



Mixed Mode Depth imaging and Partial Wide-angle imaging: Immense opportunities to explore sub-basalt reservoirs.

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Abstract:

The Mesozoic reservoirs below basalt (Sub-basalt province) are prolific producers in many exploratory basins namely, Kutch and Saurashtra offshore of Western offshore basin, the Faeroes-Shetland Basin in North Sea and many others. The seismic imaging has major stake holding in identification of entrapment conditions within Mesozoic, below basalt. The regular PP imaging (using streamer data) may not be amenable for accurate subsurface mapping. The poor signal penetration through basalt section, masking of signals with multiples and presence of converted waves namely PSP, PSPP and PSSP are some of the serious impediments.

The mode converted PSSP (symmetric waves) waves are found to be generated from basalt top (existing up to an offset distance of 8 Km +) duly validated by elastic modelling with synthetic responses. The PSSP waves were segregated in slowness domain and reflected PSSP signal was enhanced. Proper velocity estimation (RMS and Interval) could be achieved to perform time and depth imaging of PSSP waves. Mixed mode depth imaging was evolved summing PP and PSSP depth gathers which provides productive viable option for more precise structural interpretation for mapping of sub-basalt reflectors.

The partial wide-angle imaging was also carried out to retrieve signal from higher offsets (12 Km as available in data) using a simple processing technique without applying front-end mute. The deeper events below basalt (imaged using the offset range 4-12 Km) were prominently brought out. Both the methodologies (Mixed Mode Imaging and partial Wide-Angle Imaging) will aid the structural interpretation appreciably.

Introduction:

The present study was conducted using seismic data in Kutch Saurashtra shallow water of Indian west coast. Figure-1 shows the location map. Northern part of the study area has a very shallow water depth (30

m or less). Discovery of hydrocarbon was reported in Mesozoic below basalt (which is locally known as Trap) as well as in tertiary above trap.

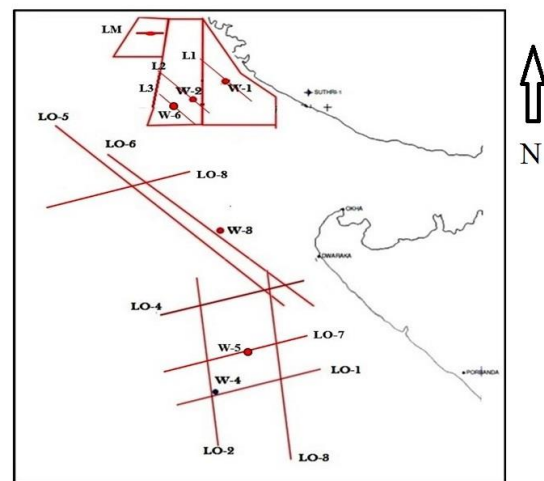
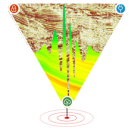


Figure-1: Location map showing the pilot lines. Lines L1- L3 (within 3D campaign processed in 2D sense), L stands for line, W for well, LO for Long offset 2D seismic lines. 3D survey bin size 6.25X25 M. Maximum Offset 5400M. Processed with 12.5 X25 M (Inline interval 25M, X-line /CMP interval 12.5M). 2D lines are Long offset lines of 12 km (LO series) streamer length. Two lines trending NW-SE joining the southern part of Saurashtra offshore with Kutch offshore. Remaining 6 lines are falling south of Saurashtra offshore covering the prominent basement feature Saurashtra arch. CMP interval 6.25 M.

Barzaghi et al, (2003) used MIP (Modelling Interpretation and Processing) to identify converted waves, namely PSSP, PSP and PSPP etc. from different horizons. Depth imaging of converted waves have been reported using estimation of Converted wave velocity scaled from PP interval velocity (scaled by V_p/V_s ratio as 1.7) by Brown et al, in 2001. Van der Baan et al., 2003 did imaging of



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PSSP waves and illustrated the events corresponding to different sequences in the section.

In present study The PSSP waves have been isolated in slowness domain, using real data (shot gathers of streamer data), adopting a suitable process and velocity has been estimated.

