SEISDIP: the "VSP dipmeter" from oriented 3 components

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Summary:

VSP surveys are commercially recorded with a single zero-offset source position and with a downhole tool including 3 orthogonal seismic sensors. For VSP acquisition in vertical wells, a hardware orientation accessory needs to be combined with the VSP tool.
An "**isotropic**" processing of the oriented 3 Components (3C) VSP data is necessary, meaning that **all** the processing operations are identically applied on the 3 components at any seismic time, ensuring the following benefits:

- The illumination of seismic reflectors is achieved in 3 Dimensions, with information about their dip and azimuth (Seisdip[*] method, described in [1]). 3C VSP yields the structural dip of seismic interfaces from the borehole up to distances of several hundred meters away from the well, even if the reflectors do not intersect the well, or are located below the well. A 3C VSP can be recorded in any well, cased or open hole. In contrast, the dip information derived from borehole wall imager tools, either by resistivity or by acoustical reflection, relates to sedimentary dips within centimeters away from the well bore, and can be recorded in open hole only.
- Reliable identification and improved discrimination of the upgoing VSP events: P or S reflected, diffracted and refracted arrivals. Only three component processing allows to disentangle a complex seismic wavefield containing mixed P and S wave mode arrivals coming from varied dipping reflectors, potentially curved, and from diffracting fault corners.
- In case of interfering reflected/diffracted events generated by lateral dip variations or tilted faulted blocks, 3C processing allows to fully understand the VSP response, while the conventional single component processing can mislead the interpreter.

Introduction:

The 3 components (3C) are industrially recorded in commercial VSP surveys, although only the vertical component is currently processed. The lack of methods and tools appropriate to take advantage of the whole 3C information is responsible for this unfortunate state of fact. The present study shows how 3 dimensional structural features can be determined by taking in account the 3 geophone components of VSP data. A test of Seisdip[*] processing was attempted on a VSP acquired in a deviated well with source located vertically above the deviated segment, so that the fix 3C inside the VSP tool could be reoriented from the direct arrival polarization. The dips were determined on only four strong deep key reflectors, noted H1 to H4.

1 - Improvement and reliability of VSP seismic imaging:

The geological structure resulting from isotropic 3C VSP processing corresponds to a gentle flexure in the well vicinity, with increasing dip from left to right on the sketch **Fig.1**: this structure is coherent with the geological structure known in the area.
In contrast, **Fig.2** illustrates an erroneous interpretation of the seismic image obtained from conventional VSP processing of the vertical component only, on which a gentle coherency enhancement is applied on the reflected wave field **Fig.3**. The interpreter is often tempted to regard the conventional VSPCDP stack image as a portion of surface seismic section, so that it would be easy on fig.3 to draw an abrupt lateral change or an accident located below the well trajectory in correspondence with the lateral interruption and strong amplitude dimming of the reflectors near Total Depth. In the present case, such an interpretation, as represented on the sketch **Fig.2**, is erroneous and incoherent with other geological knowledge. Instead of that, the 3C data analysis indicates that we are facing interfered reflections without accident (**Fig.1** and **Fig.5**).
The 3D migration of VSP reflected wave field using the 3 components of the borehole survey is a cumbersome tool to solve the structure in the well vicinity from a single record, where the limited portions of reflectors are illuminated by the surface VSP source: moreover, a VSP with zero-offset source in a vertical well cannot image the portions of reflectors down dipping away from the well.

* SEISDIP: Mark of IFP

By construction, the mirror points are seen under variable incidence angle, and the CDP (Common Depth Point) fold is low and laterally variable on VSP images from a single source.

Thus, **Fig.4** shows the 3 component (Z, HR, HT) deconvolved isotropic upgoing wavefield, HR being the horizontal component in the vertical plane of deviation containing the source. Clearly, the reflectors H1 to H4 correspond to two interfering families of events, a family of continuous sub horizontal reflections with a family of interrupted dipping reflectors only apparent on the deeper VSP levels: the interruption is particularly visible on horizontal components, and occurs when the dipping interfaces are no longer illuminated away from the well, as explained hereunder.

From analysis, the reflected wavefield polarization indicates that the continuous sub horizontal reflectors are located below the well deviation, on left side of fig.1, dipping 4-6° to the West, while the time slanted segments of interfered events correspond to reflectors located on the right side of the well, dipping 10-15° to the West. The total image results in the continuous flexure illustrated on **Fig.1** and **Fig.5**. On the Easternmost side, the reflectors are no longer illuminated because of geometrical reasons, meaning that the dip of the flexure is no longer increasing away from the well (dotted line noted "impossible lateral extension of the reflector" on **Fig.1**).

The results of the joint time and polarization Seisdip inversion of direct and reflected rays trace to trace on horizons H1 - H4, are displayed in the vertical plane of deviation (**Fig. 5**) and in the horizontal projection plane (**Fig.6**), where the VSP measurement levels on well trajectory are marked by triangles. A smoothed reflecting flexure has been hand drawn to illustrate the real structure.

On **Fig.7**, a Dip/Azimuth crossplot shows the coherency of the results, especially for the azimuths corresponding to small dip values.

2 - Comparison of resistivity dipmeter log readings with Seisdip results obtained on the well trajectory for horizons H1-H4: **Fig.8a,b,c,d.**

In the VSP corridor stack domain, the reflections are located right below the geophone, so that the Seisdip results are most accurate. Composite displays have been assembled on Figs 8, including the following conventional logs: sonic (ΔT), Gamma ray, Min/max Calipers, and dipmeter results. The Seisdip results on H1 to H4 are marked with a different arrow symbol on the dipmeter display at the reflector depth; a decrease of sonic transit time corresponds to an increase of acoustic impedance, i.e. a black peak on the seismic reflected wavefield display **Fig.4**.

