Reassessing the Petroleum Prospectivity of the Offshore Northern Perth Basin, Western Australia*

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Search and Discovery Article #10461 (2012)
Posted November 19, 2012

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG International Conference and Exhibition, Singapore, September 16-19, 2012,

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Abstract

A geological assessment of the offshore northern Perth Basin, Western Australia, has been completed as part of the Australian Government's Offshore Energy Security Program, to stimulate exploration activity and reduce exploration risk in this part of the basin. This assessment resulted in Offshore Petroleum Exploration Release Area W11-18, located approximately 200 km northwest of Perth and directly offshore from Geraldton, being released in 2011 (Figure 1). Exploration bids for this large (17,475 km^2), shallow-water release area closed in April 2012, with the outcome of bidding unknown at the time of writing.

This assessment represents the first published synthesis of data from fourteen new field wildcat wells drilled in this part of the basin since the Cliff Head-1 discovery in 2001, and includes 123 new palynological samples from 10 wells (details in Jorgensen et al., 2011). New biostratigraphic data and interpretations from these samples have been used in conjunction with legacy palynological data, well logs and lithological interpretations of cuttings and cores, to define a new chronostratigraphic sequence framework for the offshore northern Perth Basin (Figure 2). The prospectivity assessment also includes 180 new Rock-Eval/total organic carbon (TOC) and 52 vitrinite reflectance (VR) measurements from 11 wells, which have been used in conjunction with legacy geochemical data to assess the potential source rock character of the chronostratigraphic sequences. Sequences defined within the new chronostratigraphic framework have been tied to new and reprocessed seismic data acquired by Geoscience Australia (GA) (Figure 3), with the aim of characterising the distribution of potential source, seal and reservoir intervals.

Loss of petroleum accumulations because of trap breach is considered a major exploration risk in the offshore northern Perth Basin. Therefore, part of the prospectivity assessment was a trap integrity study, led by CSIRO in partnership with GA, which evaluated the

potential for fault reactivation associated with renewed Middle Jurassic extension and Valanginian breakup. The final element of the prospectivity assessment was a marine survey, which aimed to collect of evidence for natural hydrocarbon seepage, in order to provide additional support for the distribution of active petroleum systems in the northern Perth Basin.

Regional Geology of the Offshore Northern Perth Basin

The offshore northern Perth Basin comprises the Abrolhos, Houtman and Zeewyck sub-basins, the Turtle Dove Ridge and parts of the Beagle Ridge, Dongara Terrace and Greenough Shelf (Figure 1). These depocentres and structural features formed within an obliquely oriented extensional rift system on Australia's southwestern margin during the Paleozoic to Mesozoic breakup of eastern Gondwana.

The revised understanding of the tectonic evolution and depositional history of the offshore northern Perth Basin presented herein (Figure 2), and described in detail in Jones et al. (2011), is based on a sequence stratigraphic analysis of well and seismic data. Consequently, the Permian to Jurassic stratigraphy is described in terms of sedimentary sequences rather than lithostratigraphic units. Lithostratigraphic unit names have been retained from previous schemes where possible (e.g. 'Kockatea' Sequence), to provide a greater context in discussing the sequences.

The offshore northern Perth Basin has had a complex, multi-phase, history of extension and reactivation. Regional tectonic events that affected the basin and controlled sediment deposition include (Figure 2):

- Early to Mid-Permian (Cisuralian-Guadalupian) east-northeast to west-southwest extension;
- Mid-Permian (Late Guadalupian) regional uplift;
- Late Permian (Lopingian) to Late Triassic thermal subsidence;
- Possible latest Triassic to Early Jurassic west-northwest to east-southeast extension;
- Early Jurassic to Middle Jurassic thermal subsidence;
- Middle Jurassic to Late Jurassic northwest to southeast extension;
- Early Cretaceous northwest to southeast extension and local transpression;
- Valanginian regional uplift and breakup;
- Early Cretaceous to Cenozoic passive margin subsidence; and
- Miocene inversion.

