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Seismic Evidences of Fluid Accumulation and Migration: Insights from the Deepwater Niger Delta

By

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Abstract

3D seismic data acquired in the deepwater Niger Delta have been used to investigate potential links between seabed manifestation of fluid flow, potential sources of the fluids and migration conduits. The seabed consists of numerous bathymetric ridges, submarine canyons and fluid-venting structures with morphologies similar to pockmarks. An ENE-WSW trending arcuate bathymetric ridge divides the seabed topography of the studied area in the deepwater Niger Delta into northern and southern domains. The main geomorphic features in the former are fluid-venting structures clustered along and within canyons, but also within bathymetric ridges and grooves and in isolation in the latter. Analysis of sub-seabed structures using seismic attribute data computed to highlight discontinuities reveals a strong link between pockmark craters along canyon margins with vertical and lateral migration of fluids along discontinuities and damage zones next to faults in two locations. These areas are clearly linked to strong but localized seismic amplitude anomalies most likely representing hydrocarbon-water interface in the hanging wall and footwall folds.

Key words: Deepwater Niger Delta, 3D seismic data, seabed bathymetry, amplitude anomalies, discontinuities, fluid migration.

Introduction

Seabed manifestation of fluid-flow has long been recognized as a common process in active and passive continental margins[1,2]. In the Gulf of Guinea, structures related to fluid-seepage such as pockmarks and mud volcanoes have been mapped using highly specialized underwater vehicles, cruise ships and at the scale of seismic resolution[3,4]. As oil and gas exploration is intensified in geologically complex deep-water frontiers in the Niger Delta, the need for a regional understanding of fluid migration processes and interplay between sources of hydrocarbon, accumulation, migration and entrapment becomes even more important. Therefore, the application of advanced techniques for detecting fluid accumulation, lateral and vertical migration pathways is a key step in establishing trapped hydrocarbon volumes[5,6].

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In this work, 3D seismic data acquired over an area of overlapping maritime boundary between Nigeria-São Tomé and Príncipe, referred to as the Joint Development Zone (Figure 1) have been used to investigate links between seabed bathymetry, fluid accumulation, and migration processes. The seabed bathymetry was first generated by detailed line-by-line tracking of the seabed reflection. The spatial distribution of fluid-venting structures in two locations was delineated from the seismically generated seabed bathymetry. Finally, the connection between fluid-venting structures with potential sources of the fluids in the underlying seismic units and conduits for the fluid to migrate to the seabed was investigated using the seismic reflectivity volume and multi-trace similarity data. The former was used to identify seismic amplitude anomalies that may be due to fluid accumulation while the latter was computed to highlight discontinuities and damage zones through which hydrocarbon fluids can migrate. Analysis of sub-seabed reflectivity and multi-trace similarity anomalies reveals a strong link between fluid accumulation (supported by strong amplitude anomalies in the hanging wall and footwall folds), fluid migration along vertical and lateral zones of discontinuities beneath the seabed and damage zones next to the faults (as shown by discrete zones of lateral and vertical similarity anomalies in these areas) with pockmark craters along canyon margins in the two locations analyzed.

Regional geologic setting

Figure 2 is a NNE-SSW line depicting the structural and stratigraphic setting of the Joint Development Zone. Four major seismic units have been identified based on the pattern of reflectivity. The basal unit (Unit IV) is predominantly seismically transparent and interpreted to represent the crystalline basement[7]. Unit III exhibits strong reflection continuity, but is in places offset by discontinuities that appear to extend into the basement. The unit represents synrift/post-rift succession of Upper Cretaceous age[8]. Unit II is a thick zone of low seismic resolution due to incoherent reflection pattern except for regionally strong and extensive reflections in at least two locations near the top and the middle of the unit. These reflections have previously been interpreted as detachment levels of the overlying thrusts[9].This Unit represents the deepwater equivalent of the Palaeocene pro-delta marine shales of the Akata Formation, the main source of hydrocarbon generation in the Niger Delta[10]. The lack of acoustic impedance contrast within the unit was interpreted to be due to high pore pressure[11]. Unit I is made up of a well stratified seismic facies offset by predominantly seaward-verging faults. The base of the unit marks a major zone of change in facies from the stratified reflections of Unit I to the incoherent reflections in Unit II speculated to represent a major sequence boundary[8]. Unit I represents the deepwater equivalent of Miocene Agbada