The following technical information need to be kept in mind while examining the comparative displays **Fig.8**:

- The 6-arm dipmeter tool was run in a deviated well drilled with oil based mud (OBM), which is not an optimal environment for such an electrical tool. Moreover, as all the tool working with measurement pads, the dipmeter results can be severely affected by caved zones. In contrast the VSP tool ignores these types of drawbacks and can even work in cased hole with good to fair cementation.

- By principle of measurement, the dipmeter tool yields high resolution results (≤5cm or 2 inches), preferably within a given layer where the stratification is laterally continuous at the scale of the borehole diameter (0.1m to 0.4 m), and accompanied with resistivity contrasts. In contrast, the VSP Seisdip results have a seismic resolution (≥5m) and are related to seismic reflections, i. e abrupt sonic and density contrasts commonly encountered on layer interfaces. The lateral resolution of VSP on the well trajectory corresponds to an optical Fresnel zone, about a 25m radius around the well, so that the Seisdip results will be insensitive to the local sedimentary disturbances affecting the dipmeter such as boulder, conglomerates, breccia, cracks, interface ripple marks, vugs, etc...

Thus, direct comments can be derived from a quick look at **Figs. 8**:
* H1 and H4 (**Figs. 8a, 8d**) dips and azimuths are definitely restituted by Seisdip, while the dipmeter results are azimuthally dispersed; the only point of agreement is the low dip values, around 6°.
The caliper logs show a small borehole ellipticity around H1 and an excellent well condition right on H4, so that the dipmeter dispersion may be attributed to a possible lack of intra-sedimentary lateral continuity.
A large caving effect occurs slightly above H4, provoking a definite alteration of the dipmeter results.
* Horizon H2 is a strong seismic marker (**Fig. 4**), with a strong sonic and GR contrast (**Fig.8b**). The H2 interface Seisdip result is in excellent agreement with the dipmeter result on the shaly layer above H2, both in dip and azimuth, which is quite impressive for such small dip values. The layer below H2 interface, less shaly, presents less coherent dipmeter results, although with the same dip and azimuth trend as above. The caliper log shows no anomaly for H2.
* The seismic reflectors H3 (**Fig. 8c**) correspond to the top and base of a 6m layer within which the dipmeter results are dispersed, while there are extremely coherent for the adjacent formations above and below layer H3. The Seisdip result on H3 is slightly different than the dipmeter intra-sedimentary dip of the adjacent layers, although within close values of dip and azimuth, which is not geologically incoherent. The caliper log shows almost no alteration on layer H3, so that the observed dipmeter dispersion is due to a sedimentary cause (limestone). In the case of H3, the dip from VSP is more reliable than the dipmeter measurement.

Although the Seisdip result accuracy can be further improved using VSP tools with better isotropy of response (also called "vector fidelity") and built-in orientation device, the present example shows an good coherence of measurement with the dipmeter log and illustrates the specific advantages of the two techniques. In practice, these two methods of dip determination are quite complementary.

Conclusion:

On the well trajectory, the Seisdip VSP results are in agreement with the resistivity dipmeter log results when readable. The lateral sensitivity of Seisdip to a decametric scale Fresnel zone presents an advantage over the dipmeter technique, limited to a centimetric scale zone around the well, but with higher intra bed resolution.

In the present study, the 3 component VSP Seisdip processing allowed for a correct determination of the complex VSP image from a gentle geological structure where the same reflecting interface is illuminated on two different portions of the same flexure with different dips, for each given 3C receiver position. In the view of the interpreter, the present case study presents a complex VSP response from a simple gentle geological structural feature of laterally variable dip. This situation is much more challenging for the 3C VSP processing geophysicist than for the interpreter, and shows how easy it can be to derive an erroneous interpretation from inadequate analysis and processing of 3C VSP datasets. In this respect, the corridor stack domain of the VSP, i.e the 50ms time window of seismic signal immediately following the direct arrival, constitutes the easier and most reliable 3C VSP data subset to analyze.

The Seisdip method yields good results even for seismic interfaces located below the well-TD or which do not intersect the well. This specific property is valuable to explore and to confirm the geological structure at a hectometric scale in the well vicinity, up to several hundreds of meters from the well.
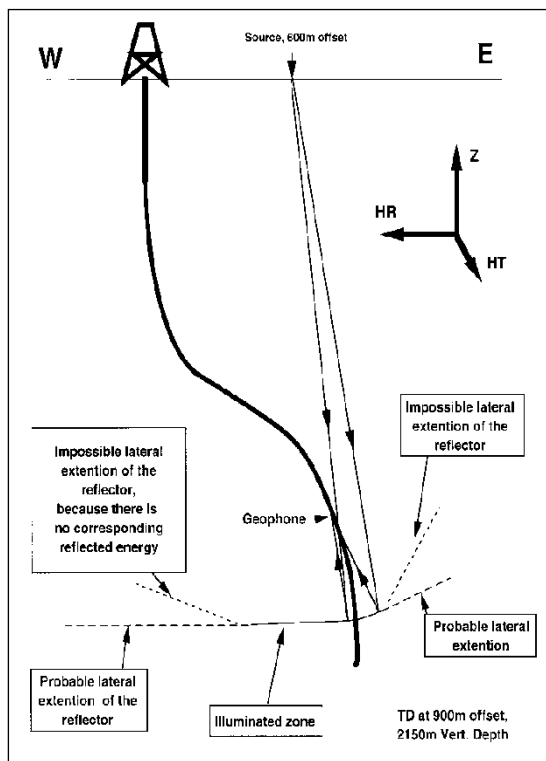

