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C. R. Geoscience 336 (2004) 407–414



Tectonics

## Pre-drill surface seismic in the vicinity of the AIG-10 well and post-drill VSP

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Received 17 November 2003; accepted after revision 1 December 2003

Written on invitation of the Editorial Board

### Abstract

Pre-drill reflection surface seismic was carried out in the Aigion city area in February 2001. The poor quality of seismic reflections obtained from standard processing did not allow us to refine the location of the vertical well AIG-10 to be drilled. Subsequently, a brief study of refracted seismic arrivals was attempted in order to better define the well location, in conjunction with observations from a shallow well. In 2002, after drilling, an innovative 6-VSP position well seismic survey was successfully run, using a four-component downhole sensor tool, i.e., three orthogonal geophones and a hydrophone. Refracted seismic events and first arrivals from VSP indicated the throw of the Aigion Fault and the fault plane dip; a secondary accident striking about south–north was detected about 100 m west of the well. No P–P seismic reflection was evidenced from standard VSP processing. **To cite this article:** C. Naville et al., *C. R. Geoscience* 336 (2004).

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### Résumé

**Sismique de surface avant forage du puits AIG-10, et VSP (Vertical Seismic Profiling) après forage.** Une campagne de sismique réflexion de surface fut tirée dans la zone d'Aigion en février 2001 : les résultats du traitement standard réflexion, trop pauvres, n'ont pas permis d'affiner le modèle structural pour implanter le puits vertical AIG-10. Une brève étude des arrivées réfractées fut alors tentée, afin de mieux définir la position du forage, combinée à des observations d'un puits à faible profondeur. À l'automne 2002, après forage, une campagne de sismique de puits innovante, comprenant six VSP, fut conduite en utilisant un outil de puits à quatre composantes de réception : trois géophones orthogonaux et un hydrophone. Les arrivées directes et diffractées des VSP ont permis de préciser le rejet vertical de la faille d'Aigion et le pendage du plan de faille, tandis qu'un accident secondaire sensiblement nord–sud à 100 m à l'ouest du puits a été révélé. Aucune réflexion P–P n'a été mise en évidence par le traitement VSP. **Pour citer cet article :** C. Naville et al., *C. R. Geoscience* 336 (2004).

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*Keywords:* Corinth; seismic; Aigion Fault; AIG-10 well; VSP; refraction; diffraction; hydrophon well sensor

*Mots-clés :* Corinthe ; sismique ; faille d'Aigion ; puits AIG-10 ; PSV ; réfraction ; diffraction ; capteur de puits

## 1. Pre-drill surface seismic survey and results

A grid of four surface seismic reflection lines was recorded by the Patras University (UPSL) in order to image the Aigion area and to refine the location of vertical well AIG-10 to be drilled in the harbour zone of the Aigion City. The drilling objectives of AIG-10 well were (A) to cross the Aigion Fault in the 700–1000 m depth interval, and (B) to encounter the limestone substratum before intersecting the Aigion Fault, so as to enable studying the effects of fracturing and faulting within the limestone formation: this was motivated by the importance of carbonates as hydrocarbon bearing reservoirs. Unfortunately, the surface reflection seismic imaging is poor to null, in spite of the good quality of the raw seismic records acquired: Fig. 1 shows a correlated field record, using a 50 000-lbs peak-force vibrator, stack of three sweeps 8–80 Hz, 120 traces, 15 m apart. Worse, on the seismic line L2 across Aigion city, no result could be obtained in the northern compartment of the Aigion Fault, either from reflection or refraction seismic methods, which locally indicates a high level of heterogeneity.

Consequently, the southern compartment was briefly studied using the refracted arrivals of a  $4000 \text{ m s}^{-1}$  marker, corresponding possibly to the top of the carbonate substratum of interest, allowing to estimate its depth (Gardner method, 1939, [1]); Fig. 2 shows a couple of direct and reverse shot displays from line L2, in reduced time ( $T - X/V$ ), showing a well-defined  $4 \text{ km s}^{-1}$  refraction marker in secondary arrival at intercept time 370 ms, with a critical offset difficult to read, about  $900 \pm 100 \text{ m}$ . The three-velocity layer sketch in Fig. 3 shows the depth estimate of the refraction markers from ground level; the velocities are derived from the observed direct and refracted arrivals. At the time, the  $3150 \text{ m s}^{-1}$  conglomerate formation was assumed to extend down to the  $4 \text{ km s}^{-1}$  refraction marker assimilated to carbonates, so that no velocity inversion was expected, and the refraction critical offset had not been used to estimate the overburden velocity. Therefore, the resulting 660 m depth prediction for the presumed top of carbonates in the

southern compartment represents a maximum depth value.

