Orientation of a 3-C VSP dataset acquired by integrated geophone sensor and MEMS inclinometer devices; 3C VSP orientation field QC

W. Wills, M. Nott-Bower, G. Tubridy, Avalon Sciences Ltd, and C. Naville, IFPEN, France*

SUMMARY

Orientation of the three components (3C) of a VSP is developed in the present paper in order to take advantage of the vector fidelity of the recorded seismic response of the modern VSP tools, i.e. the identity of the mechanical response to a calibrated seismic pulse received by the VSP tool from any spatial direction.
A new commercial downhole VSP tool electronics module has been recently implemented with a 3C solid state inclinometer system called a High Side Indicator (HSI), which measures the direction of the pull of gravity and calculates the angles of roll and vertical inclination in each shuttle of a borehole seismic toolstring. A third party high precision magnetometer/inclinometer has been successfully combined with one of the shuttles, in order to help verify tool string HSI orientation measurement performance in both the low deviated cased and open hole well sections. By so doing, the VSP tool manufacturer expects to (a) replace the old-fashioned gimbal settings systems with equivalent or superior solid state electronic solutions for VSP tool orientation, and (b) encourage full 3C processing of all downhole datasets, even those acquired within rig source VSP survey geometries.
This paper illustrates the new HSI technology through a field test VSP example.

INTRODUCTION

Accurate orientation of downhole receiver arrays through the use of inclinometer devices would more easily facilitate the three-component processing within zero-offset VSP's, with the aim of producing a P-P up-wave and converted P-S shear up-wave image from improved horizontal data. This would lead to better structural imaging not only in the immediate borehole vicinity, but also beyond the depth of the exploratory well.
Roll and inclination angles are determined from an accelerometer subsystem (referred to in this paper as High Side Indicator HSI) which measures the direction of the pull of gravity. If combined with fluxgate magnetometer data (usually acquired during or after each drilling phase) the roll and inclination angles enable determination of the horizontal components of the earth's local magnetic field; this information defines the well azimuth trajectory Azimuth (HAZI ±360°) and borehole vertical inclination (DEV Angle 0-90°). For the purposes of this paper HAZI has been defined from the WellTrack deviation listing with DEV and tool arm roll angle (RB) defined from the HSI accelerometers. The current accuracy of the accelerometers tested for inclination measurement is ±0.1° with tool roll accuracy ±0.25° when positioned >9.9° from vertical (limit to be reduced). The integrated roll/dip 'High Side Indicators' denote tool inclination from vertical and clockwise roll (looking downhole) as described by the parameters in Fig.1.