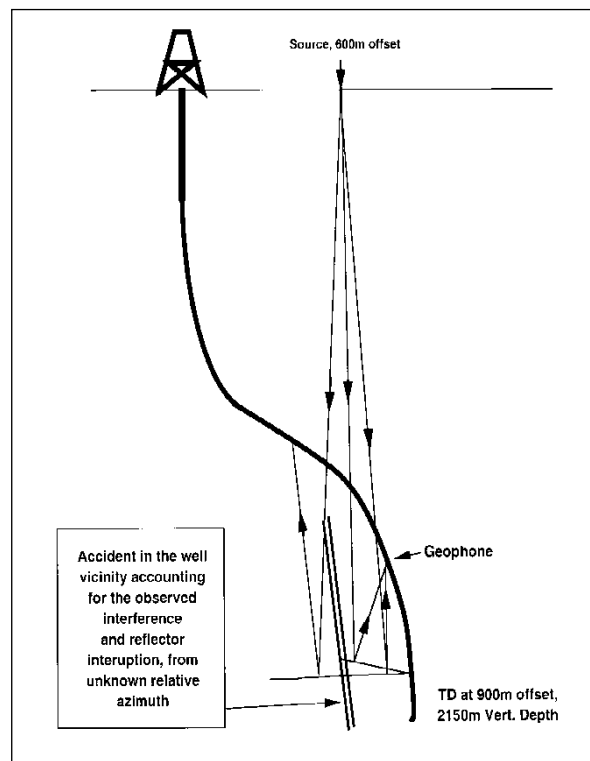Fig. 1: VSP imaging in deviated well, sketch of geological flexure, Vertical plane of well deviation

Fig. 2: Incorrect VSP interpretation from conventional VSP-CDP stack built from single component processing and monocline interface modeling of the well vicinity
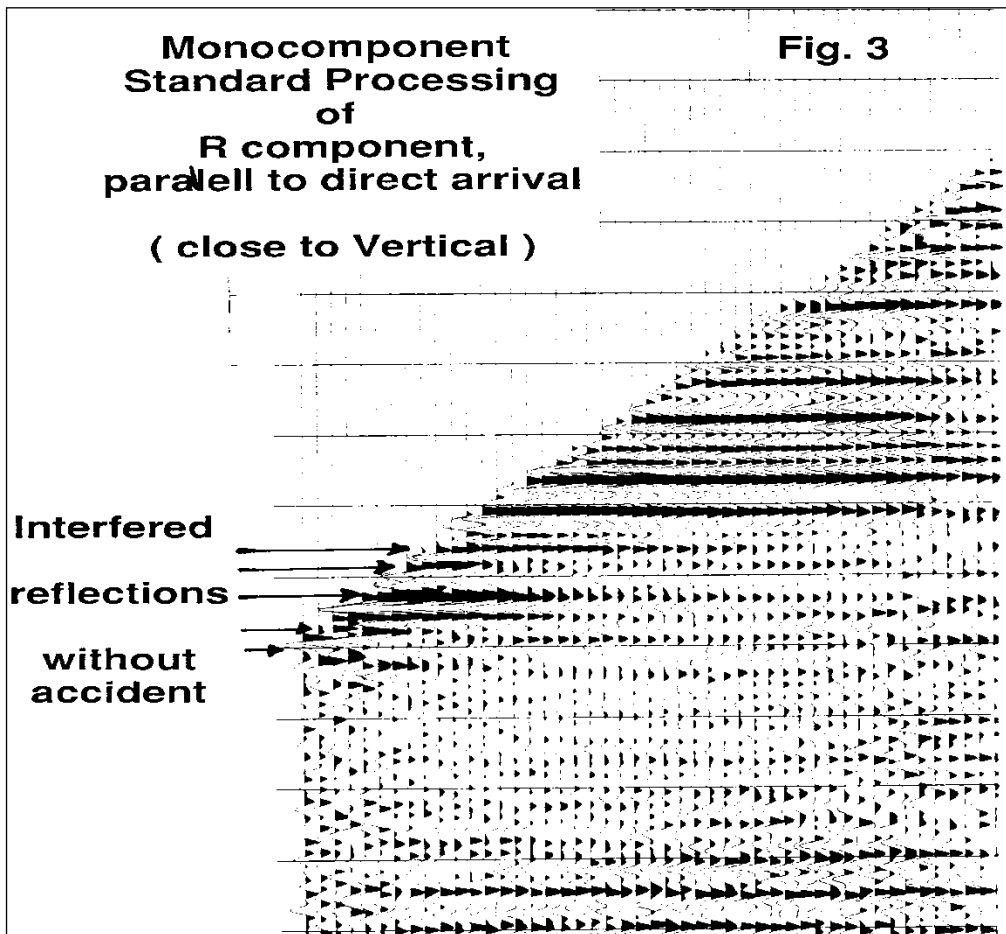
Fig.3: Single component standard processing of R component, parallel to direct arrival
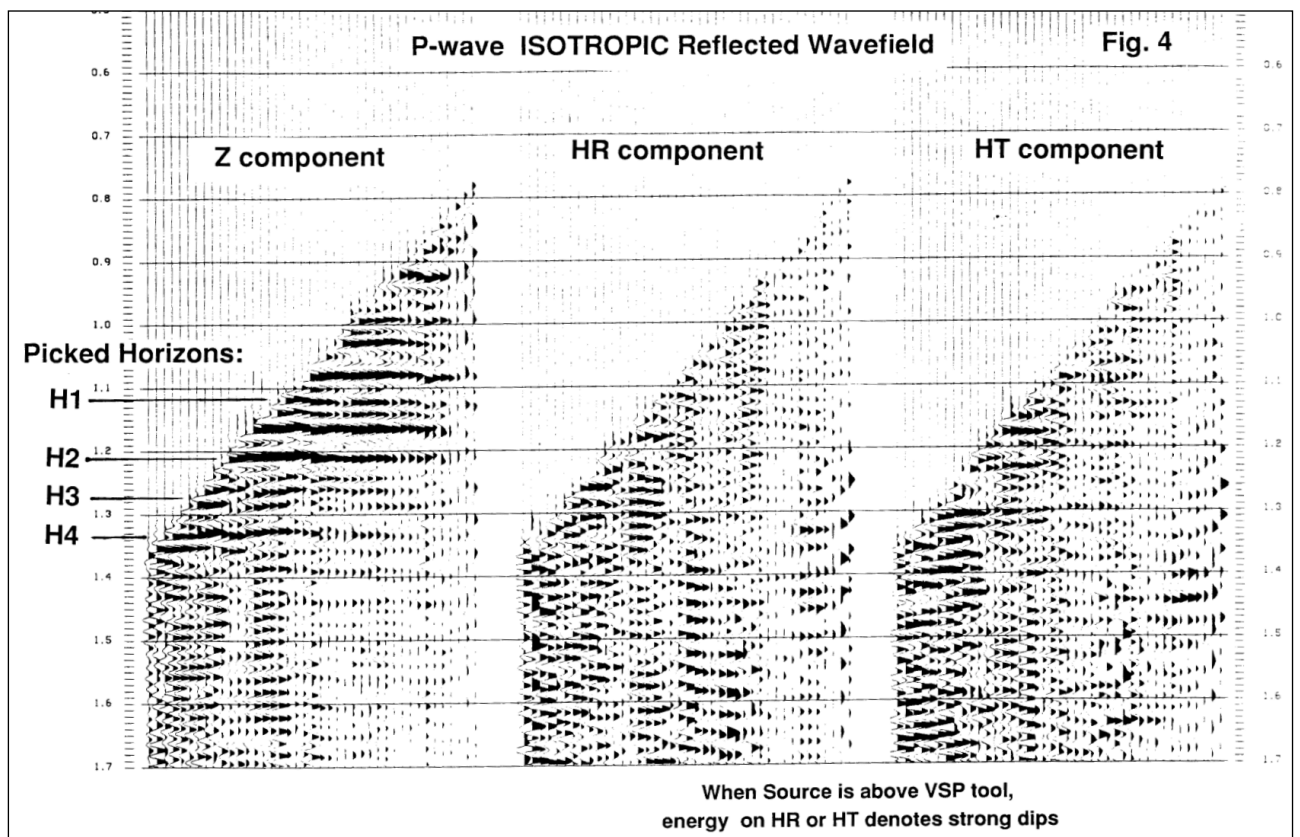