In the northern compartment, the depth of the top carbonate target was derived from the following estimation of the Aigion Fault throw: a shallow well previously drilled in the conglomerates encountered in the northern compartment around 160 m depth/MSL; as the elevation of the outcropping conglomerates in the southern compartment is 100 m, a 260 m throw value was taken.

## 2. Suggestions for further surface seismic processing

(1) Fig. 1 shows from line L1 a clear diffraction pattern associated with the Aigion Fault. Many similar patterns have been observed on all lines, and can be used to map the main accidents around Aigion.

(2) Reflection reprocessing with improved mute, static and stacking velocities.

## 3. Post-drill well seismic survey using wireline VSP (Vertical Seismic Profiling) technique

The AIG-10 well successively encountered a slow velocity ( $2500 \text{ m s}^{-1}$ ) shale layer below the conglomerates, at 300 m, a high velocity ( $3600 \text{ m s}^{-1}$ ) radiolarite formation around 520 m, and very-high-velocity carbonates ( $5500 \text{ m s}^{-1}$ ) at 696 m. The well intersected the Aigion Fault at 760 m, reached then a 1000 m total depth into  $5000 \text{ m s}^{-1}$  carbonates. After drilling and wireline logging, a six-source position VSP survey (Fig. 4) was successfully operated by UPSL/IPGP/IFP, using the new SSR–CGG VSP tool, characterized by improved coupling isotropy, with the following initial aims:

(1) to illuminate the major structural features in the well vicinity: faults, dipping reflectors, etc., and obtain seismic velocity measurements in P and S modes;

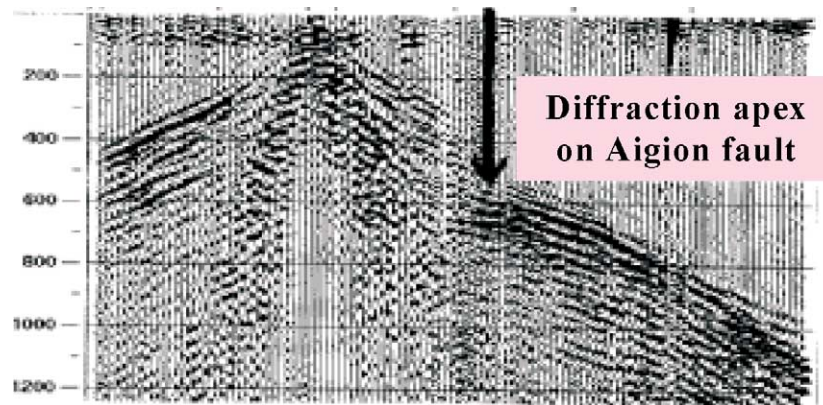


Fig. 1. Raw surface seismic record on line L1: diffraction generated by the Aigion Fault.

Fig. 1. Enregistrement sismique brut, ligne L1 : diffraction sur la faille d'Aigion.