Evidences of Mode converted waves:

While processing 3 component VSP data of one well, W-5. radial component (after tool spin correction) exhibited P-S mode conversion from basalt top (Figure-2a). These P-S waves may generate reflected PSS waves which when encounters Basalt (in reflection mode) may provide PSSP waves. Unpublished ONGC processing report also shows the probable presence of PSSP waves in a test processing of 3D data (Figure 2b).

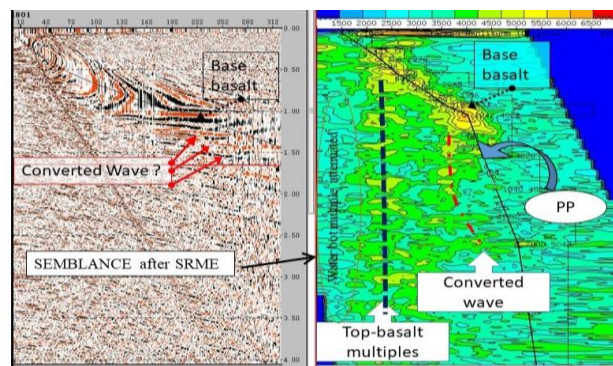
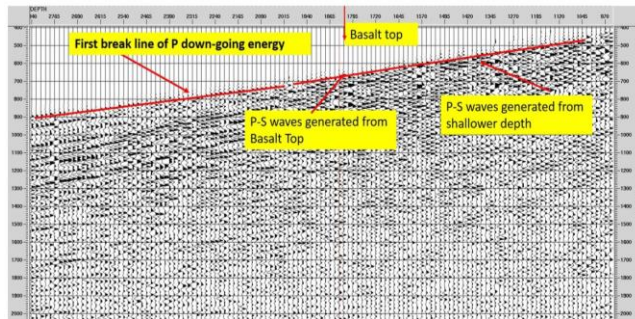


Figure 2(a) top: radial comp. of VSP data after tool spin correction which weakened P-waves (First arrival) and focused P-S waves generating from Basalt top. Figure 2(b) at bottom shows velocity semblance after initial stages of processing of 3D data. Probable presence of Converted waves from basalt top may be available in data.

Elastic modelling for confirmation of PSSP waves:

One dimensional geological model is shown in Figure 3(a). This is input for carrying out elastic modelling (done using MATLAB software with some inbuilt functions available in CREWES toolbox). The other inputs are BHC sonic log, density log and shear sonic logs (DSI logs) of the well W-5 well (left panel of figure 3-b). The modelled outputs confirm that generation of PSSP waves from basalt top may be possible. The right panel of Figure 3(b) shows plots of reflection coefficients vs offset diagram. The PSSP waves, though weak, could be visible within offset range from 2 Km to 8km plus offset. Synthetic gathers of PP, PSSP and another symmetrical mode converted wave PPSPP, derived from modelling exercise, are also displayed in Figure 3(c). These model responses provide crucial insights towards the occurrence of different waves which are helpful in later stage of segregation of PSSP energy.

The direct arrival and reflections corresponding to different horizons (as incorporated in input model) namely Eocene top, Paleocene top, Basalt top, basalt base and some sub-basalt horizons are clearly seen in PP synthetic seismogram (gather). In PP section a strong multiple is generated from basalt top is also visible which is intersecting one sub-basalt event at an offset of 4000 m. The sub-basalt event is originating from 4.8 s in PP section. The same sub basalt event is appearing at 5.5 s in PSSP synthetic seismogram and intersecting multiple from basalt top at an offset of 6000 mt. The basalt base is strong, at 2.5 s in PP section where as in PSSP section, same basalt base is appearing later because PSSP waves are slower than PP waves and it is reasonably strong in PSSP gather. There is no change in the onset time of multiple events, appearing from basalt top in PP and PSSP synthetic gathers.

Horizon	Depth (M) MSL(36)	Vp (M/sec)	Vs (M/sec)	ρ (gm/cc)
Water bottom	30	1500	866	1.9
Early Miocene	772	2700	1558	2.23
Early Eocene	1645	2900	1674	2.27
Paleocene	1748	3050	1760	2.30
Trap Top	1923	3224	1900	2.33
Trap Base	4204	4826	2584	2.57
Bhuj Top	4323	3661	2417	2.58
Gas sand	4480	5061	3090	2.53
Late Jurrasic	4750	4816	2980	2.50

Figure 3(a): One dimensional geological model passing through well W-5.

