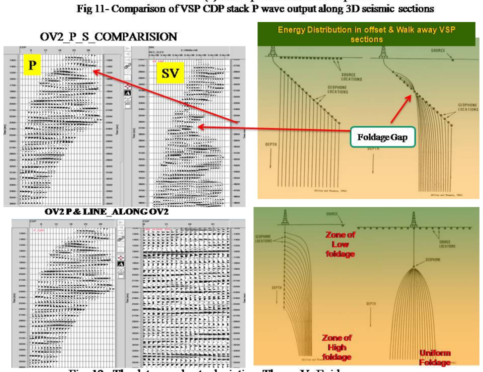


Fig- 12 The data gap due to deviation :Theory Vs Evidence.

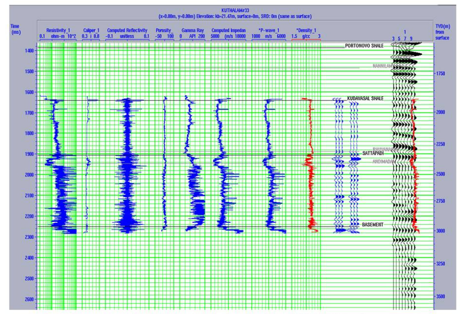


Fig 13 Integrated display of well logs& VSP CDP stack

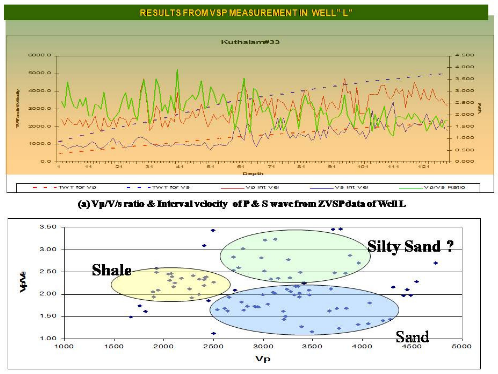
Application of P- and Sv- Wave Attributes for Reservoir Studies:

A. Calibration of seismic signature and lateral extension of pay/sand/event of interest:

The deliverables of Multi component VSP data are VSP-CDP sections /migrated outputs in depth domain (images) & Velocity attributes of P and S waves. The common application is TD conversion of seismic data & utilization of deterministic velocity function of P and S waves.

Integrated correlation of well logs (namely Resistivity, Gama Ray, Porosity, Density etc.) with VSP CDP stack is illustrated in fig-13.The well reflections within Nannilam, Bhubangiri, & Andimadam Formations are visible in VSP-CDP stacks are conformable with the boundaries showing contrast in petro-physical properties in well log display. Nannilam & Andimadam top are strong reflections in 3D seismic as well as VSP section. The event corresponding to Bhubangiri top is a strong cycle in P wave VSP section, though weak in 3D seismic. This prominent illustration of seismic in P wave VSP, is due to noise free environment within the well and higher temporal and spatial resolution inherent with VSP data.

The hydrocarbon bearing sand, within Andimadan Formation (above basement) occurring at 2950 M (2260 M sec) and the reflection corresponding to basement can be chased in sections of various offset profiles and can be mapped in work stations using suitable application software (which are not available with us) for further reservoir delineations.



(a) Vp/V/s ratio & Interval velocity of P & S wave from ZVSP data of Well L

Fig-14 Lithology estimation using Vp/Vs ratio (b) Cross plot of Vp /Vs & Vp

B. Lithology Estimation using P & SV Velocity:

The eminent researchers namely, Pickett, Tatham, Toksoz carried out extensive

Seismo-acoustic modeling in laboratory, on the use of P and S wave velocity attributes & Vp/Vs ratio for prediction of porosity, lithology, gas saturations and Lithology crack spectra, within reservoir, simulating confining pressure (Overburden Pressure). They prepared master curves (Pickett & Tatham) for lithology prediction using Vp/Vs values. According to Picket diagram, the Vp/Vs value ranges 1.65 - 1.75 for sandstones; 1.85-1.95 for lime stone and 2.0 -3.0 for shale, Under usual confining pressure at that depth.

Attempt has been made to calibrate the observed lithology in the well "L" despite the limitations of our data (Neither densely sampled data nor pure Shear wave source is used for acquisition). Table-1 show, the observed Vp/Vs values against the respective formation encountered in well "L". The values are consistent and matching with the values of Pickett diagram. A cross plot of Vp/Vs against Vp shows segregation of probable sand-shale & silty sand (?) population Fig-14. Similar exercise along offset survey directions will provide very important inputs for assessing lithology of any proposed development location away from the well, using the results of Multi azimuthal Offset 3 Component VSP surveys.

TABLE-1: Lithology --- Vp/Vs Chart

Formation	Vertical Depth (Top)	Lithology	Vp/Vs
Karaikal Shale	1014	Shale,Siltstone & Sandstone with traces of Limestone	2.15
Kamalpuram	1292	Shale with minor Sandstone & Siltstone	1.94
Portonovo Shale	1547	Shale,Sandstone & Siltstone	2.27
Nannilam	1709	Shale,Siltstone & Sandstone	2.06
Kudavasal Shale	1956	Shale	2.17
Bhuvanagiri	2358	Sandstone and Shale	1.59
Sattapadi	2389	Shale	1.71
Andimadam	2448	Sandstone and Shale	1.91
Basement	3014	Weathered and Fresh Basement chips	
	3060	Drilled Depth	

C. Anisotropic study using P & SV velocity:

Anisotropy causes the changes in physical property say seismic velocity either along direction or in polarization of travelling waves. As reported in literature, platey clay fragments (preferentially, aligned by gravity during deposition) produce anisotropic shale rocks. At the sedimentary scale, interleaved sand, silt and shale units produce anisotropic formations. Under this situation, the horizontal velocity usually exceeds vertical velocity. The polar anisotropy, which is caused by layering is most commonly encountered and strongest which can distort structural mapping beneath anisotropic layer e.g. massive shale body.