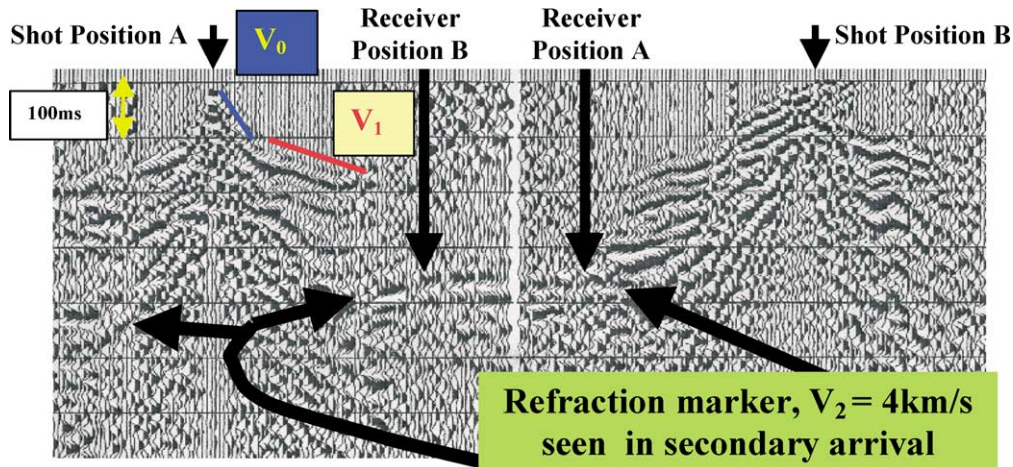


Fig. 2. Refraction arrivals on the presumed limestone marker, southern compartment of the Aigion Fault: direct and reverse records, in reduced time (correction  $T - X/V$ ) with  $V = 4 \text{ km s}^{-1}$ .

Fig. 2. Arrivées réfractées du marqueur présumé du toit des calcaires, côté sud de la faille d'Aigion : tirs directs et inverses, rejeux en temps réduits ( $T - X/V$ ), avec  $V = 4 \text{ km s}^{-1}$ .

- (2) to investigate the reasons for the lack of surface seismic results in the immediate well vicinity;
- (3) to study the additional information brought by the hydrophone measurements;
- (4) eventually, to study the S-wave anisotropy, which can be chancy in a faulted geological environment.

VSP parameters: depth sampling, deep part: 10 m, 15 m above; sweep 8–100 Hz; sampling rate: 2 ms.

The VSP survey took place after removal of the drilling machine due to operational and financial

reasons. Unfortunately, the well could not be cleaned when the VSP tool could not be lowered deeper than 755 m. The VSP acquisition is detailed in the EU 3F-CORINTH second-year progress report.

#### 4. VSP processing results

Surprisingly, in spite of major velocity contrasts expressed by the sonic log and by the interval velocities derived from direct arrival VSP times, the 3C or hy-

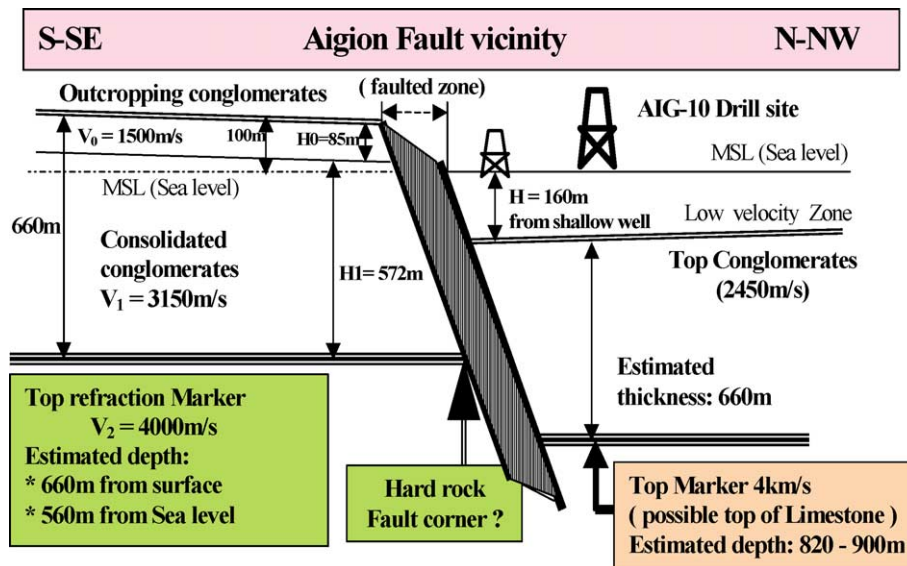


Fig. 3. Pre-drill structural sketch in AIG-10 well vicinity. The  $4 \text{ km s}^{-1}$  refraction Marker depth on the southern side of the Aigion Fault is estimated at 660 m from the surface. On the north of the Aigion Fault, a shallow well encountered the top of conglomerates at depth 160 m/MSL. Therefore, the  $4 \text{ km s}^{-1}$  refraction Marker was expected on the northern side of the Aigion Fault in the depth range 820–900 m/MSL.