Petroleum Systems and Hydrocarbon Potential

All available source rock geochemical data from offshore northern Perth Basin wells, including TOC, Rock-Eval pyrolysis and VR, were compiled from well completion reports and destructive analysis reports. In addition, geochemical analyses for source rock evaluation were carried out on 234 samples from 15 offshore northern Perth Basin wells in order to fill data gaps. In particular, samples were collected from six recently drilled wells (Dunsborough-1, Fiddich-1, Flying Foam-1, Frankland-1, Moondah-1 and Perseverance-1) where geochemical data had not yet been acquired. The plot of TOC versus hydrogen index (HI) shown in Figure 4 illustrates data from 22 offshore wells, subdivided by stratigraphic units as defined within GA's newly revised sequence stratigraphy (Figure 3). Based on these Rock-Eval pyrolysis data, several potential source rocks are recognised.

The Irwin River Coal Measures contain very good source rocks for generating mainly gas (Figure 4). The bulk of the Irwin River Coal Measures samples are organic rich with a TOC average of about 6%, with more than 80% of samples showing a TOC content above 2%. This organic richness is associated with HI values of 50-200 mg HC/gTOC, typical of gas-prone organic matter.

The latest Permian to Early Triassic Kockatea Shale has long been known to be the source of onshore oil and condensate accumulations from the greater Dongara area fields (Summons et al., 1995; Thomas and Barber, 2004). More specifically, the primary source of these oils is constrained to the sapropelic interval in the Hovea Member at the base of the Kockatea Shale, which was deposited in an anoxic marine environment (Thomas and Barber, 2004; Grice et al., 2005). The Hovea Member contains oil-prone sediments of excellent source quality onshore and displays very distinct geochemical signatures, the most typical of which are the presence of C_{33} n-alkylcyclohexane and ^{13}C depleted isotopic values (< -32‰).

In contrast to the onshore, the basal Kockatea Shale has previously been dismissed as a good source rock for generating oil offshore, based on limited offshore well data (Crostella, 2001; Jones and Hall, 2002; D'Ercole et al., 2003). The lack of well control at that time precluded a clear understanding of the source potential of the Hovea Member offshore. The discovery of oil sourced from the Kockatea Shale in the Cliff Head field has since called this assessment into question (Thomas and Barber, 2004). The Hovea Member is now recognised in 18 wells in the offshore northern Perth Basin, based on GA's revised stratigraphic interpretation (Jones et al., 2011), and shows good to excellent source rock potential for generating black oil (Figure 4). More than half of these samples are characterised by TOC greater than 1% and HI values exceeding 300 mg HC/gTOC, which is typical of rich oil-prone source rocks. The rest of the Kockatea Shale above the Hovea Member has only poor source potential due to uniformly low TOC (<1%; Figure 4). Samples with TOC greater than 0.5% are fairly hydrogen rich with HI values averaging about 300 mg HC/gTOC; they have, therefore, some potential for oil and gas generation.

Jurassic sequences have variable source potential. The Cattamarra Sequence appears to be a good source rock for generating gas, with minor liquid potential, based on the average TOC of 3.2% and average HI of 103 mg HC/gTOC (Figure 4). Sediments from the Middle Jurassic Cadda Sequence are organically rich with more than 90% of samples showing a TOC greater than 1%, however, only a third of these samples have HI values greater than 100 mg HC/gTOC with the potential to generate gas. The Middle to Late Jurassic Yarragadee Sequence is characterised by highly carbonaceous sediments, with more than 75% of samples having TOC exceeding 2% while the average TOC of all samples is approximately 12% (Figure 4).