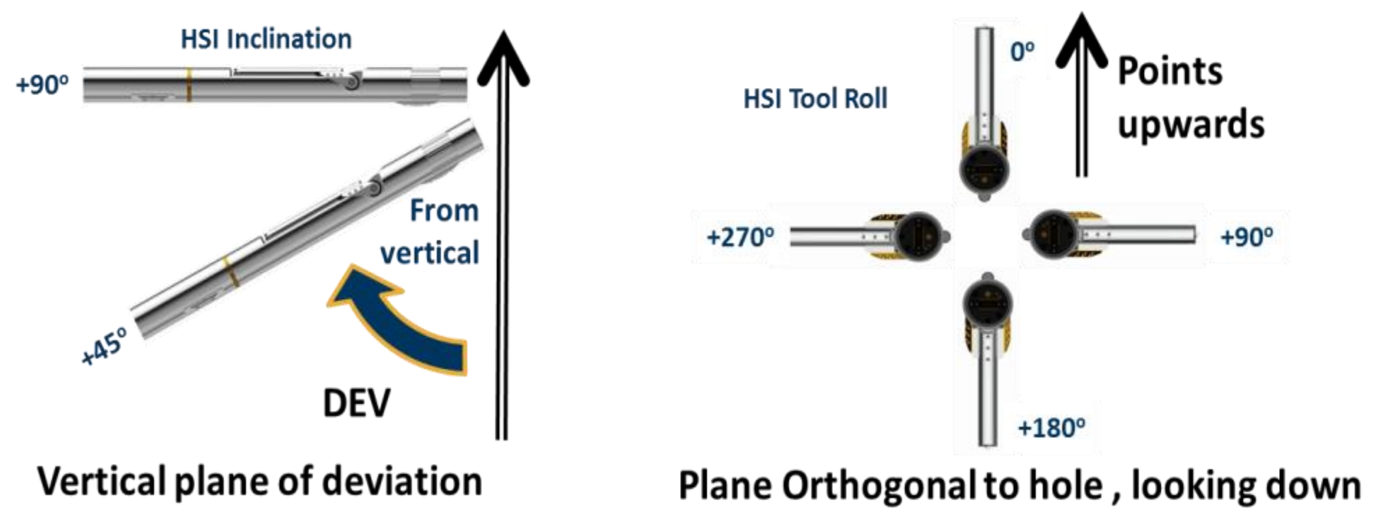


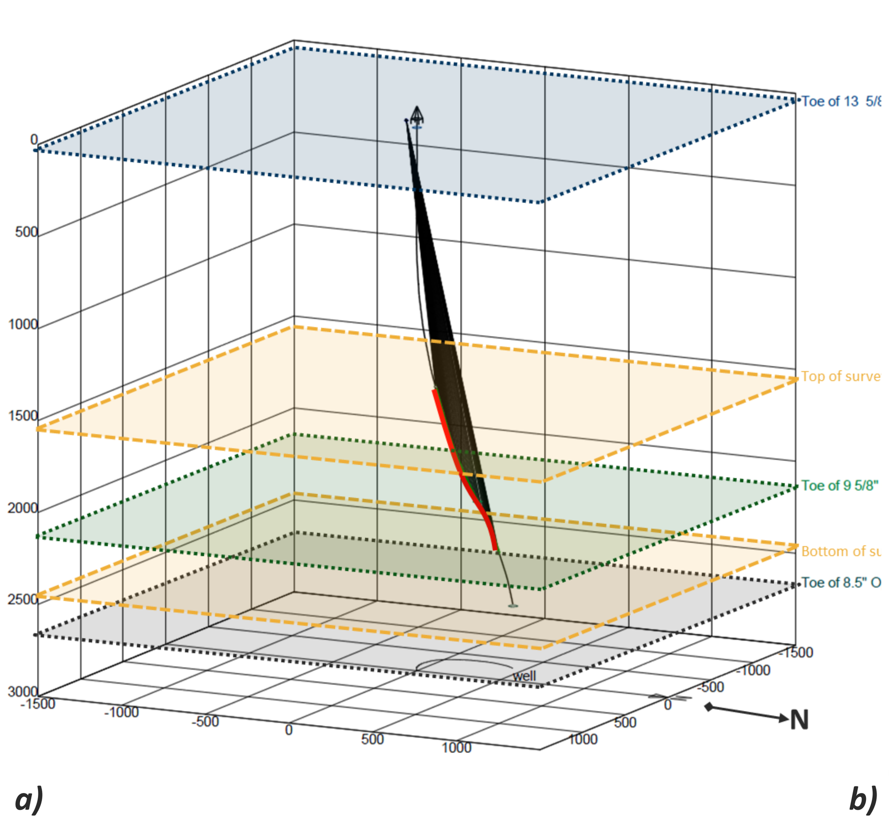
Figure 1 – Schematic defining tool vertical inclination (left) and tool arm roll angle RB from high side origin (right).

SURVEY CONFIGURATION

As is typical of many rig source VSP's, the surveys are shot partly in cased wells and partly in the open hole (OH) deep well component towards TD (total depth). This can often be within both vertical and deviated well sections. For the purposes of this survey, the RH15 Rosemanowes test facility borehole in Cornwall, UK was selected. The hole comprises a cased well section which is predominantly near vertical at the shallowest 500m, then proceeding to incline 10° from the vertical in a westerly direction, before deviating North at ~1700m MD with an increasing inclination towards 30° from the vertical within both the deeper cased (toe of casing at ~2215m) and bottom open hole sections (Fig 2b). The RH15 borehole transects the locally fractured Carnmenellis 2-mica granite formation, the predominantly vertical fractures being a product of prior cross well hydrothermal injection practices (Pearson et al., 1989).