Fig. 3. Schéma structural du voisinage du puits AIG-10, avant forage. La profondeur du marqueur réfraction à  $4 \text{ km s}^{-1}$ , du côté sud de la faille d'Aigion est estimée à 660 m par rapport au sol. Du côté nord, un puits peu profond a rencontré le toit des conglomérats à 160 m par rapport à la mer. Ainsi, la profondeur minimale du marqueur à  $4 \text{ km s}^{-1}$  a-t-elle été estimée à  $660 + 160 = 820 \text{ m/MSL}$ .

drophone VSP processed results do not evidence clear P–P reflected events, even on the depth stations located right above the major impedance contrast levels. Only a few coherent P–S-converted reflected line-ups appear after velocity-filter removal of the downgoing P-wave train, and call for further analysis. As the amplitudes of VSP reflection are about one order of magnitude lower than direct arrivals on raw signals, the high-energy direct, diffracted or refracted arrivals have been studied and yielded additional structural information.

On Offset VSP#3, with source located right on the surface trace of Aigion Fault, the direct arrival at shallow depth (right side of displays in Fig. 5A and B) is abnormally weaker than in depth, in contrast with all other five VSPs (e.g., Fig. 6A). Actually, in the deep part, the first-arrival wave train (left half displays in Fig. 5A and B) exhibits a high-energy refraction pattern with apex at 500–520 m, right at the top of a high-velocity radiolarite layer, at  $3800 \text{ m s}^{-1}$  (Fig. 5C). From depth 480 m to 520 m, the direct arrival polarisation is near horizontal, but oriented slightly downwards, indicating that a high-energy downgoing P-

wave propagates along the fault plane, then refracts towards the well whenever the velocity is significantly lower in the northern low compartment of the fault. Above depth 520 m, the polarisation observed at the well indicates that the velocity in the southern side of the fault is lower than  $5000 \text{ m s}^{-1}$ , meaning that the top of the carbonates is lower than 520 m on the southern side (Fig. 5C).

Additionally, on the deep part of VSP#3 (leftmost traces in Fig. 5A and B), a weak refracted first arrival appears below depth 600 m, with vertical incidence at the well measuring  $70^\circ$  (Fig. 5D). Given the depth at which this weak refracted arrival appears (600 m) and the geometry, the hard carbonate fault corner is expected around 550 m (D1 on sketch in Fig. 5C and D). Knowing the velocity in both fault compartments between 660 and 690 m, the dip of the Aigion Fault plane has been estimated from the incidence angles (see Fig. 5D). The  $60^\circ$  dip value obtained closely corresponds to the dip of a straight line joining the surface source position VSP#3 to the intersection of the well with the fault at depth 760 m, which is in agreement with the dipmeter log measurements.