Burial history modeling by Thomas and Barber (2004) suggested the timing of oil generation from the Hovea Member is virtually coincident with gas generation from the underlying Permian Irwin River Coal Measures. Thus, in most areas, the oil charge from the Hovea Member is in direct competition with any gas generated from the Permian section, as seen in the Dongara Gas Field and in the Caryngninia Formation in Leander Reef-1 (2,849-2,852 m RT; Volk et al., 2004). Gorter et al. (2004) provide the main source of information for modeling hydrocarbon generation in the offshore northern Perth Basin. These authors modeled hydrocarbon generation from the basal Kockatea Shale, Cattamarra Coal Measures, Cadda Formation and lower Yarragadee Formation source rocks in the Houtman Sub-basin. In the deeper depocentres, the basal Kockatea Shale could have expelled oil in the Early to Middle Jurassic. Early Jurassic structures would be needed to trap migration from this basal Triassic source, but it is unlikely that there would have been an effective Cadda Formation regional seal at the time of migration. Modeled oil and gas expulsion from the Cattamarra Coal Measures occurred at about the time of deepest burial in the latest Jurassic to earliest Cretaceous (135-150 Ma), immediately preceding uplift and erosion, and minor oil and gas were expelled during the latest Cretaceous and Cenozoic.

The dominant play type tested in the offshore northern Perth Basin is Late Permian/Basal Triassic sandstones (previously variously referred to as Dongara, Wagina or Wittecarra formations), sourced and sealed by the Kockatea Shale within tilted fault and horsts blocks (Figure 3). Prospective fault plays also occur at higher stratigraphic levels within the Triassic–Jurassic succession, especially within faulted roll-over anticlines, often associated with crestal collapse. A potential, large upper Permian stratigraphic play occurs within two large depocentres approximately 20 km and 50 km, respectively, to the west of Leander Reef-1. These depocentres contain a thick basinal succession with high amplitudes and continuous reflectivity, that progressively onlaps the upper Permian unconformity and is overlain by a thick section that, in part, includes the Kockatea Shale (Figure 5). The basinal succession has not been intersected by any wells. Quaife et al. (1994) assigned an undifferentiated Late Permian-Early Triassic age to this succession, and suggested that the seismic character is consistent with a marine, possibly interbedded carbonate and clastic unit up to 550 m thick, overlain by a basinal shale up to 500 m thick, in turn overlain by the transgressive Kockatea Shale. This basinal succession is interpreted as a clastic lowstand basin fan complex, correlative with lowstand incised valleys into which the Dongara Sandstone was deposited.

The major exploration risks in the offshore northern Perth Basin are effective seals, trap breach and preservation of palaeo-accumulations. The degree of faulting generally increases outboard from the Abrolhos Sub-basin to Houtman Sub-basin, but increased risk associated with this trend may be partially offset by a concurrent outboard increase in thickness of regional and intraformational seals. Ineffective traps at the time of migration is ascribed to fault breach and lack of cross-fault seal due to sand-sand juxtaposition. Widespread breach of previous oil accumulations is indicated by the identification of paleo-oil columns in 11 offshore dry wells (Kempton et al., 2011). Breach of paleo-accumulations could be attributed to fault reactivation and structuring associated with Early Cretaceous breakup, post-breakup regional westward tilting or Miocene inversion of faults (Kempton et al., 2011). In structures not breached by faults or subsequent structuring, gas displacement may contribute to preservation risk of oil (Kempton et al., 2011).

Regional Trap Integrity Study

The trap integrity study focused on several drilled prospects which are covered by three-dimensional (3D) seismic data and contain both breached and preserved oil columns all sourced and sealed by the Triassic Kockatea Shale. 3D deformation and fluid-flow numerical modeling was applied to these prospects to simulate the response of trap-bounding faults to Jurassic-Early Cretaceous NW-SE extensional reactivation and, therefore, to investigate hydrocarbon preservation risk in the Abrolhos Sub-basin during this time. The detailed results of this regional trap integrity study will be made available as a CSIRO open-file report (Langhi et al., 2012), which can be downloaded from either the CSIRO or Geoscience Australia websites.