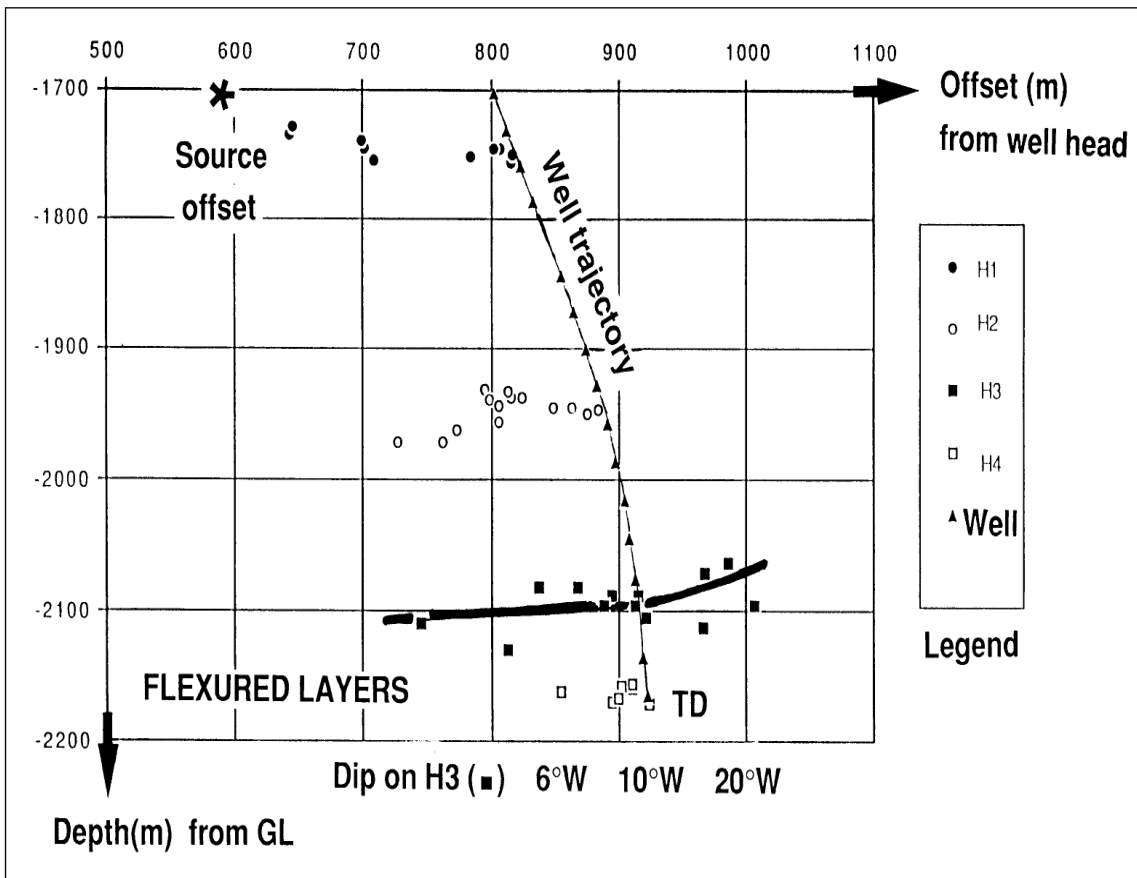Fig.4: 3C P-wave ISOTROPIC Reflected Wavefield and picked horizons