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Formation. The formation consists of alternating sands and shale beds. The sands are known to be the main hydrocarbon reservoir rocks, while the shales are the sealing units[10]. In the shallower parts of the unit, the reflections are interpreted as unconformities, while the top of the unit is the seabed reflection. Faults in the area are predominantly seaward-verging with a reverse sense of displacement with low angle dips typical of thrust faults. The faults merge into a basal detachment surface within Unit II. Fault spacing is variable but ranges between 2 and 6 km. Displacement is predominantly within Unit I and, in the shallower parts of the unit, the faults grade into hanging wall folds before reaching the seafloor, forming prominent bathymetric ridges incised by NNE – SSW trending canyon systems[12]. The folds are geometrically similar to fault-bend, fault propagation and detachment folds[9].

Methodology

Data

The post-stack time-migrated 3D data have inline and crossline spacing of 25 and 12.5 m respectively. The recording interval is 8 s with a 4 ms sampling rate. The dominant frequency varies from 40 to 60 Hz between 3.0 and 5.0s two-way travel time. A frequency of 46 Hz that appears to be the strongest in the amplitude spectrum plot was used to calculate the resolution of the data. The data are displayed with a reverse polarity and have been zero-phased migrated with vertical scale in seconds (s) two-way travel time (TWTT). The maximum vertical resolution is ~10 m at shallower sections but deteriorates to ~18 m at deeper sections of the data. The loss of seismic resolution is attributed to fluid overpressures and the attenuation of propagating seismic waves with increasing depth[13].

Mapping seabed reflection

An illuminator amplitude volume of the data was first created to facilitate rapid auto-tracking of reflection events based on enhanced amplitude signals. The seabed reflection is a strong trough that was tracked line by line across the area (3000 km^2) in the inline and crossline directions based on visual amplitude character recognition using advanced 2D and 3D horizon-seeker auto-hunt tool where the reflection is strong, continuous and well resolved. However, the horizon was manually tracked where the reflection is complex especially at the base of canyons and crests of bathymetric ridges. The seabed vertical resolution is ~8m and was depth converted using a velocity of 1500m/s.

Multi-trace similarity computation

An attribute that detects and highlights the waveform similarity of adjacent trace pairs and the time difference between the traces interpreted as vectors was computed to highlight discontinuities and damage zones. A high similarity means the trace segments are similar in wave-shape and amplitude. Low similarity implies that the traces are dissimilar probably due to deformation[14]. For improved detection of faults and visibility of fault zones, the attribute was computed trace to trace guided by the dips and azimuths of the traces. The similarity data are displayed in grey scale normalized to between 0 and 1. Darker shades (similarity values approaching 0) are interpreted as due to increasingly dissimilar traces and represents faults, discontinuities, and damage zones. Lighter shades (similarity values approaching 1)

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are due to increasingly similar traces. Multi-trace similarity was restricted to seismic Unit I based on the premise that low similarity anomalies are likely to be due to the brittle deformation of the Agbada Formation. The chaotic and poorly defined pattern of similarity in Unit II represents the overpressured and shaly units of the Akata Formation. Comprehensive description of the mathematics of similarity computation applied to the data is described in[14,15,16].