3D geomechanical modeling simulated the response of trap-bounding faults and fluid flow to Jurassic-Early Cretaceous NW-SE extension. Calibration of the modeling results with current and palaeo-oil columns demonstrates that fluid flow along faults correlate with areas of local high shear and volumetric strains. The concentration of this deformation leads to: (1) an increase in structural permeability promoting fluid flow; and (2) the development of hard-linkage between reactivated Permian reservoir faults and Jurassic faults producing top seal bypass. The modeling found that several key structural factors controlled the distribution of these permeable fault segments during reactivation: (1) faults oriented between NNW and ESE were found to be at high risk of failure during the extension; and (2) fault intersections were also found to generate high permeability zones prone to leakage. In addition, large faults optimally oriented for reactivation preferentially accommodate strain and help shield nearby structures, as is the case with the Geraldton Fault immediately to the west of the Cliff Head Field (Figure 6).

Hydrocarbon Seepage Survey

The GA-0332 survey was undertaken between 20 September and 18 October 2011 and used the Australian Government's Marine National Facility, the RV *Southern Surveyor*. 3,473 km^2 of multibeam bathymetry, 4,038 line km of sub-bottom profiler, 1,546 line km of sidescan sonar and echosounder data were acquired to map seafloor and water column features and characterise the shallow sub-surface sediments. A remotely operated vehicle (ROV), supplied and operated by research collaborators from the Royal Netherlands Institute for Sea Research and from the University of Ghent in Belgium, was also deployed in selected areas to observe and record evidence of seepage on the seafloor. 71 sediment grabs and 28 gravity cores were collected. Selected samples have been analysed for headspace gas, high molecular weight hydrocarbons and infaunal content for potential indicators of thermogenic hydrocarbons.

The survey results show a series of features consistent with known hydrocarbon seeps in other areas of the Northwest Shelf over a recently reactivated fault and a paleo-fluid migration pathway from the Houtman Sub-basin to the Wittecarra Terrace. These features include: amplitude anomalies in the shallow strata; raised, high-backscatter regions and pockmarks on the seafloor; and hydroacoustic flares identified with the sidescan sonar (Figure 7). The ROV underwater video footage did not observe active hydrocarbon seepage (i.e. bubbles) but identified a dark-coloured fluid in 500 m water depth proximal to the sidescan flares. A natural hydrocarbon seepage interpretation for this part of the offshore northern Perth Basin is not conclusive but the correlation of several indicators is significant.

Natural oil seepage along the Houtman Fault System would suggest that hydrocarbons are reutilising paleo-fluid migration pathways in the vicinity of the Houtman Fault System. If this is the case, intact traps along recently inverted structures could still be receiving and accumulating hydrocarbons.

Conclusions

This study has provided a new understanding of the extent, structural framework, and depositional fill of Permo-Triassic and Jurassic depocentres within the offshore northern Perth Basin, which facilitates the identification of proven and untested plays throughout the region. Source rock sampling from recent exploration wells also proves that, offshore, the Hovea Member has good to excellent source rock potential for generating oil. Permian (Irwin River) and Jurassic (Cattamarra) intervals in offshore wells have good to very good source rock potential, and indications of Permian and Jurassic sourced hydrocarbons in Leander Reef-1 and Houtman-1, respectively, suggest that older and younger petroleum systems may also be effective in the offshore part of the basin. Therefore, the offshore northern Perth Basin is highly prospective for oil and gas sourced from one or more of these petroleum systems.

The key risk for exploration in the region is trap breach due to major basin inversion associated with tectonic breakup in the Early Cretaceous. The trap integrity assessment discussed herein is a step towards the development of a regional predictive approach for assessing this risk in the offshore northern Perth Basin. The predictive approach of this technique could be applied to newly identified, and yet to be drilled, prospects to help reduce risk for future exploration.