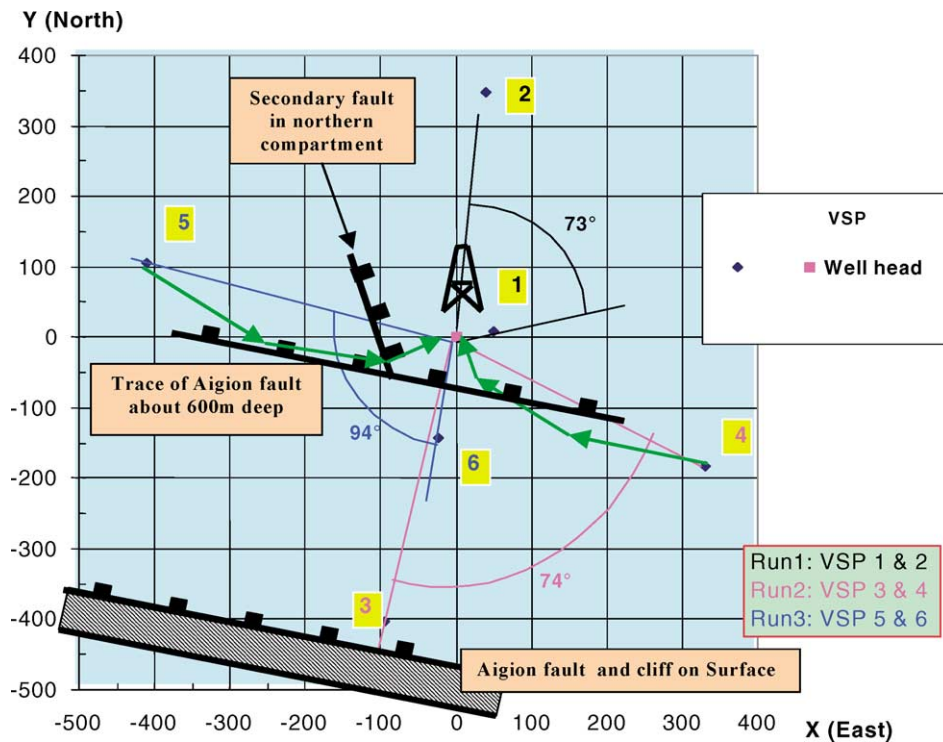


Fig. 4. Plane view of wellhead and VSP source positions: VSP#3 yields the dip of the Aigion Fault plane ( $60^\circ$ ), and the vertical throw of the Aigion Fault (about 150 m). Below depth 600 m, VSP# 5 detected a secondary accident located 100 m west of the well. Conventionally, the direct arrival azimuths of all VSP's nearly follow the source to well direction. However, the direct arrival azimuths of VSP#4 and 5 are deviated below 600 m due to total refraction on the nearby Aigion Fault plane (green rays), confirming the higher velocity in the southern fault compartment, as the fault plane is associated with a strong lateral velocity contrast.

Fig. 4. Schéma de position de la tête de puits AIG-10 et des sources PSV : PSV#3 donne le pendage de la faille d'Aigion ( $60^\circ$ ), et le rejet de faille (environ 150 m). Au-dessous de 600 m, le PSV#5 a détecté un accident secondaire situé à 100 m à l'ouest du puits. Par convention, l'azimut d'arrivée directe PSV est assimilée à la direction source-récepteur/puits (hypothèse de milieu stratifié horizontal). Dans le cas présent, les azimuts d'arrivée directe des PSV#4 et 5 sont fortement déviés au-dessous de 600 m par la réfraction totale sur le compartiment sud de faille d'Aigion toute proche (rais verts), confirmant ainsi l'accroissement brutal de la vitesse dans le compartiment sud, au travers du plan de faille.

On Offset VSP#5, located west of the well (Fig. 4), an obvious diffraction pattern appears (see Fig. 6A), expressing the presence of a secondary accident characterised by a hard rock edge about 650 m deep, with a downthrow looking eastward to the well (Fig. 6B). The polarisation from oriented 3C geophones indicates a P-wave mode diffraction, and a subsequent time inversion computation yields a distance of about 100–120 m to the well. The strike of this accident trends toward SSE–NNW, although it could not be sharply defined since orienting the horizontal components was delicate.

As a matter of fact, the direct arrival polarisations from VSP#4 and 5 strongly deviate from the source-

to-well-receiver radial direction below 600 m, due to the close proximity of the high-velocity southern compartment of the Aigion Fault, generating a partially refracted propagation along the fault plane, as illustrated by the green rays in Fig. 4. Although each VSP run was recorded with two sources in different azimuths from the well, VSP# 4 and 5 could not be used to orient the horizontal components.

## 5. Hydrophone VSP data

Strong P-tube upgoing converted arrivals appear on the hydrophone signals (Figs. 5A and 6A), mainly