A 3-component borehole seismic Geochain* geophone string was initially deployed to a measured depth (MD) of 2510m within the open hole section of the RH15 well. The recording system comprised of 5 receiver satellites with a 15m vertical spacing, each equipped with integrated roll/dip inclinometers (HSI). In addition to the 3C geophones, a proven third party high precision magnetometer / inclinometer directional sensor (APS orientation tool), was coupled to tool 5 of the Geochain tool string (Fig 2c). Measurement of the move out in high side roll angle between the tool 5 Geochain inclinometer and the APS tool was then used to QC the HSI roll and inclination accuracy.
A static vibroseis source was positioned a short 122m offset due East from the well head. Once the downhole tools were locked to the casing/formation via a mechanical coupling arm, 4 linear 8-100Hz sweeps were performed for each common depth stack. The process was repeated with a constant 15m vertical spacing up to 1550m MD delivering a seismic profile within both the cased well and open hole (Fig 4b).

*** Geochain** : Mark of Avalon Sciences Ltd



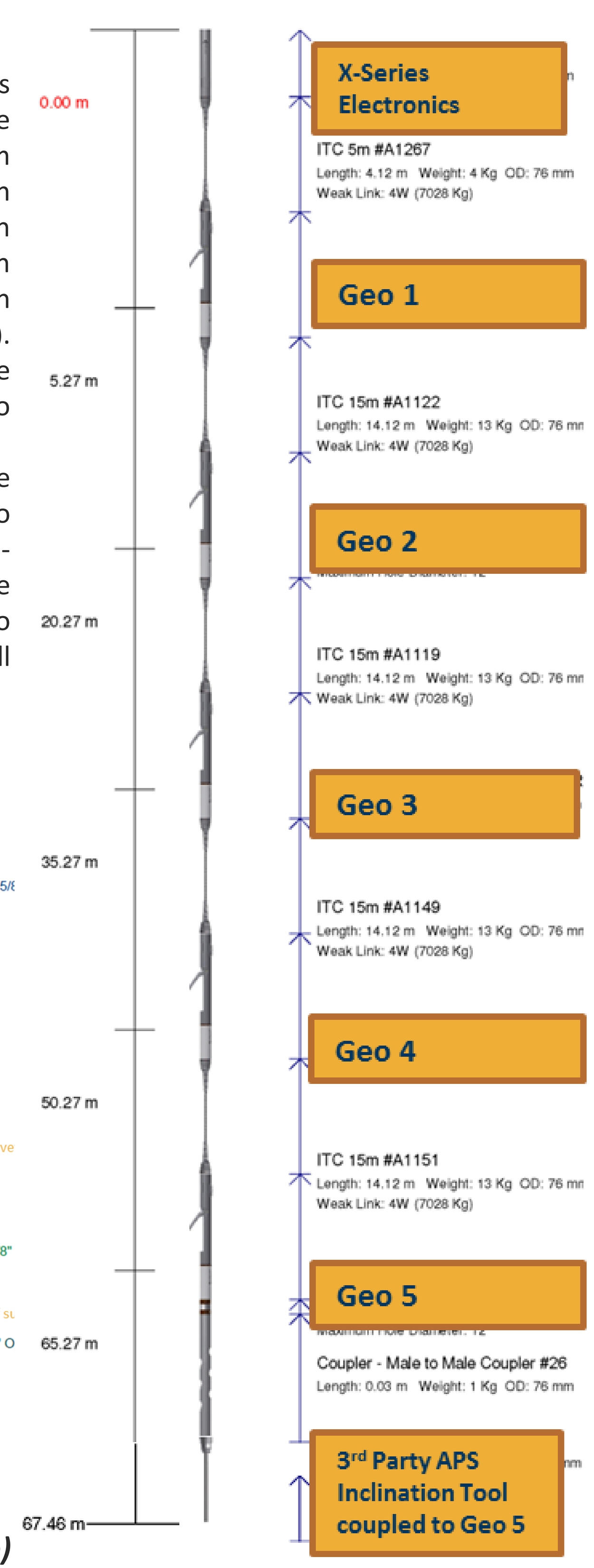


***Figure 2** – RH15 Borehole **(a)** oblique well profile view showing survey aperture (1550-2450m MD), red line.*
***(b)** borehole receiver string schematic: Geochain* 5 level VSP tool combined with APS directional sonde.*