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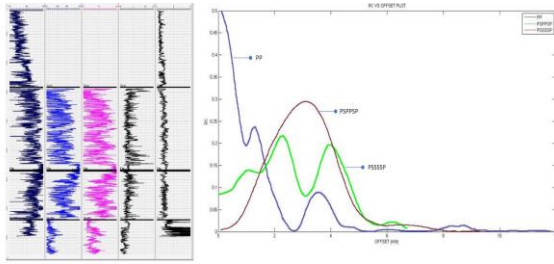


Figure 3(b), The left panel shows input logs sonic, density, DSI, Resistivity etc., of W-5 well. The right panel shows Reflectivity vs Offset diagram (X axis). The blue color for P waves, green for PSPPSP waves and red color representing curves for PSSP wave. It is interesting that PSSP waves may occur within offset range 1.5 Km to 8 Km plus offset.

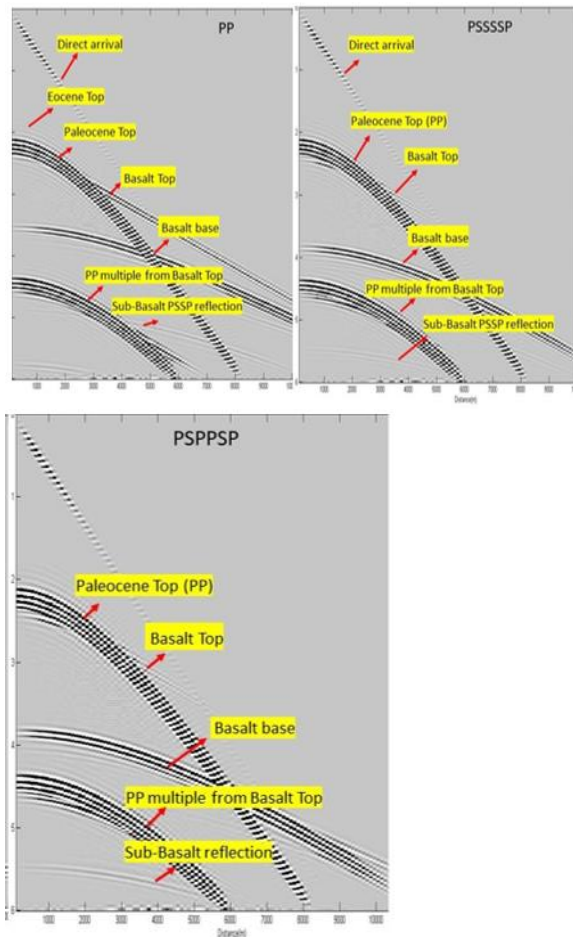


Figure 3(c): The synthetic responses derived from model are displayed for PP, PSSP and PSPPSP waves from different interfaces as mentioned in input model.

Isolation of PSSP waves:

The flowchart explaining the segregation, conditioning of PSSP waves and the sequences of Mixed mode depth imaging is mentioned in Annexure-1.

Mode converted PSSP waves are very weak energy and it is very difficult to segregate PSSP waves from strong PP waves and noises. At the first phase of the study, PP time imaging and depth imaging of 2D pilot lines were performed by efficiently de-noising in shot, CMP, and offset domain. Multiples were attenuated adequately using parabolic radon, FK, and hyperbolic radon filter in cascade. The input CMP gather for PSTM, de-gained and reverted to shot domain and subtracted from Nav-merged shot gather.

This subtracted output, ensured removal of major part of PP energy and it contained weak PSSP energy. Subsequent noise elimination (of left over PP energy and other noises) resulted enhanced PSSP energy. Figure 4(a) shows gather and selection of mute parameters in slowness domain to preserve PSSP energy and reduce PP energy below basalt. After elimination of multiple the low frequency PSSP waves are visible in Figure 4(b). At shallower offset the multiples (originating from basalt top) are interfering with signal. After adequate de-noising the velocity of PSSP waves could clearly be estimated which is much slower than PP waves. The figure-5 illustrates the velocity semblance which has been used in multiple attenuation in cascade.