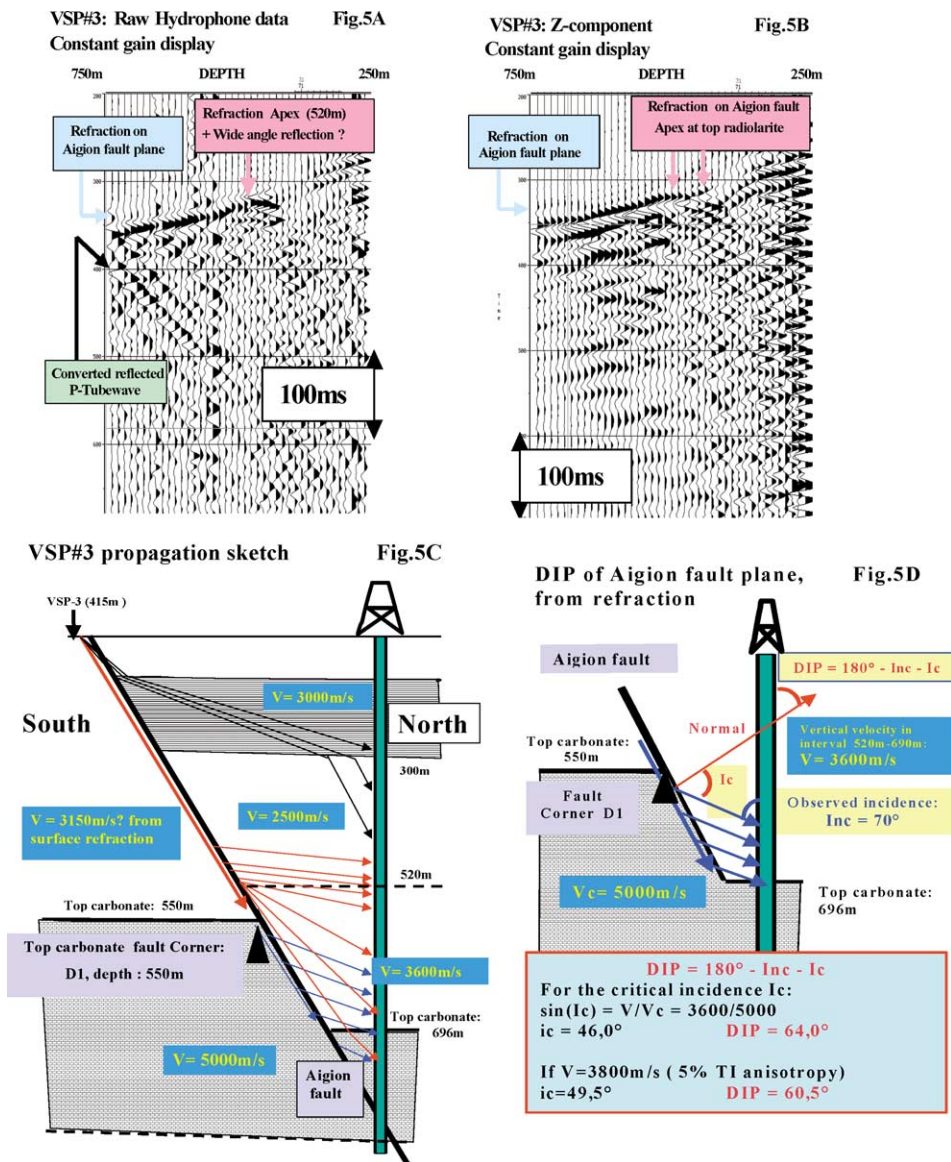


Fig. 5. (A,B) P-wave refraction on Aigion Fault plane, actually observed on Offset VSP 3. (C,D) Sketches of Refracted propagation on Aigion Fault plane. Black rays: weak amplitude, near-vertical polarisation. Red rays: strong amplitude arrivals; above and around the apex depth 520 m, top of the high-velocity  $3800 \text{ m s}^{-1}$  radiolarite layer, the propagation is nearly horizontal: it indicates that the downgoing propagation roughly follows the Aigion Fault plane, then refracts towards the well. Blue rays: medium amplitude, Refraction on fault plane along high velocity carbonates, vertical incidence measured:  $70^\circ$ , leads to a  $60^\circ$  DIP for the Aigion Fault plane (D). It implies that the depth of the hard carbonate fault corner D1 is about 550 m.

Fig. 5. (A,B) Réfraction en onde-P sur le plan de faille d'Aigion, observé sur PSV#3-offset. (C,D) Schémas de propagation réfractée le long du plan de faille d'Aigion. Rais noirs : amplitude faible, polarisation proche de la verticale. Rais rouges : arrivées d'amplitude forte : à proximité de la profondeur d'apex 520 m, correspondant au toit d'un banc de radiolarite de vitesse élevée  $3800 \text{ m s}^{-1}$ , la propagation est proche de l'horizontale : l'onde descendante se propage donc le long de la faille d'Aigion, puis se réfracte vers le puits, impliquant une vitesse plus élevée dans le compartiment sud. Rais bleus : amplitude moyenne, réfraction sur le plan de faille au droit des carbonates de vitesse très élevée : l'incidence verticale mesurée à  $70^\circ$  conduit à un pendage de faille de  $60^\circ$  (Fig. 5D). L'arête D1 du toit des carbonates côté sud se situe à environ 550 m de profondeur.