Orientation pre-processing Methodology using EULER angles

Full 3-C processing of VSP datasets requires 3 orientation steps. Traditionally, the first rotation is that of the relative bearing (RB) angle, which is described in the plane orthogonal to the tool axis. RB is measured clockwise looking down from the vertical plane (borehole "high side" origin direction towards the direction of the arm opening (Fig. 3a). Angle RBx is the Relative Bearing angle of recorded component HX, 1st input of first rotation; the second input is component (-HY), opposite to HY, pointing +90° from HX, looking down. Components (YH) horizontal and (XV) pointing upwards in the vertical plane result from the first rotation (Fig.3a); then the successive second (well inclination) and third (well azimuth) rotations can be performed as described in Figure 3. It should be noted that although both well inclination and azimuth can be derived from the well deviation listing, the HSI accelerometers will give a more accurate tool inclination value for each satellite, especially near casing collars or within open hole environments.

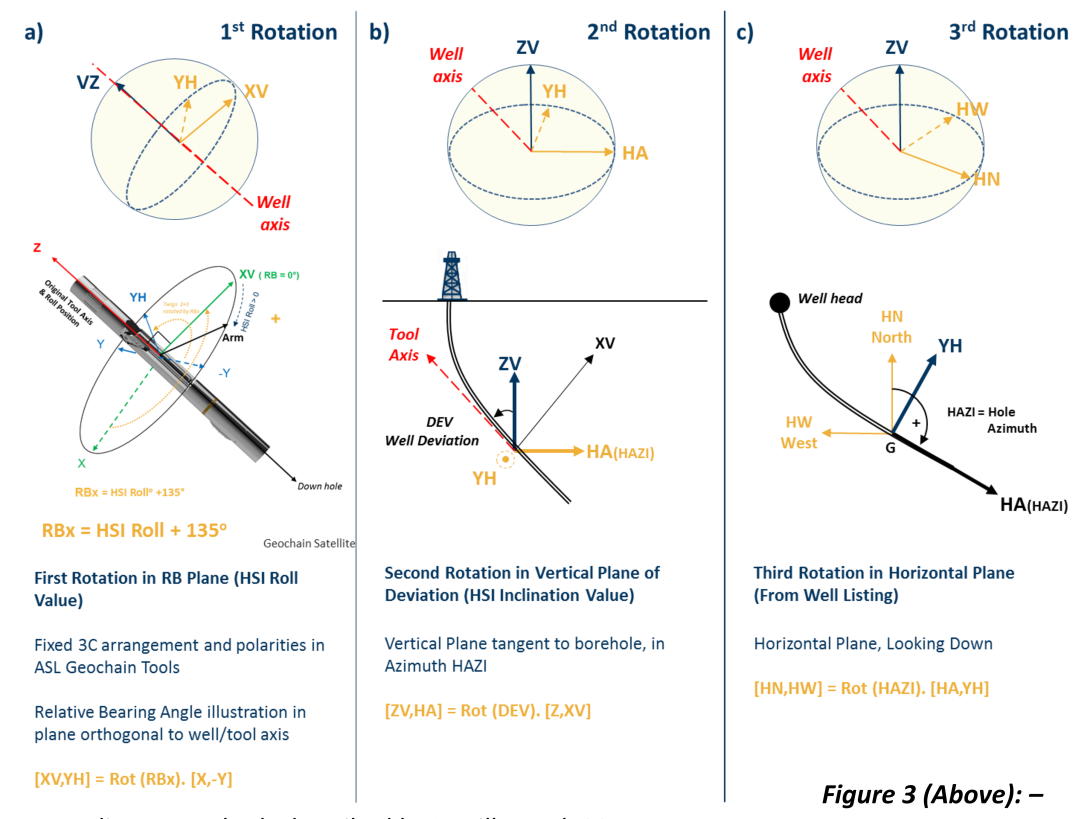


Figure 3 (Above): –
The 3C orientation survey angles for each rotational processing step according to methods described by Naville et al, 2015.
a) Rotate twigs HX, -HY by RBx (HSI roll +135°), aligning HX with XV, maintaining twig polarity, therefore ***[XV, YH] = Rot (RBx). [HX, - HY]***
b) Rotate VZ by Tool inclination i.e. VZ to vertical with inclination angle DEV, VZ, therefore: ***[ZV, HA] = Rot (DEV). [VZ, XV]***
c) Rotate by Tool azimuth (HAZI), into HNorth and HWest. ***[HN, HW] = Rot (HAZI). [HA, YH]***

RESULTS

The VSP was recorded using a three component (3C), 5-level Geochain tool string fitted with individual relative bearing/roll angle sensor for the orientation of X,Y components where the borehole inclination exceeds 9°; as a result, the 3C rotated successfully into the geographic system. Figure 4 illustrates the raw data and the first rotation in the X-Y plane orthogonal to well axis: the result after maximization of the direct P arrival (Fig4c), is unreliable where the direct P polarisation is near parallel to well axis, while the High Side Indicator RB angle rotation yields oriented results in a more straightforward manner (Fig. 4d) .