Results and discussion

Seabed bathymetry

An ENE-WSW trending ridge divides the seabed bathymetry into the northern and southern domains in water depths ranging from 1300 to 1900 m (Figure 3). Bathymetry in the northern domain is smooth to slightly undulating with a relief that slopes regionally down to the northwest. The major structural features are NNE-SSW trending meandering canyons that cut across the ridge. In deepwater settings, the canyons typically provide the routes for transporting reservoir-quality sands (turbidites) from the shelf and slope onto deep-water marine fans[17,18]. Extensive craters of fluid-venting structures with morphologies similar to pockmarks[19]constitute the main bathymetric feature in the proximal parts of the northern domain. The pockmarks are clustered along the margins of the canyons, within linear and meandering zones of discontinuities and randomly distributed. In the proximal parts of the canyon, the structures are broadly distributed, while in the distal parts of the canyon, the pockmarks are clustered next to the canyons. Similar structures on the lower slope of the Congo Basin are interpreted to be due to shallow buried deep-water sediments[6]. However, random distribution of pockmarks with no clear link to canyons may probably be due to changes in fluid expulsion mechanisms (e.g. variation in porosity and permeability, lack of conduits for migration). Water depth in the southern domain varies from 1900 to 2500 m. The bathymetry in the southeast is rugged and dominated by NE-SW trending ridges and grooves. In the southwest the seabed consists of ~~an~~ N-S trending and highly sinuous canyons. It is likely that gravity-induced debris flow may be a major source of sediments feeding the canyons as shown by geomorphic features similar to slide scars on the margins of a major zone of elevated bathymetry. This paper focuses on investigating the connectivity between the pockmarks, fluid accumulation and potential conduits for fluid migration to the seabed in two locations with the densest concentration of fluid-venting structures (Figure 4 and Figure 5).

Linking seabed bathymetry with sub-seabed seismic structure

Figures 4 and–5 show seismic and multi-trace similarity vertical cross sections highlighting the patterns of reflectivity and multi-trace similarity across the areas with the densest concentration of fluid escape features in Figure 3. Multiple zones exhibiting amplitude

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brightening are clearly evident in the hanging wall and footwall of the folded thrusts within seismic Unit I (green arrows in Figure 4a and Figure 5a). Although the link between amplitude brightening and fluid accumulation is not usually straightforward, bright spots and associated flat spots may be due to changes in acoustic impedance not related to hydrocarbons[20]. In this example, the fluids are possible hydrocarbon accumulations trapped within permeable beds beneath the seabed, as shown by strong amplitude anomalies – typical of direct hydrocarbon indicators (DHIs) in the shallower parts of seismic Unit I. Additional fluid sources could probably be found in the hanging wall and footwall folds exhibiting stacked amplitude anomalies with widths of up to 3 km (Figure 4a).

Two distinct patterns of multi-trace similarity anomalies are observed in Figures 4b and 5b. The horizontal red arrows highlight discrete zones of low similarity at the location of discontinuities beneath the seabed in the shallowest parts of seismic Unit I coincident with pockmark craters on the seabed. The green arrows in Figures 4b and-5b show damage zones next to the faults highlighted by dip-steered multi-trace similarity computation techniques. Although deformation in fault zones may be beyond the limits of seismic resolution, damage zones next to faults may be due to the distortion of reflection events and or typically poor imaging behind faults. The visibility of these zones has been enhanced by applying dip-steering for similarity computation (green arrows) and is clearly connected to discontinuities (vertical red arrows). These zones are considered potential conduits for vertical and lateral migration of fluids along bedding parallel damage zones to the seabed (dashed red arrows in Figures 4b and-5b). Outcrop-scale analysis of normal faults has shown that gouge generation in fault zones can enhance the porosity and permeability of the fault core thereby facilitating the migration of hydrocarbon fluids along fault zones[21].

Comparing seismic reflectivity with multi-trace similarity anomalies, a strong connection between fluid-venting craters, vertical zones of discontinuities beneath the seabed and strong amplitude anomalies in multiple locations within seismic Unit I highlighted in the boxed regions in Figures 4a and 5a. However, the intense deformation in the crestal parts of the folds in Figures 4b and 5b (as shown by the anomalously low multi-trace similarity) implies that there is the likelihood of fluids leaking vertically to the seabed. Additional questions then arise regarding the integrity of any caprock units (if any) supposedly sealing the crestal parts of the folds for any commercial accumulation of hydrocarbon in these areas.

Summary and Conclusions

Techniques for predicting fluid accumulation and migration pathways have been applied to a 3D seismic imaging of parts of the compressional deepwater Niger Delta. Analysis of the seabed bathymetry and sub-seabed structure reveals a close correlation between pockmark craters, fluid sources and migration pathways to the seabed. Seismic amplitude anomalies show that fluid accumulation in hanging wall and footwall folds is clearly connected to the seabed via discontinuities and damage zones next to the faults. This observation raises the possibility that significant hydrocarbon accumulation could have been leaked to the seabed through conduits concentrated primarily along canyon margins. The results have tacit implications on the hydrocarbon prospectivity of the deepwater Niger Delta area that overlaps the maritime boundary between Nigeria-São Tomé and Príncipe.