Acknowledgements

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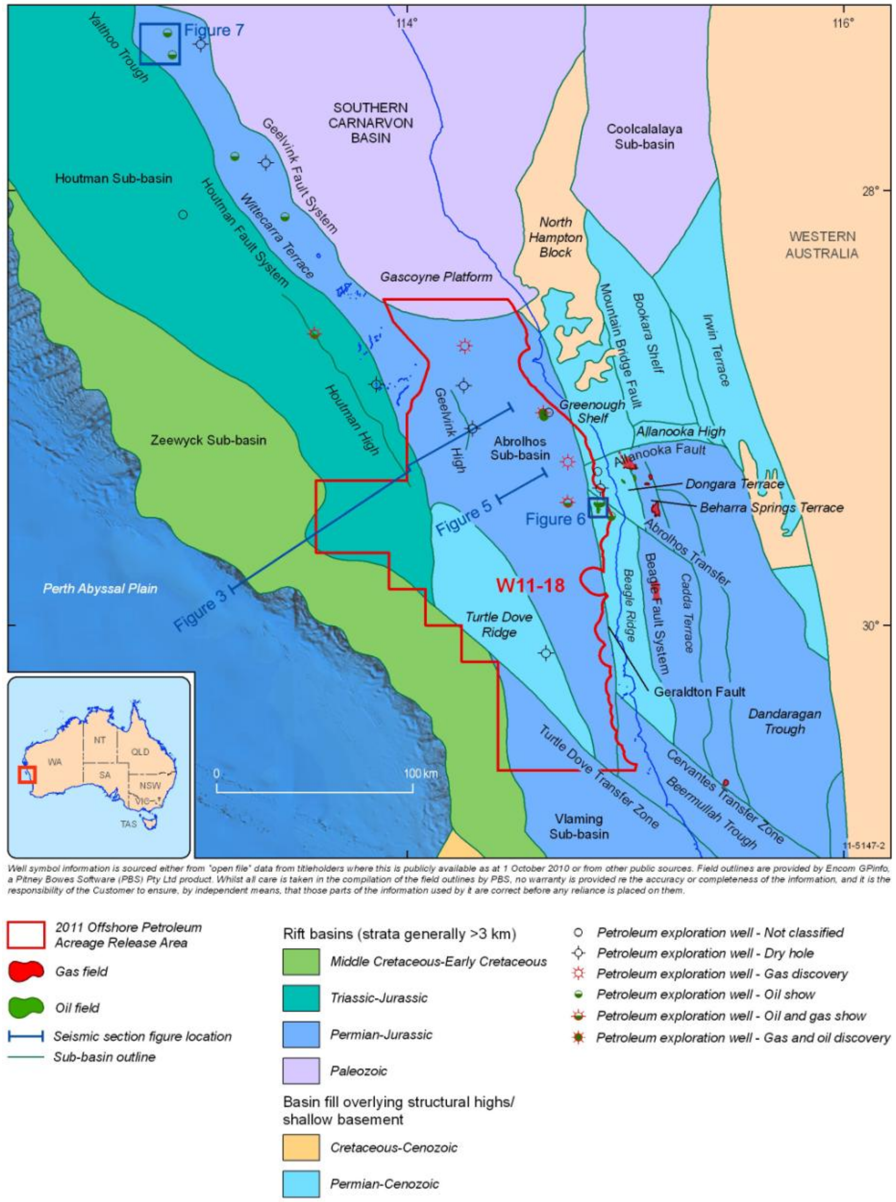

Figure 1. Structural elements of the offshore northern Perth Basin showing Release Area W11-18 and location of Figure 3, Figure 5, Figure 6 and Figure 7.