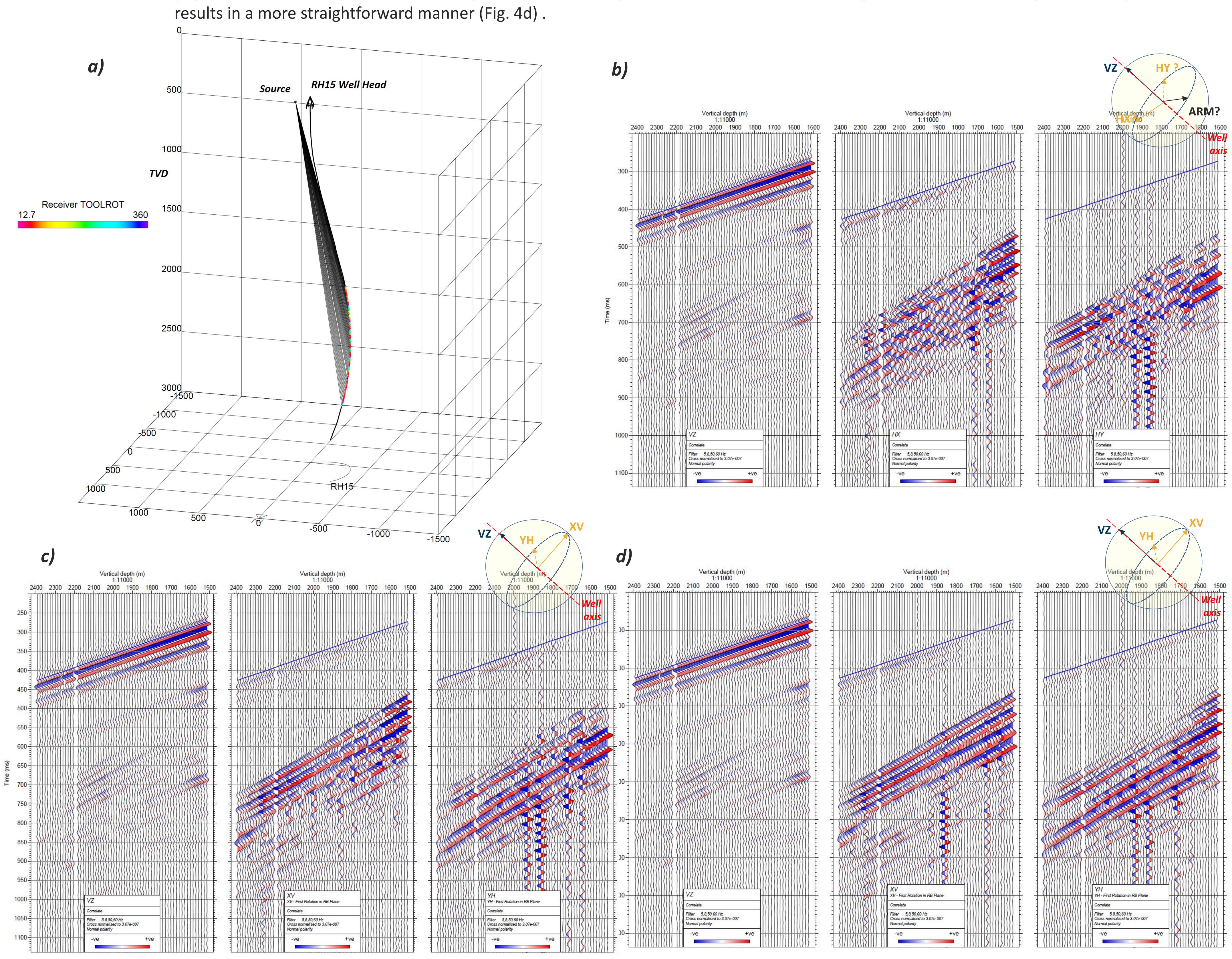