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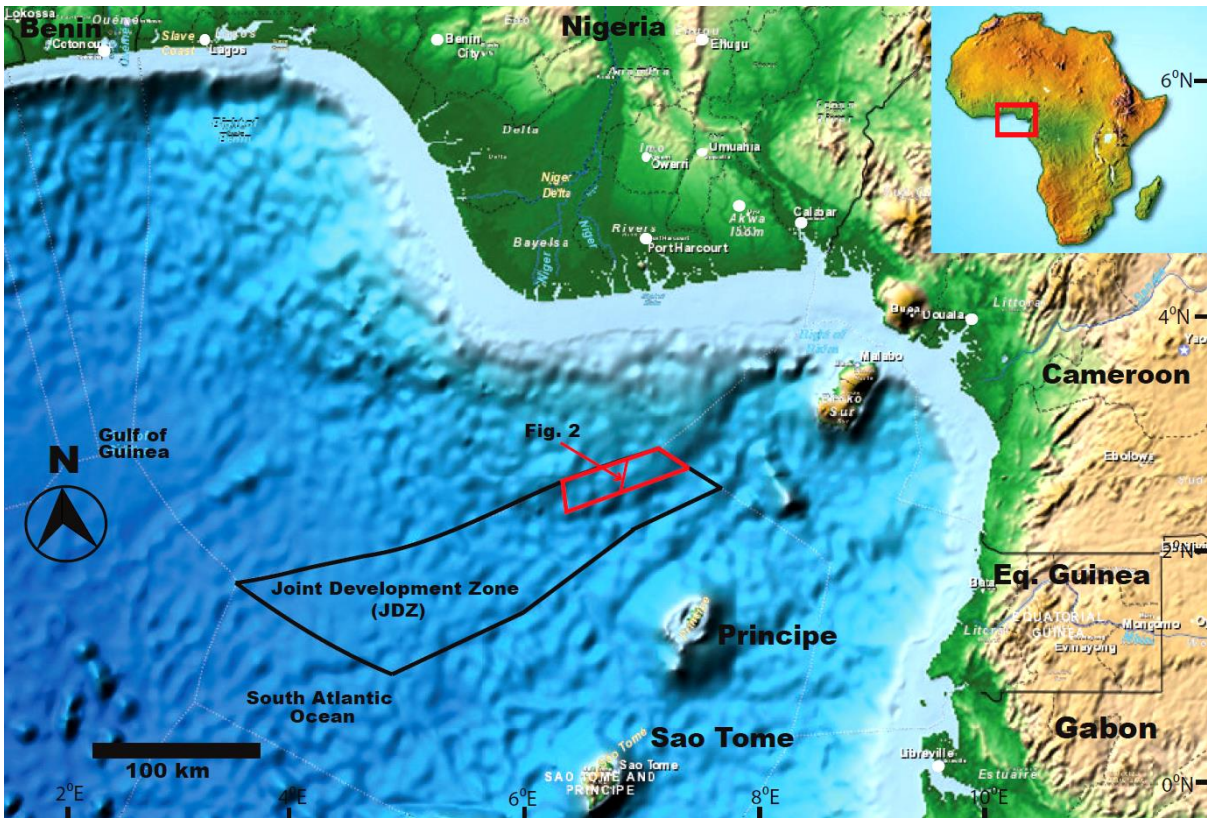

Figure 1: Map of the Gulf of Guinea showing the location of the study area.