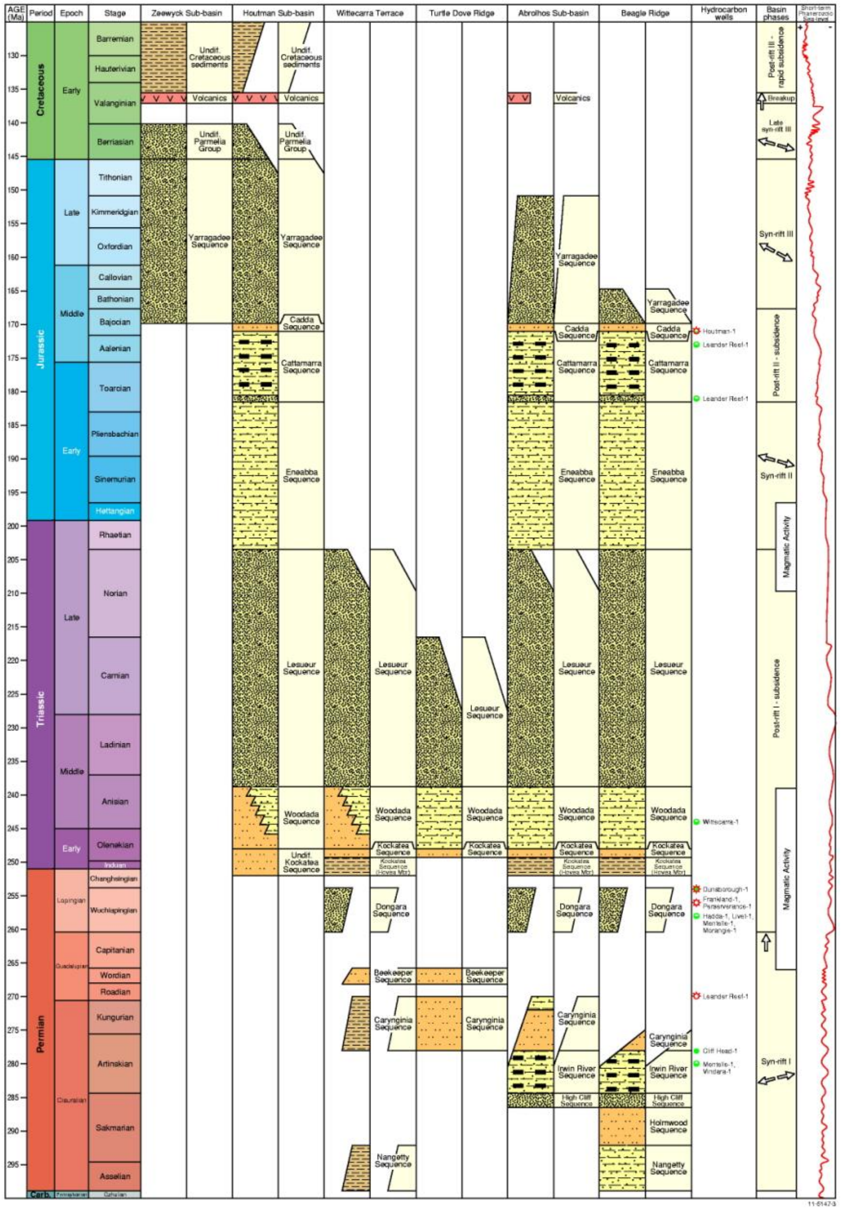

Figure 2. Stratigraphic chart of the offshore northern Perth Basin, showing depositional sequences, hydrocarbon shows and accumulations, and major phases of basin development. Geological timescale after Gradstein et al. (2004) and Ogg et al. (2008). Sea level curve after Hardenbol et al. (1998), Haq and Al-Qahtani (2005) and Haq and Schutter (2008).