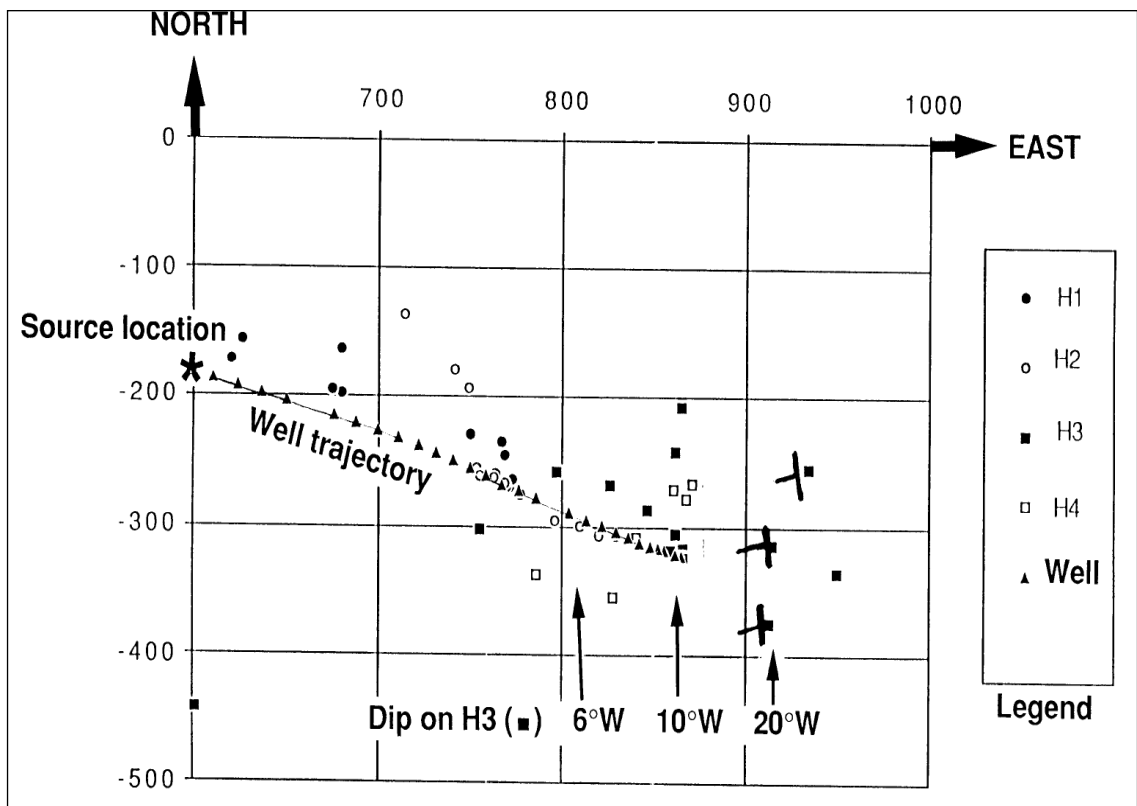Fig. 5: Mirror point location in VERTICAL plane of deviation

Fig.6: Mirror point location in HORIZONTAL plane, horizontal distances are in meter from wellhead origin
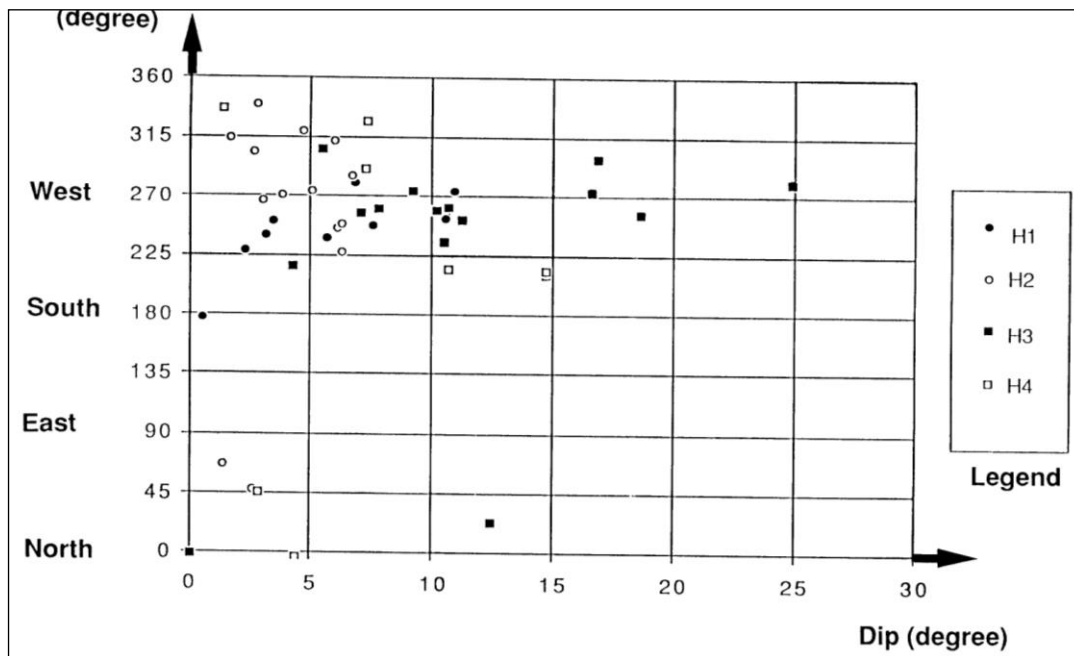
Fig.7: Dip / Azimuth crossplot