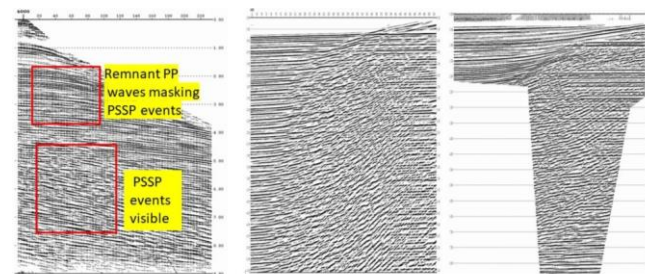


Figure-4(a) left panel: Initial PSSP gather +noise. Central panel is subtracted shot gather in τ -p domain. Right panel is the selection of the adequate muting below basalt (τ -p muting), slowness range defined by $1/V_p \text{ basalt} \leq p \leq 1/V_s \text{ basalt}$. Output of τ -p muting is PSSP gather + Noise + left over PP energy shown in left panel. This zone muting is preserving weak PSSP waves.

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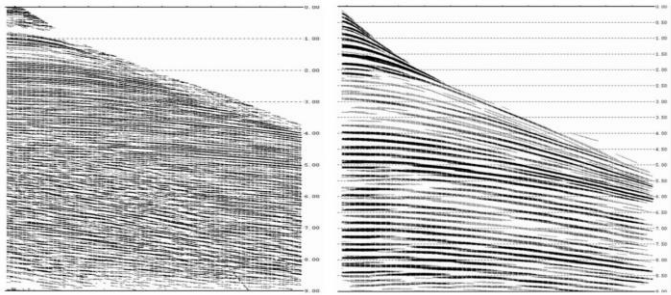


Figure 4(b). Enhanced PSSP gather after multiple attenuation (right panel). Left panel is same gather shown in left panel figure 4(a). Multiples are present in shallower offset which are attenuated in subsequent phases.

The attenuation of each noise components namely remnant PP waves, Multiples, cross noise sweeping from basalt etc. are satisfactorily accomplished using different processing modules and RMS velocity field was estimated.

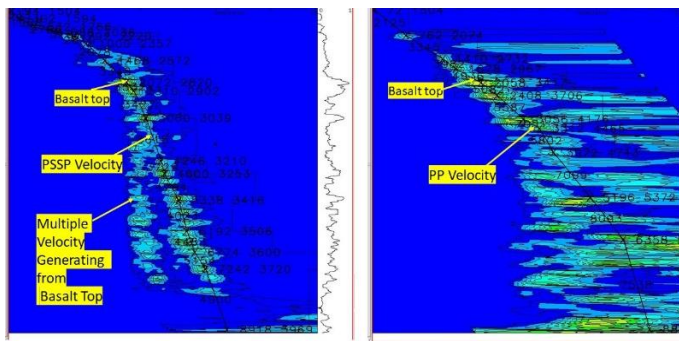


Figure-5. Velocity semblance of a line LO-3 after further de-noising using ZMULT. In left panel velocity of a multiple generated from basalt top and the trend of PSSP velocity are very clear. In subsequent application of parabolic radon, hyperbolic radon and ZMULT filters the multiples and unwanted waves are minimized and realistic velocity could be estimated.

Time imaging of PSSP waves:

DMO and Pre stack time migrations were performed for PP and PSSP waves for LO-7 (E-W line) and LO-2 (N-S) lines. The reflections are compared in PP and PSSP sections the trends have reasonably good character matches. Figure 6(a), shows DMO stacks (100 % zero offset sections) of PP and PSSP sections of LO-7.

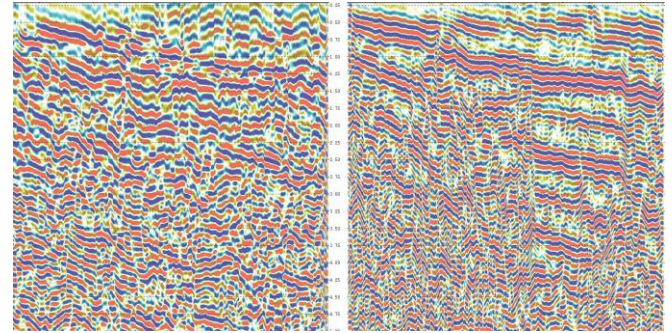


Figure 6(a). shows DMO stack of Line LO-7. Left panel PSSP DMO stack and right Panel PP DMO stack. Reflection trends show good character match in both sections.