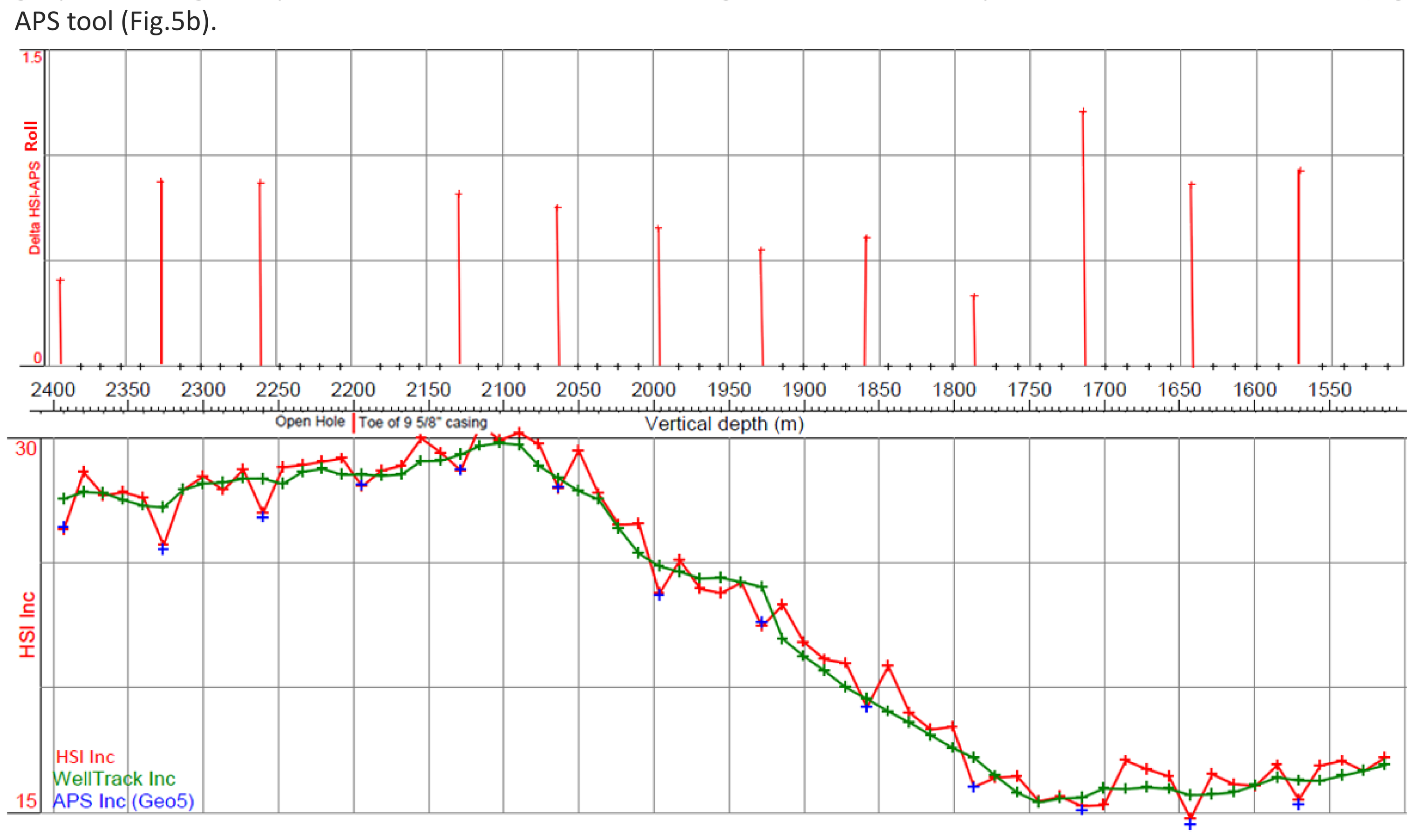