Acknowledgements:

Addendum (2018) :

The 3C borehole seismic applications has not been industrialized yet, probably due to the lack of systematic addition of reliable, adequate and affordable orientation hardware to the commercial VSP tools, the potential of the oriented 3 components of Rig-source VSP's have been demonstrated by a few publications, namely :

- ✓ Salt proximity survey: locating high amplitude scatterers located on a salt dome wall,**[2]**
- ✓ 3C geophone on gimbal, with Trunnion setting(ref. SEISDIP poster, page 4), in a sufficiently deviated borehole, can be oriented using the geometrical parameters of borehole trajectory, namely hole inclination and hole azimuth; an example of such application can be found in **[3]**.
- ✓ A method similar to Seisdip was independently developed by Texas A & M. geophysicists in 1988 **[4]**.
- ✓ 4C VSP tool, fix 3C geophone + inclinometer + hydrophone; VSP in deviated/horizontal well in **[5]**.
- ✓ All Offset VSP's recorded in near vertical well, the direct P-wave is maximized in order to provide the VSP tool orientation, assuming that the direct P-wave ray propagates in the vertical plane containing the source and the downhole receiver. Onshore S-wave source zero offset VSP dataset are often oriented using the direct P-wave polarization of a O-VSP recorded in the SAME RUN.

References (prior to 2001) :