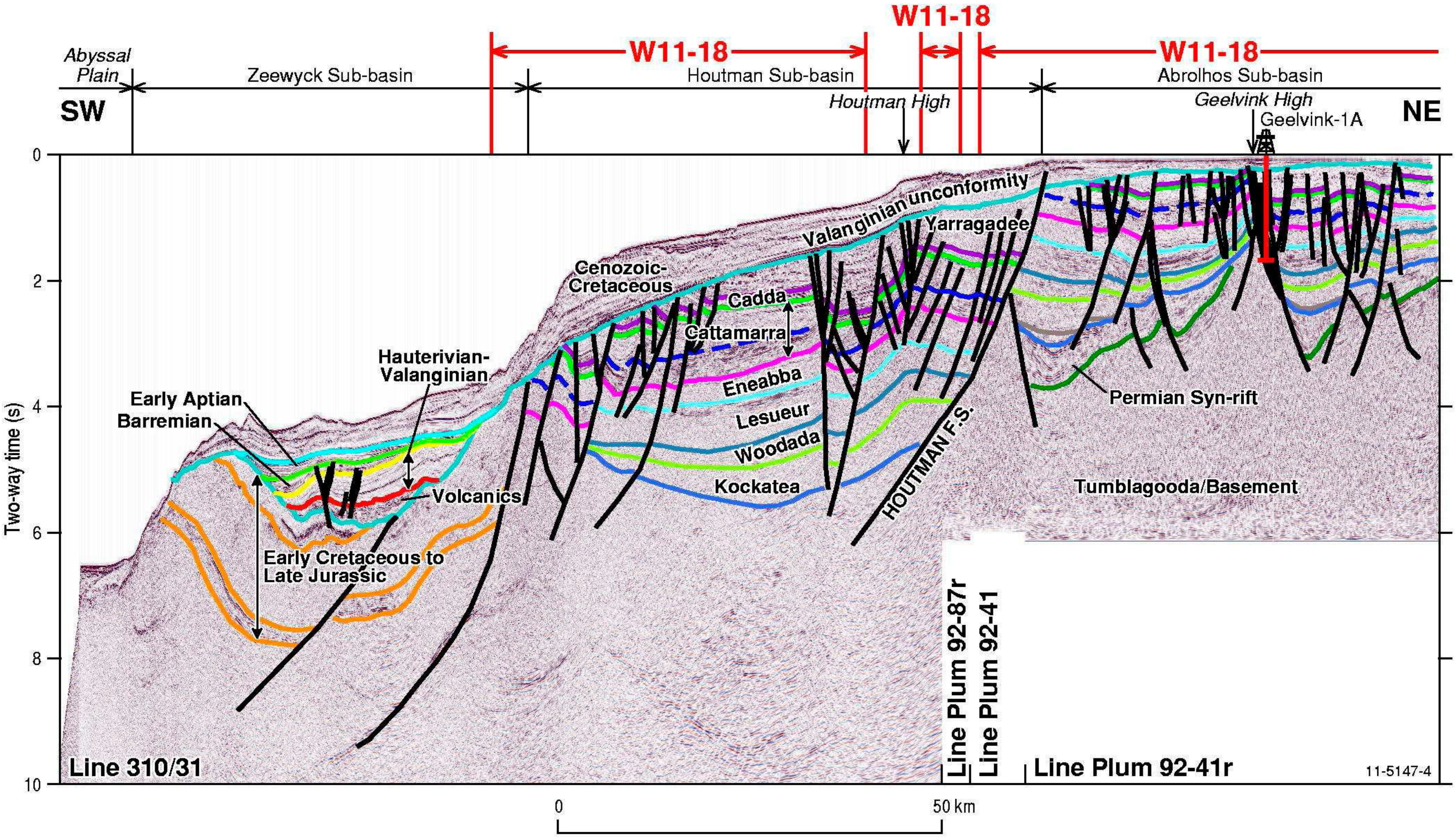

Figure 3. Seismic transect (portions of seismic lines 310-31, Plum 92-87r, Plum 92-41 and Plum 92-14r) through the Abrolhos, Houtman and Zeewyck sub-basins. Location of transect shown in Figure 1.