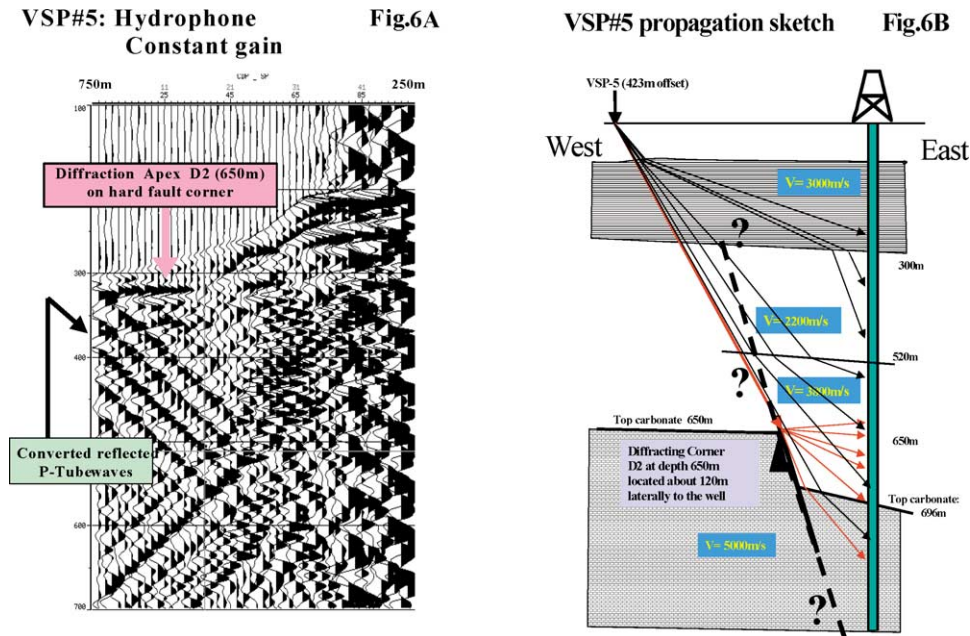


Fig. 6. (A,B) Observation from Offset VSP 5 (west): black rays, direct arrival; red rays: strong diffraction on hard rock fault corner with apex above the carbonates depth at the well; the well is located on the low compartment of the fault (B).

Fig. 6. (A,B) Observations sur le PSV#5-Offset (ouest). Rais noirs : arrivée directe ; rais rouges : diffraction de FORTE amplitude sur une arête de faille saillante, de roche indurée, avec apex à 650 m, au-dessus de la profondeur des carbonates rencontrés au puits ; le puits est localisé dans le compartiment abaissé de cet accident, comme indiqué sur la Fig. 6B.

generated right at the depth of a permeable fracture/fault, at 744 m. The amplitude variations of P-tube arrivals at 744 m versus VSP source azimuth need to be better understood and geologically interpreted. Small P-tube conversions appear in the cased part right at the level of earth impedance contrasts. The hydrophone data show none of the strong S-wave events recorded by the 3C geophones. Many undesired downgoing tube wave arrivals are recorded by the hydrophone only: they would have been attenuated by aerating the mud column if the VSP operation had been carried out in presence of the drilling machine, as initially planned.

## 6. Methods used

Since no reflection were apparent after processing, the first and secondary VSP arrivals of high energy have been analysed, inspired by methods described in references [1–3], related to the recognition and analysis of refraction and diffraction patterns.

## 7. Preliminary conclusions on the AIG-10 VSP study

The oriented four-component VSP constrained the geometry of the Aigion Fault, narrowing the fault dip to 60–64° to the NNE, with a throw of 150 m instead of 260 m prior to drilling.

The VSP revealed the existence of a secondary accident striking about SSE–NNW in the lowered northern compartment of the Aigion Fault, located about to the 100 m west of the well at 650 m depth, with an eastward downthrow of about 50 m, as illustrated in the plane view sketch in Fig. 4.

The 4 km s<sup>-1</sup> refraction marker observed in the southern compartment needs to be identified, its depth remains to be updated from geological constraints, using the velocity model of upper layers from sonic log and VSP in replacement of the pre-drill single 3150 m s<sup>-1</sup> upper-layer model of Fig. 2.

Although additional seismic results can be expected from more extensive data processing, the question

raised by the lack of seismic reflection in surface and well seismic remains to be answered.

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