[1] C. Naville, IFP: Method for processing oriented multi-component seismic well data: US Pat.6,076,045, 1998
[2] Illka Noponen, Geosource, Inc. : Application of VSP Observations of Steeply Dipping Salt Interface Reflections to Reservoir Development, Abstract BHG1.4, 55th Annual International SEG Meeting, 1985.
[3] Timothy B. Barker and Carlos E. Guzman, Shell Offshore Inc.: Defining the Salt with walkaway VSPs and a Salt Proximity Survey, Auger Field, gulf of Mexico, Abstract CH3.3, 62th Annual International SEG Meeting, 1992.
[4] Terry W. Spencer, Gregory A. Smith and Woon Hyun Cho: Vertical seismic profile polarization method to determine reflector orientation, GEOPHYSICS, Vol.53, N0 9, September 1988
[5] J.L. Mari and Christian Wittrich, Inst. Français du Pétrole, Raoul Goefer and A.M. Spreux, Elf Aquitaine: Vertical Seismic Profile in Horizontal Wells, JPT, December 1990, pp.1486-1493, or SPE19856
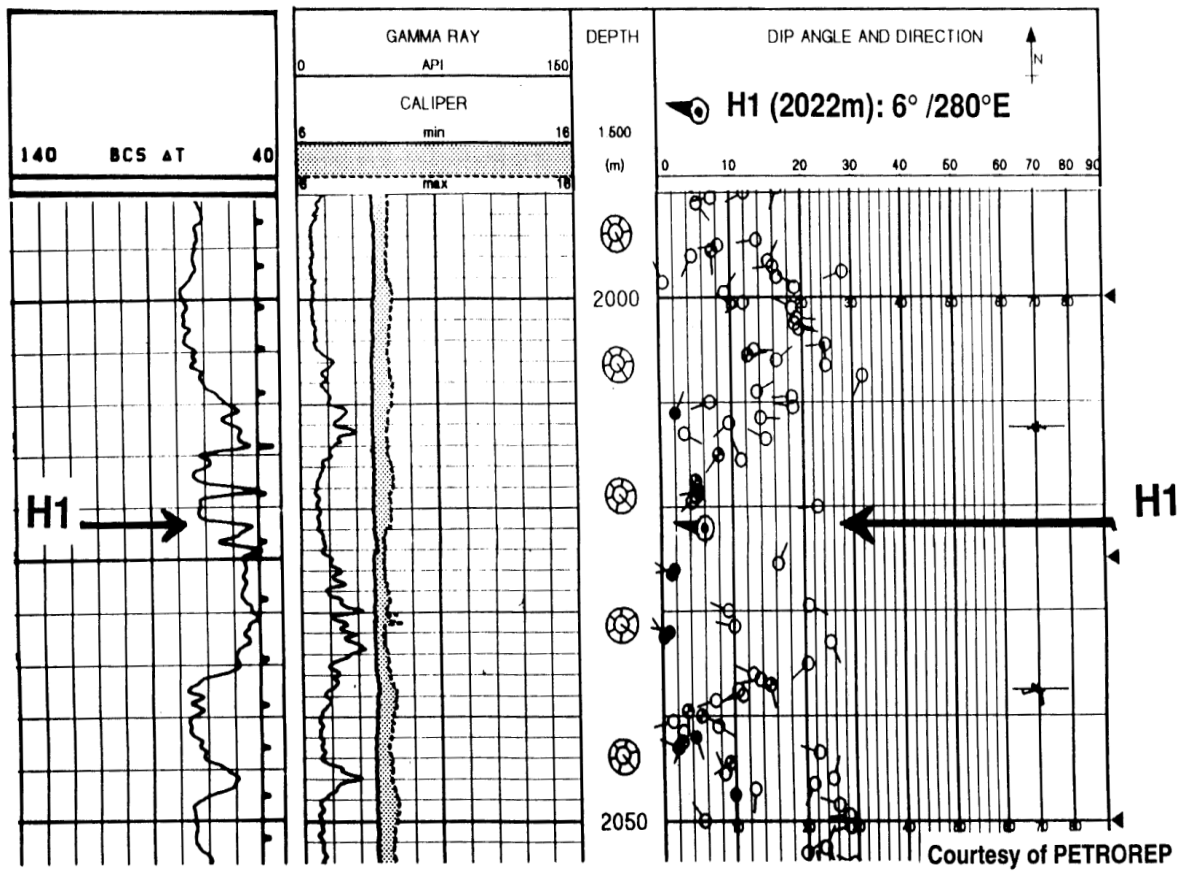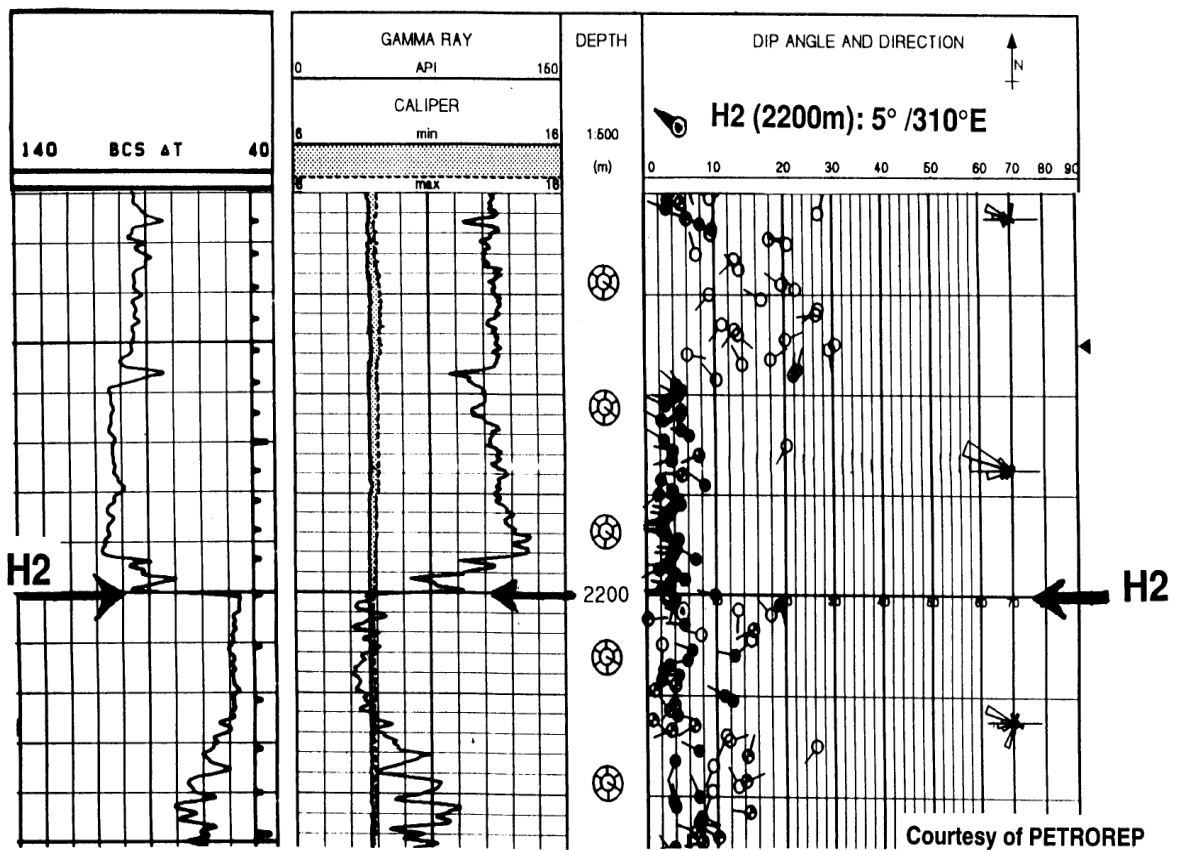
Fig. 8a: SEISDIP result on H1 (2022m): 6°/280°E