Figure 4** – **(a)** Well view with clamped receivers coloured according to HSI roll angle. **(b)** Correlated raw common depth stack plot. **(c)** Roll rotation using direct P-Maximization (HX, -HY).* ***(d)** Roll Rotation using High Side Indicator (HSI +135°) RB angle applied to HX,-HY twigs of stack plot. **All data filtered HC 55Hz, 3C constant gain displays

The raw VSP data was correlated and stacked as shown in fig. 4b. Distinct direct P-down arrivals on the vertical components and strong shear arrival on the horizontal twigs (with some weak direct P-down amplitudes). The inbuilt HSI and third party APS measurements were recorded once tool arms were clamped and tools had settled. The HSI data was employed to perform the 1st rotation of the X-Y components producing the plot shown in figure 4d, which could be easily produced on the field site as an overall QC of the VSP data right after acquisition. The APS roll measurements allowed for a calibration comparison of HSI fidelity for the directly coupled geophone 5. Figure 5 plots the delta APS versus HSI roll angle values for each depth location of bottom tool # 5 (Fig 5a) and inclination angles from HSI, Hole survey, APS tool (Fig.5b).



(a) Trace Attribute of delta HSI tool roll and 3rd party APS tool roll coupled to Geo5 (Red).

(b) Graph vs TVD plotting recorded tool inclination values (degrees from vertical) for HSI, APS and Well deviation listing.

***Figure 5 (a)** RB angles calculated from the third party APS tool also agreeing to within 1.5° of the HSI accelerometer values of the directly coupled Geophone 5 satellite . **(b)** Inclination angles from the APS tool (blue) also agreeing to within 1° of the HSI accelerometer values (red), but differing up to 2.5°from the smooth borehole survey inclination values (green).*

CONCLUSIONS

In order to verify the overall behavior of the new toolstring, a test VSP was successfully carried out in the deviated part of a cased and open-hole well section, with inclination between 15 to 30°. Historically, VSP tool manufacturers have been reluctant to add integrated orientation devices unless the mechanical tool coupling characteristics of the VSP tool is sufficient to guarantee the vector fidelity of the recorded seismic response, i.e. the identity of the mechanical response to a calibrated seismic pulse received by the VSP tool from any spatial direction.
The criterion of vector fidelity consists in the visual coherence of the oriented 3C signals on adjacent VSP depth levels, which is demonstrated on the present test VSP, mainly below 60Hz. Implementing downhole VSP tools with a 3C solid state inclinometer system and at least one magnetometer should encourage the full 3C processing of all downhole datasets, even those acquired within rig source VSP survey geometries.
Firstly, the VSP hardware and acquisition software worked as expected.
Secondly a basic field QC procedure was defined, which includes at least the roll angle rotation and associated 3C VSP displays. From this the field engineer and the client supervisor can be reassured as soon as possible about the overall VSP data quality and usability for advanced full 3C VSP processing by the geophysicists and interpreters.

Going Forward:
The current roll angle accuracy of the HSI system has potential to be improved for hole inclinations lower than 10°. In turn, the vector fidelity characteristics will progress as the processing of oriented 3 components will be requested for Rig source VSP's in areas of complex geological structures.

ACKNOWLEDGEMENTS

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