As told, earlier the anisotropic velocities were computed after applying the slant path correction to First Break times (F B) for each Offset directions. This modifies the actual source offset F B time to projected zero offset F B times for P waves & S waves for anisotropic velocity computation along survey directions.Three Survey directions OV1 (along north), OV5 (along south west) and OV6 (along south east) were preferred for analyzing, P and S wave anisotropic velocity (Fig-15).The percent difference between the largest and smallest velocities is the measure of anisotropic intensity. The velocity variations along above mentioned survey directions are compared. The anisotropic variation in case of P waves is significant within Portonovo shale & Nannilam Formation, 14% velocity variation (from minimum to maximum value) and within Sattapadi shale 16%. The shallower formations & Andimadam shows smaller velocity variation of 6%. However S wave anisotropic velocity also supports the above observations with stronger anisotropic variation (Fig-15) within Sattapadi Formation (53%), and Portonovo--Nannilam Formation (35%). Andimadan Formation shows

20 % velocity variations. The intensity of anisotropy extends from SW to N & NE direction. This is an interesting observation and requires 3D shear seismic survey for confirmation of this anisotropic behavior and identification of fracture pattern for further studies.

Conclusion:

The processing of 3 component VSP data in a deviated well is a challenging assignment especially in absence of adequate processing software. The results of P wave sections (the structural trends of the reflectors) are comparable with the RC sections of 3D volumes along the survey directions. Shear wave sections cannot be compared in absence of Surface Shear seismic data. But VSP sections are crucial inputs for further reservoir studies.

The Vp/Vs ratio also conform well to the encountered lithology in well "L" and similar exercise can be useful to predict the lithofacies, away from the well (to validate any proposed drilling locations in the neighborhood of the well "L"). The anisotropic model is brought out using the anisotropic velocity analysis along the survey directions which may be helpful for correcting the velocity field in order to prepare an accurate depth map, if necessary.

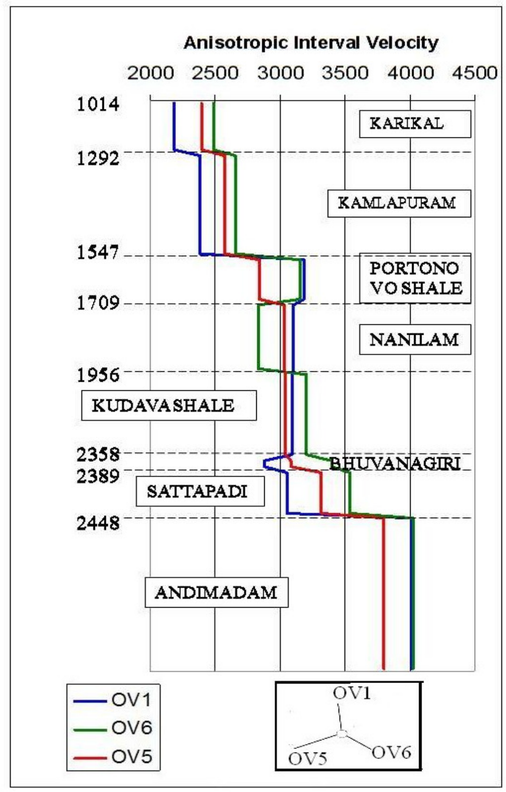


Fig. 15 (b) Anisotropic SV velocity along survey directions

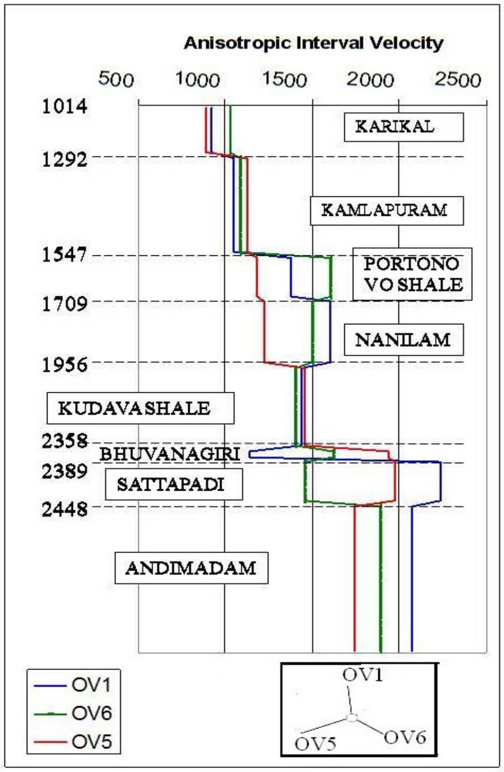


Fig. 15 (b) Anisotropic Sv velocity along survey directions

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