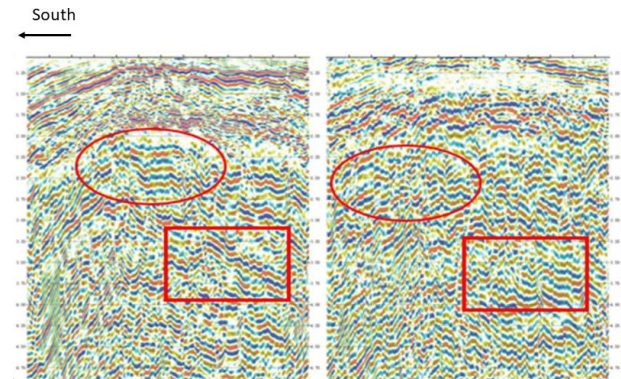


Figure 6(b). Comparison of PP and PSSP PSTM stacks of line LO-2. Left is PP section, right PSSP section. Trends of reflectors in both section match well.

As expected, the events in PSSP sections are appearing at a greater time. Both PP and PSSP images were displayed with space varying gain.

Depth Imaging of PP and PSSP waves:

The tectonics of Kutch and Saurashtra blocks is very complex. In study area the water depth is very shallow. But volcanic eruptions in different phases during KT time have changed the disposition of existing sedimentation. The multiple basaltic flows interlayered with sedimentary sequences, presence of Intrusive (feeder to basalts) and presence of lime stones might result high degree of lateral inhomogeneity within Mesozoic, which may result non hyperbolic moveout of the reflections appearing below trap. Thus, Depth imaging is the better solution to address this lateral in-homogeneity. Depth

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imaging of selective lines (one E-W line LO-7 and one N-S line LO-2) was performed after Depth interval velocity model building using the GEODEPTH software. In two lines LO-1(E-W) and LO-2 (N-S), model building was done using layer stripping method and in LO-7 (E-W) CVI was used and the interval velocity sections were prepared. The velocity up gradation was done by picking residuals and using grid tomography. The refined interval velocity section and final CMP gathers are inputs for PSDM. The depth residuals picked at the time of up-grading interval velocity (final iteration) of PP and PSSP waves which exhibited smaller variation from zero line which were also adjusted. Figure-7 shows PP and PSSP depth sections of Line LO-2 at the bottom with residual analysis for PP and PSSP on the top. As illustrated, the PP and PSSP depth sections of line LO-2 shows good tie in depth domain and delay of PP and PSSP residuals are negligibly small. This led us to think about mixed mode depth imaging of PP and PSSP PSDM gather.

Mixed mode depth imaging:

The residual analysis on PSSP and PP gathers (Figure. 7) during up gradation of interval velocity (with few iterations of grid tomography (for Line LO-2), confirmed that the PP and PSSP depth stacks/gathers had minimum depth mismatch up to 8 Km. No depth mismatch is found close to the markers like Paleocene top, basalt top, basalt base. The idea of mixed mode depth stacks combining PP and PSSP gathers, coined. PP depth gathers have greater energy and higher bandwidth compared to PSSP gathers. Both PP and PSSP depth gathers were cleaned using radon filter & FX-de-con etc. The wavelets were extracted from two PSDM stacks, of (PP and PSSP), scaled to time. A suitable match filter was designed with due care (after adequate amplitude scaling, same BP filter application), for matching PP depth gathers to PSSP depth gathers. Match filter was applied on PP depth gathers so that wavelet wise two gathers do not vary. Then CMP wise vertical summation of PP matched gather and PSSP gathers were performed to derive a mixed mode (PP + PSSP) gather as a single summed gather for all CRPs. Subsequently, this summed gather was stacked and cleaned to give finally mixed mode stack of PP and PSSP energy. Here it is assumed that PSSP wavelets do not suffer any splitting in to slow and fast components (no anisotropic change). It is also assumed that PSSP energy is not transformed/modified due to presence of high relief

structure (if exists) in path of its propagation, below basalt. The mixed mode section of LO-2, was cleaned and displayed in Figure-8(a). The mixed mode results followed by match filtering gives immense improvement in imaging the topography below basalt. Many deeper events close to Saurashtra arch and below have emerged very strong with very good continuity, which were sporadically noticed in PP and PSSP depth sections. The summation of PSSP and PP waves have attenuated noise during vertical summing. The mixed mode stack is highly conducive for structural interpretation below basalt.