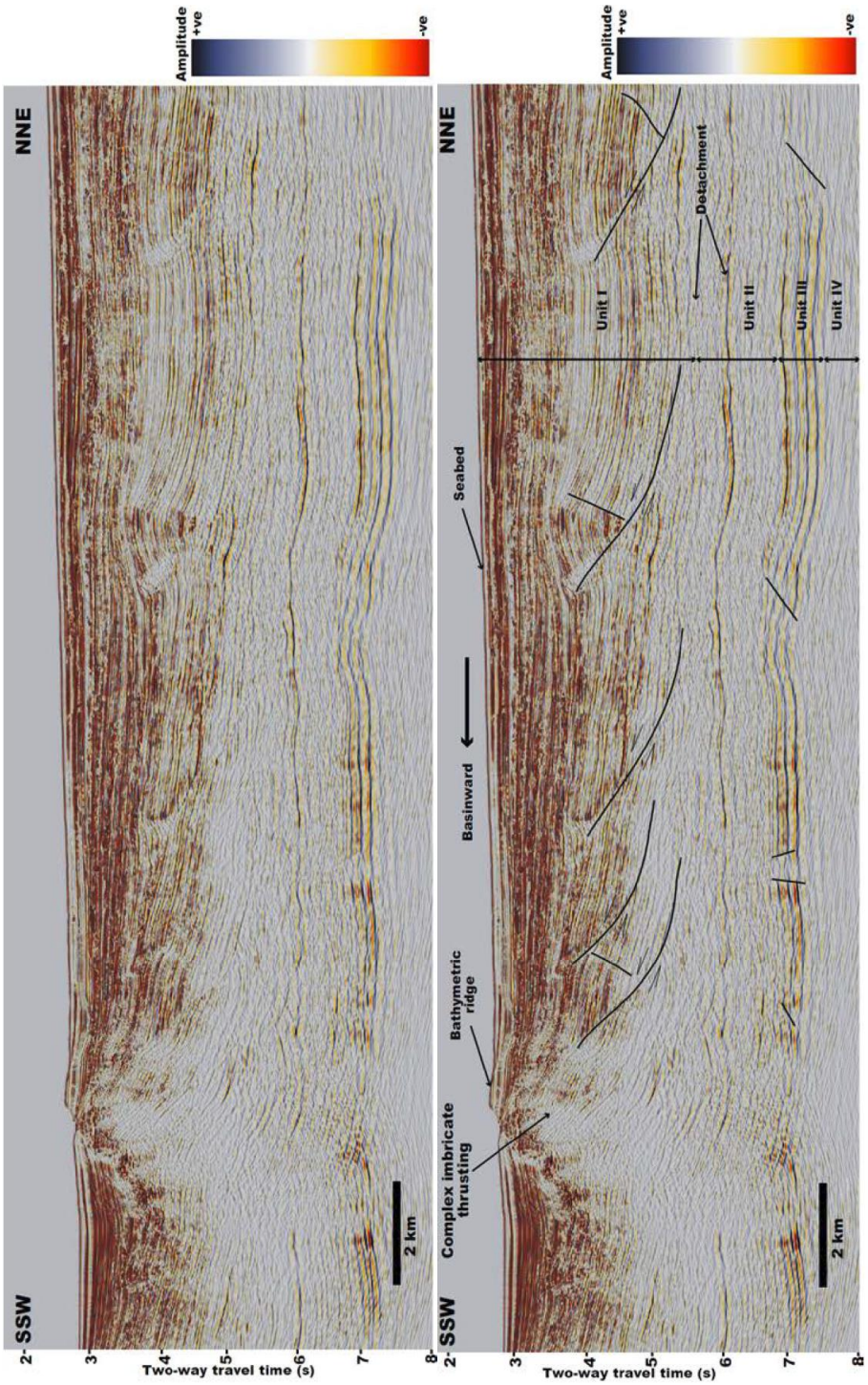

Figure 2: Uninterpreted (Top) and interpreted (Bottom) regional line illustrating the deformational and seismic stratigraphic patterns in the area. The curvilinear black lines indicate the location of the faults. Vertical scale is in seconds (Two-way travel time) and horizontal scale is in meters. Vertical exaggeration is ~1.5x horizontal scale.