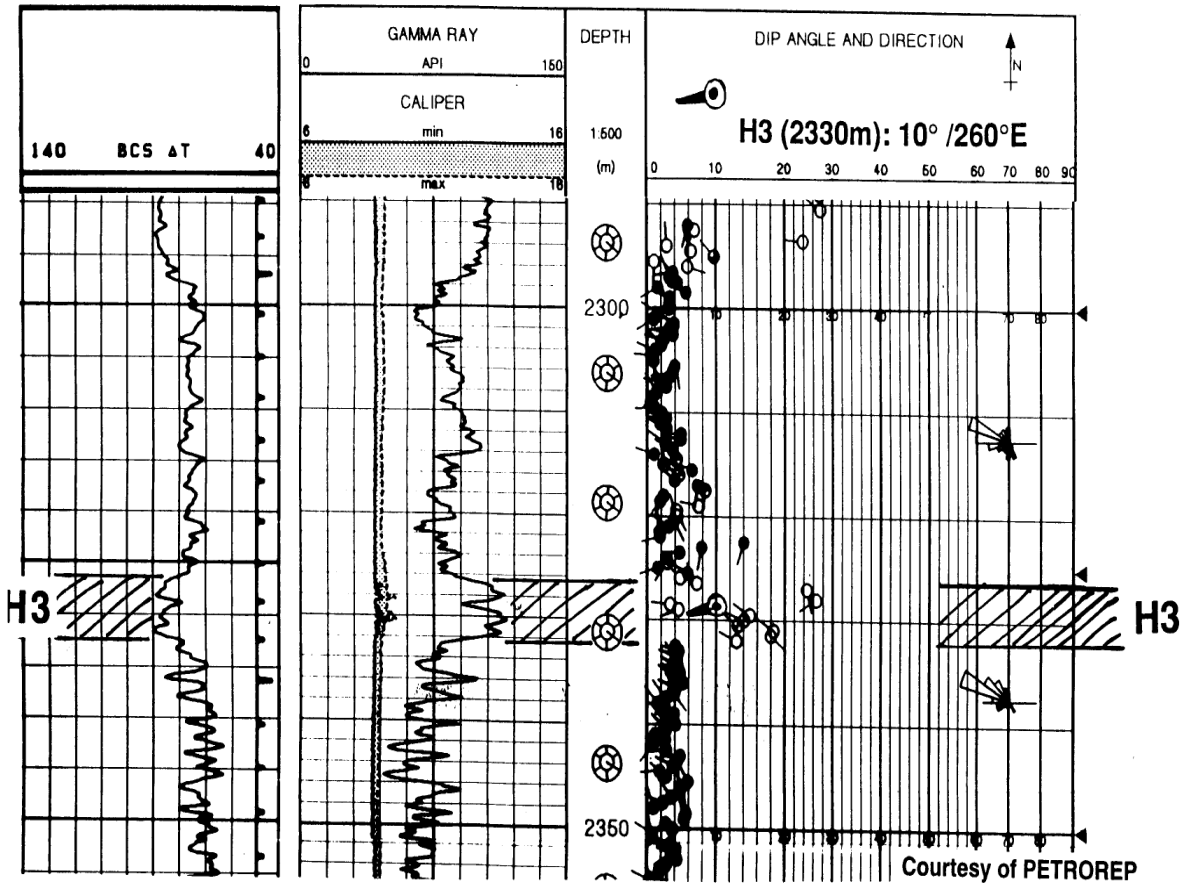Fig. 8b: SEISDIP result on H2 (2200m): 5°/310°E
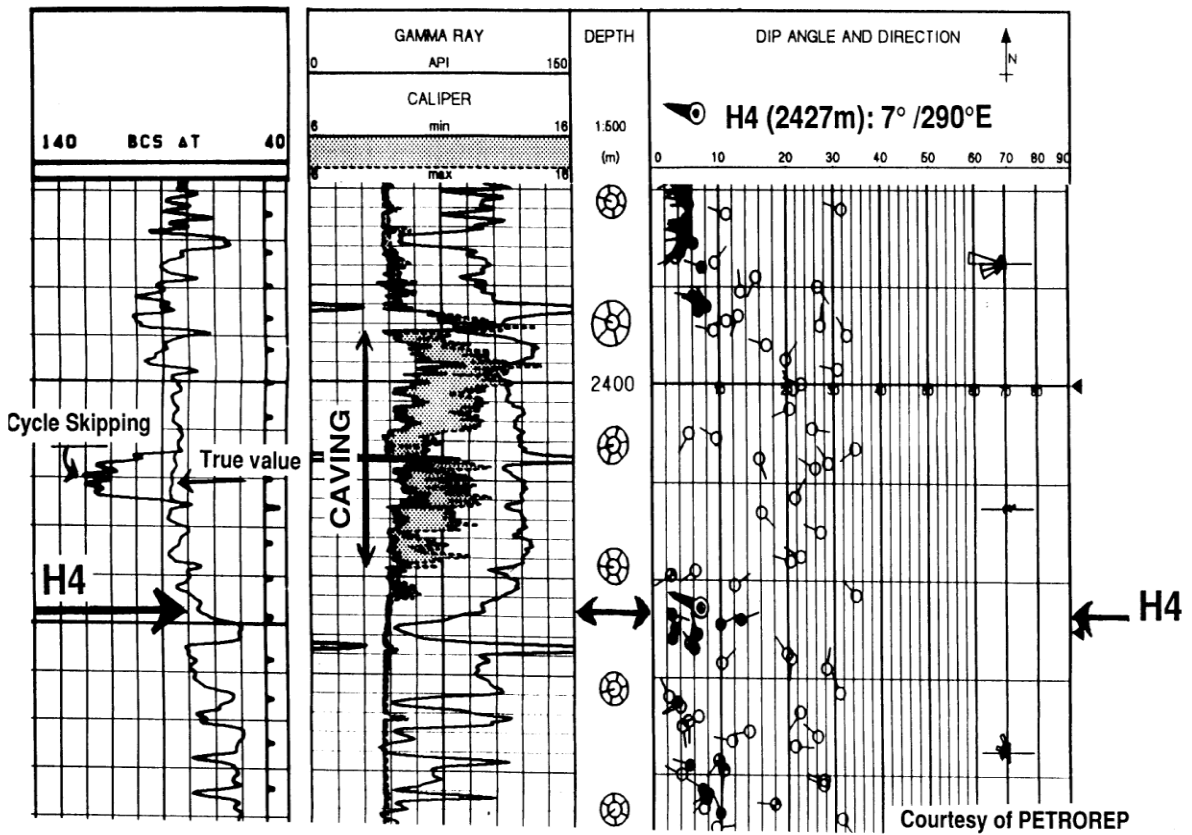
Fig. 8c: SEISDIP on H3 (2330m): 10°/260° E

Fig. 8d: SEISDIP result on H4 (2427m): 7°/290°E