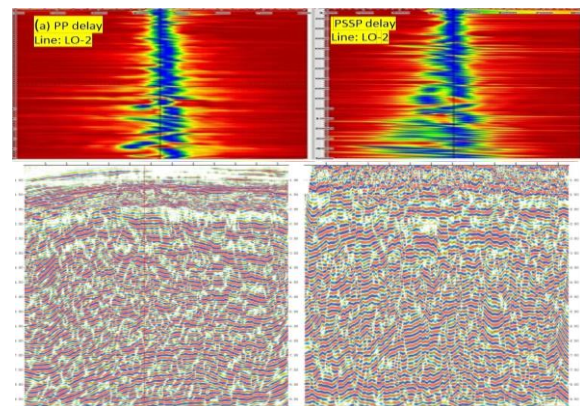


Figure 7 (top): Display of PP residual (left) and PSSP residual (right). Delays are minimum up to 8 Km. Line LO-2.

Figure-7 (bottom): PP depth section is at left and PSSP depth section at right. Line LO-2.

Figure-8(b) shows correlation of VSP corridor stack of W-4 well with mixed mode section of LO-2, scaled to time. Important horizons are marked on the section. Good well tie (calibration), ensures proper mapping of energy in Mixed mode section.

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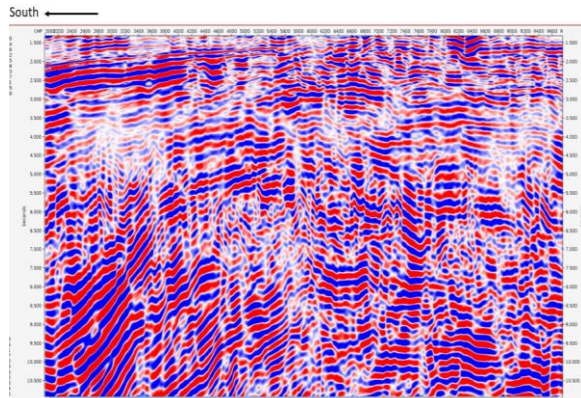


Figure-8(a) Full section PP+PSSP Mixed mode stack (scaled to time) Line LO-2 after cleaning. Very clear reflections in sub-basalt regime.



Figure-8(b): The well tie of VSP corridor stack (of W-4 well) spliced at well location on the (PP + PSSP) mixed mode depth section scaled to time of line LO-2 also confirms the genuine mapping of energy on mixed mode section and proper calibration.

Partial Wide-angle imaging:

Wide angle imaging is a powerful imaging technology practiced in seismic industry specially to probe deeper objects. In routine imaging, source to receiver offset has a maximum, of few kilometers (say 4-6 Km), covers the near vertical range of incidence angle. Typical Long-offset profile may be 25-30 km long spread. Data of Feroes Shetland basin of North Sea is displayed in Figure 9(a). Hassan Masoom Zadeh (2005), demonstrated aptly in his master's thesis that the near offset segment of data, may usually be infected by ground rolls, guided waves, direct arrivals super imposed with high frequency noise, refracted waves, and other noises. This contamination is less at larger offset and the rays are not near vertical. Zhang Wenbo et.al., 2004 published some interesting facts, on wide angle

reflectivity through theoretical computation of simple two-layer case. They computed the reflection coefficients of P wave in the interface with different ratios of velocities V_1/V_2 and ray parameters p_1/p_2 . When incident angle i is less than i_c (critical angle), the reflection coefficients are relatively stable. When the incident angle is close to the critical angle, the reflection coefficients drastically increase unless it reaches the maximum value at critical angle. The reflection starts quickly decreasing when i is larger than critical angle i_c . Figure-9(b). Thus, if we can retain the reflectivity at higher offset (wide angle reflection), without applying front end muting superior imaging below basalt may be achieved. In fact, Wide angle imaging has been very successful in complex noise dominated geological province namely sub-basalt/sub-salt regions. Figure-9(c) shows,