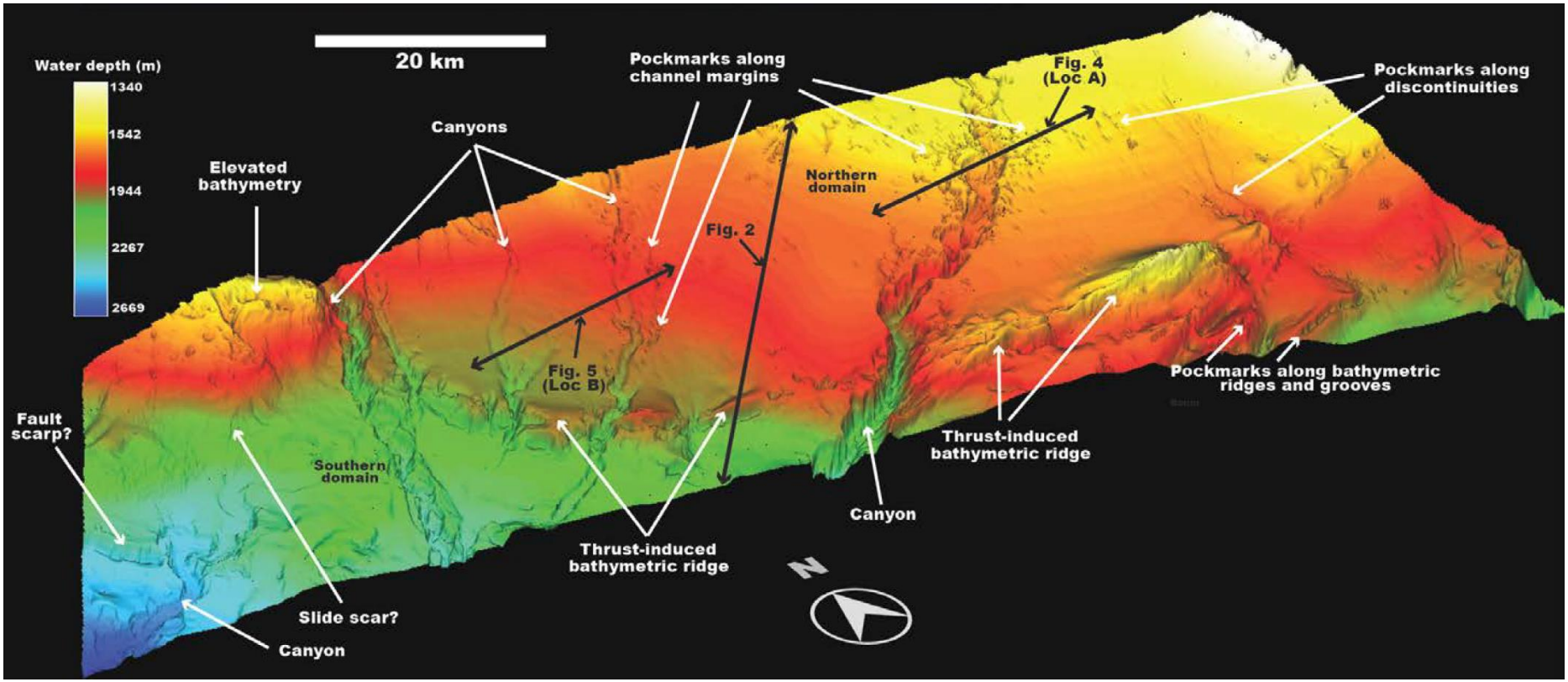

Figure 3: Perspective view of the seabed horizon showing present-day bathymetry. Note the dense concentration of pockmarks in the proximal parts of the canyon margins in the northern domain. Figures 4 and 5 are cross sections across the two areas with the densest concentration of fluid-venting structures on the seabed. Vertical exaggeration is ~1.5x horizontal scale.

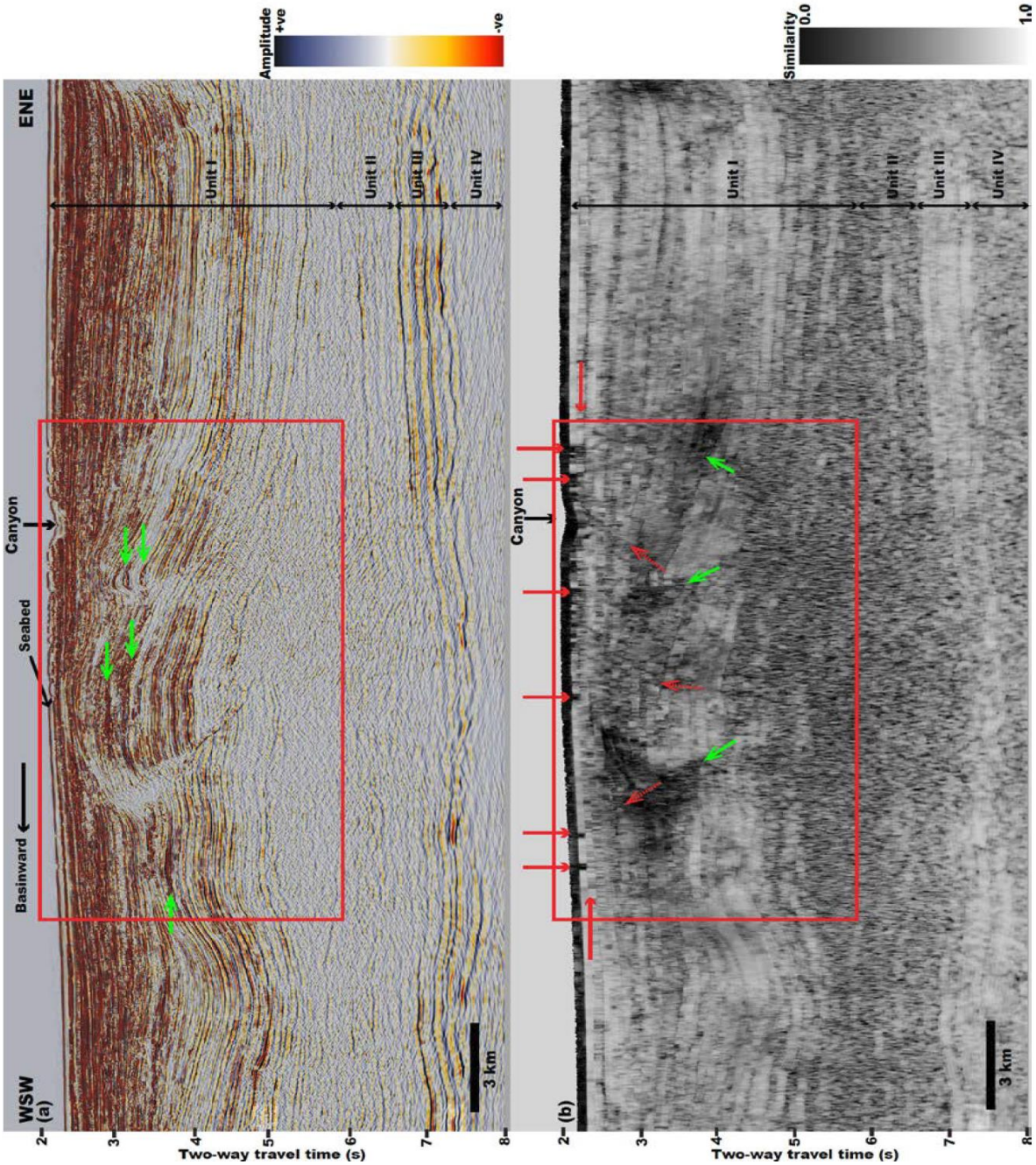

Figure 4: Seismic reflection (a) and multi-trace similarity (b) vertical cross sections from location A highlighting close connection between pockmark craters (Vertical red arrows in Figure 4b), discontinuities (Horizontal red arrows in Figure 4b), damage zones next to faults (Green arrows in Figure 4b), and amplitude brightening within Unit I (Green arrows in Figure 4a). The dashed red arrows show possible conduits for the leakage of fluids to the seabed. The location of the cross section is shown in Figure 3. Vertical scale is in seconds (Two-way travel time) and horizontal scale is in kilometres. Vertical exaggeration is ~1.5x horizontal scale.