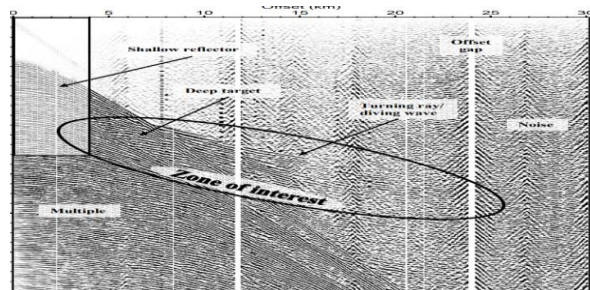


Figure-9(a): Long offset shot gather in Feroes Shetland basin (After Hassan Masoom Zadeh). Offset 30 Km.

Multiples are infecting the near offset data. Deeper targets could be retrieved after attenuating turning rays and other noises.

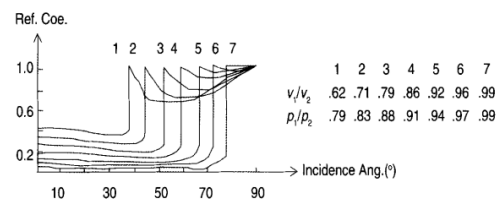
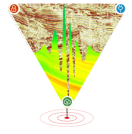


Figure-9(b): Variation of reflectivity with incident angle. Two layer case as computed by Zhang Wenbo et.al., 2004.

Presence of turning rays, diving rays and other reverberations which are very common in sub basalt



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regime, can be attenuated by successful zone muting in τ -p domain. The mute selection in τ -p domain can therefore be very crucial to eliminate complex noise pattern like turning rays, diving rays etc. as shown in Figure 9(c) and uncontaminated reflections at higher offsets can be retrieved.

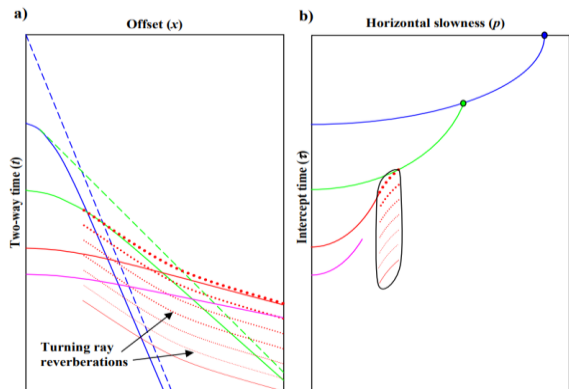


Figure 9c: selection of proper muting in slowness domain can attenuate turning rays which are common in sub-basalt regime (After Hassan Masoom Zadeh). The uncontaminated reflections at higher offsets can be retrieved to give value addition.

Kutch Saurashtra basin is a deep basin where the Mesozoic is occurring at a depth of 3 km plus below basalt and probably extending up to 12 km plus depth. The maximum spread length of our 2D profile (available) is 12 Km, which is strictly not meant for wide-angle imaging. However, a simple processing approach is followed to preserve wide angle response.

The shot gathers initially de-noised, in x - t domain using RVMO and other modules (Epos-3 software), subsequent cleaning was done in τ - p domain. The output of this stage let's call input data (A), taken in to τ - p domain to retain linear noise, while all other signals are killed (B). The train of linear noises with slopes from both directions, generating from basalt top, sweeps across and normally mask the deeper reflections. The V sum of polarity reversed noise (B) with input (A) has very effectively attenuated the noise trend. This is subtraction of linear noise.

Figure-10 shows, various stages of noise attenuation (de-noising in different stages) and reflected signals from basalt base and below, have been brought out. The raw gather figure 10 (a) is badly affected by swell noise and all other linear noises which are

masking signals at deeper levels as well as higher offset, Figure 10(b) shows initial cleaning in slowness domain after applying RVMO (assume output named as A). Figure 10(c) exhibits all kinds of linear noises (with dips in either direction) which are preserved by changing mute parameters (output B). Now the data shown in figure 10(c) and 10(b) are summed (after reversing the polarity of linear noise). This gave a gather drastically minimizing the noise contamination. Further cleaning was performed using several processes namely τ - p decon, parabolic radon without applying surgical mutes as displayed in figure 10(d). No front-end mutes in x - t domain were applied, to retain the signals at higher angle. The stretching effect at higher offset is noticeably minimum. Figure-10 (a) to Figure10(d) shows the cleaned gathers right from raw data.