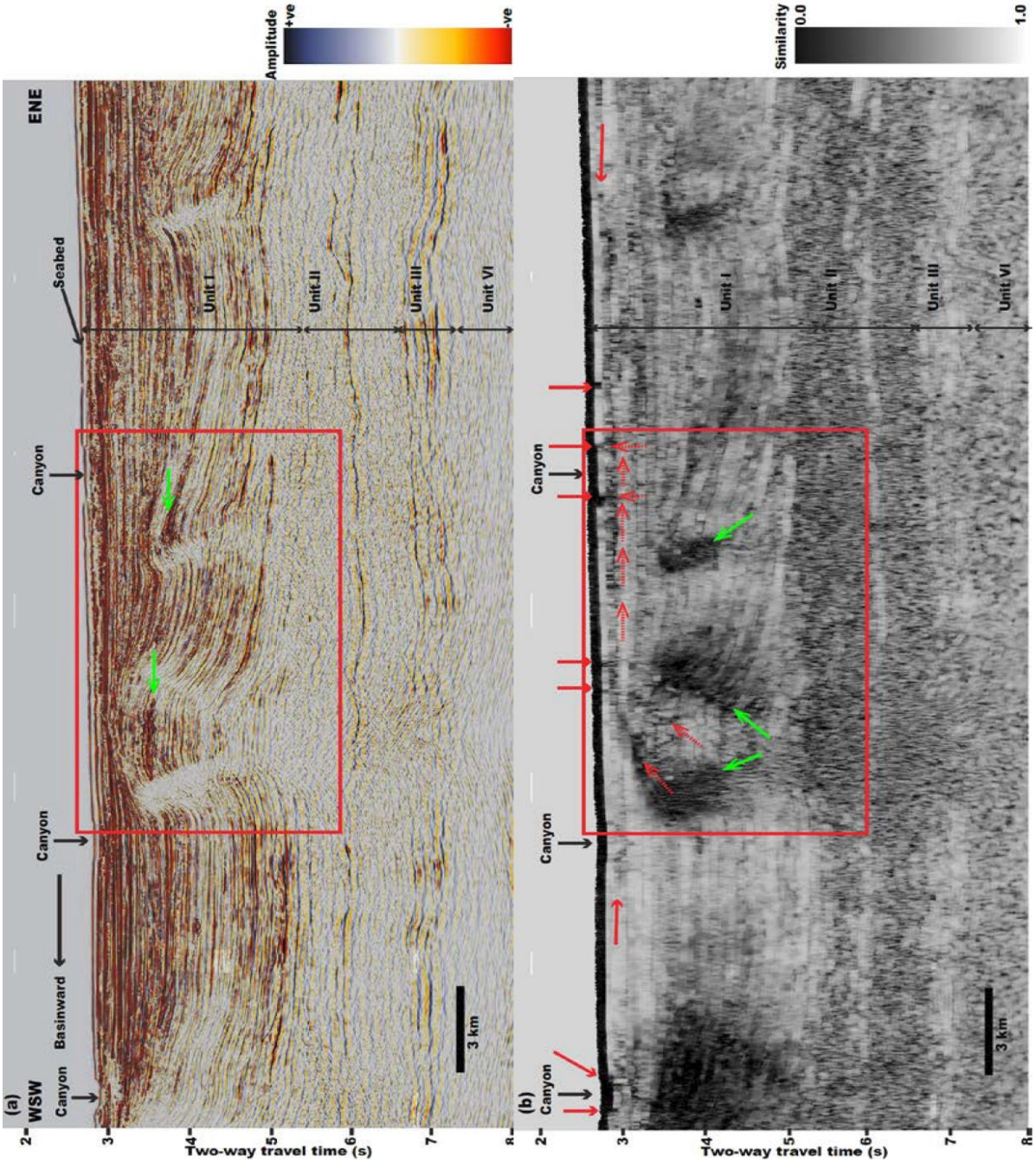

Figure 5: Seismic reflection (a) and multi-trace similarity (b) vertical cross sections from location B highlighting close links between pockmark craters (Vertical red arrows in Figure 4b), discontinuities (Horizontal red arrows in Figure 4b), damage zones next to faults (Green arrows in Figure 4b) and strong amplitude anomalies within Unit I (Green arrows in Figure 4a). The dashed red arrows in Figure 4b show possible conduits for the leakage of fluids to the seabed. The location of the cross section is shown in Figure 3. Vertical scale is in seconds (two-way travel time) and horizontal scale is in kilometres. Vertical exaggeration is ~2x the horizontal scale.