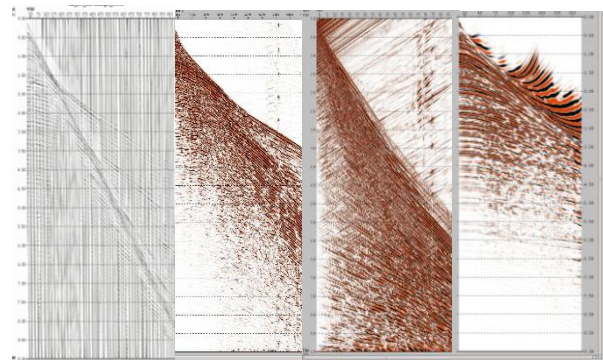


Figure-10(a)-10(d). The gathers through various cleaning stages starting from shot gather. Stretching effect at higher offset is also not observed.

The data was processed in τ - p domain except velocity analysis and migration. The imaging was performed using two offset ranges (1) 150 M to 4000 M and (2) 4000-M to 12000 M. The results are displayed in figure-11.

Figure 11(b) shows results of migration on data sets in offset range 4000-12000 Mt. The deeper events corresponding to Saurashtra Arch are well brought out which are missing in Figure 11(c) the normal full offset stack. This achievement is due to inclusion of reflectivity at higher offsets (without application of front-end mute).

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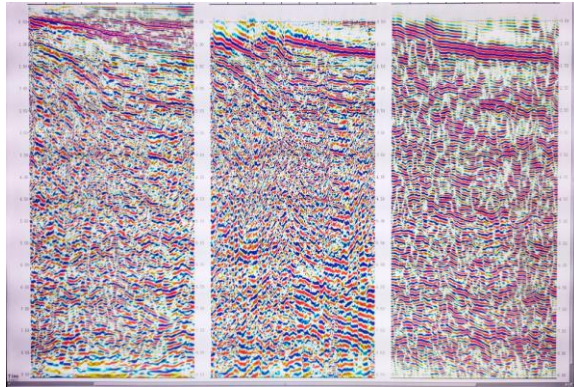


Figure 11: (a) (b) (c)

The figure 11(a) shows image (migrated section) of offset range 150-4000 M. Figure 11(b) shows results of migration on data sets in offset range 4000-12000 M. The deeper events corresponding to Saurashtra Arch are well brought out which are missing in Figure 11(c) the normal full offset stack. The deeper events at higher offset are brought out decisively by attempted wide angle imaging, figure 11(b).

Conclusion: The high acoustic impedance contrast between basalt and tertiary (above), reduce the energy transmission drastically. Most of the acoustic energy bounce from the top of basalt. The multiple reflections originate from basalt top as first order or second order free surface multiple. Anomalous V_p/V_s ratio generates symmetric and asymmetric mode converted waves (P-S), PSP and symmetric PSSP and PSPPSP waves from basalt top. These are noises in P-P imaging. Basalt has rugose (wrinkled and corrugated) character clubbed with varying thickness and internal velocity heterogeneity and it complicates the wave propagation. The high frequency of incident wavelet is drastically attenuated and incoherently scattered. Back scattered noises are also generated. These are constraints in sub-basalt imaging and exploring Mesozoic reservoirs which are producers in Kutch Saurashtra regions.

In absence of multi component OBC or OBN data, usage of mode converted PSSP waves is reasonably a viable option and mixed mode depth imaging has substantial opportunities to explore sub-basalt provinces (Mesozoic reservoirs). The symmetrical PSSP waves can be processed using the modules used for processing PP waves. The partial wide angle (offset only 12 Km) imaging using higher offset reflectivity beyond critical angle without using front-

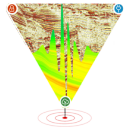
end muting as normally done, has also formidable success to map the deeper horizons. However, Mixed mode depth imaging is just in the initial stage. It needs further refinement. We expect that people in exploration industry will pay due attention and enrich the methodology in future.

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Annexure 1 -Sequences of mixed mode depth imaging