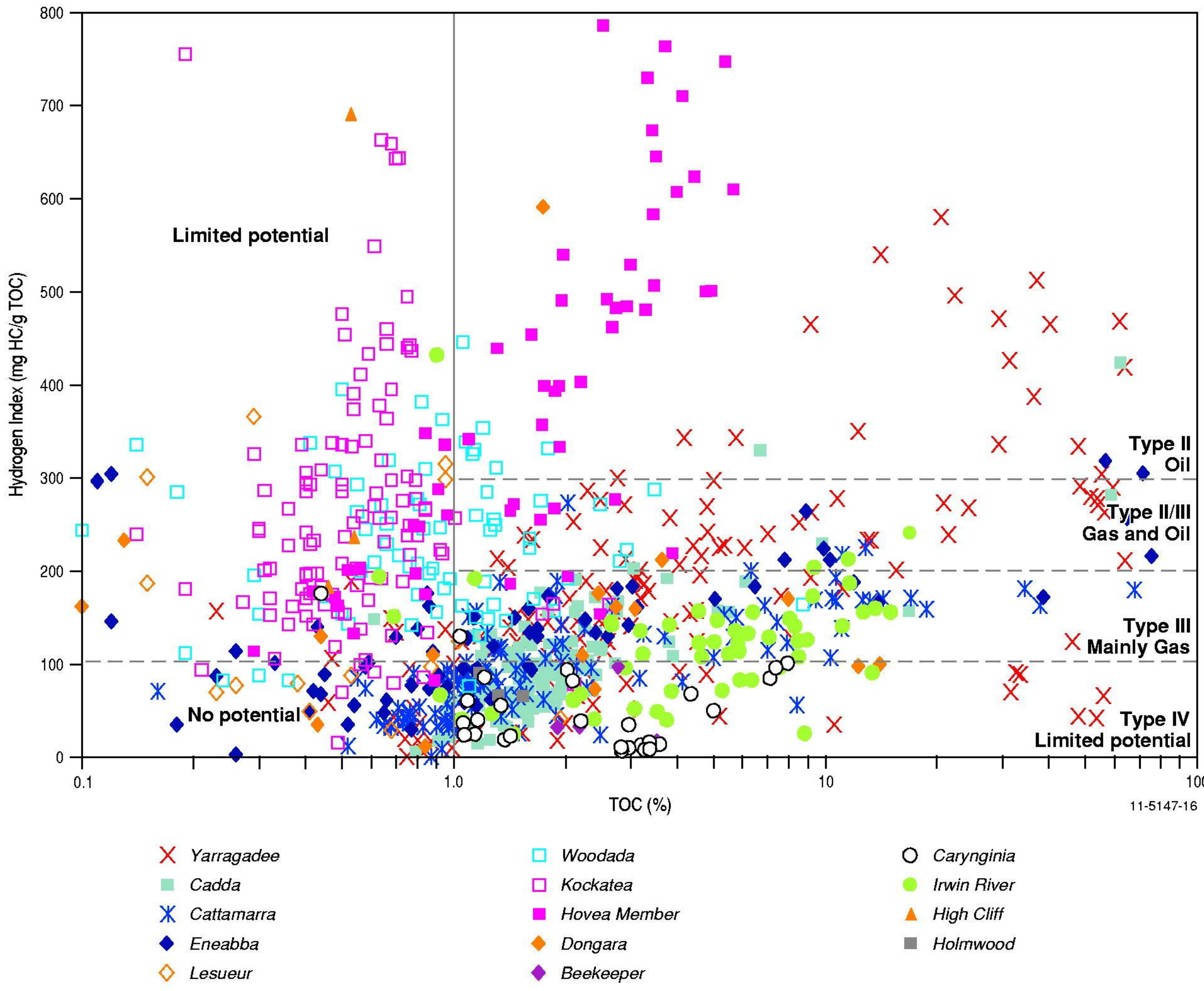

Figure 4. Source rock character (TOC vs HI) of samples from stratigraphic sequences in the offshore northern Perth Basin.

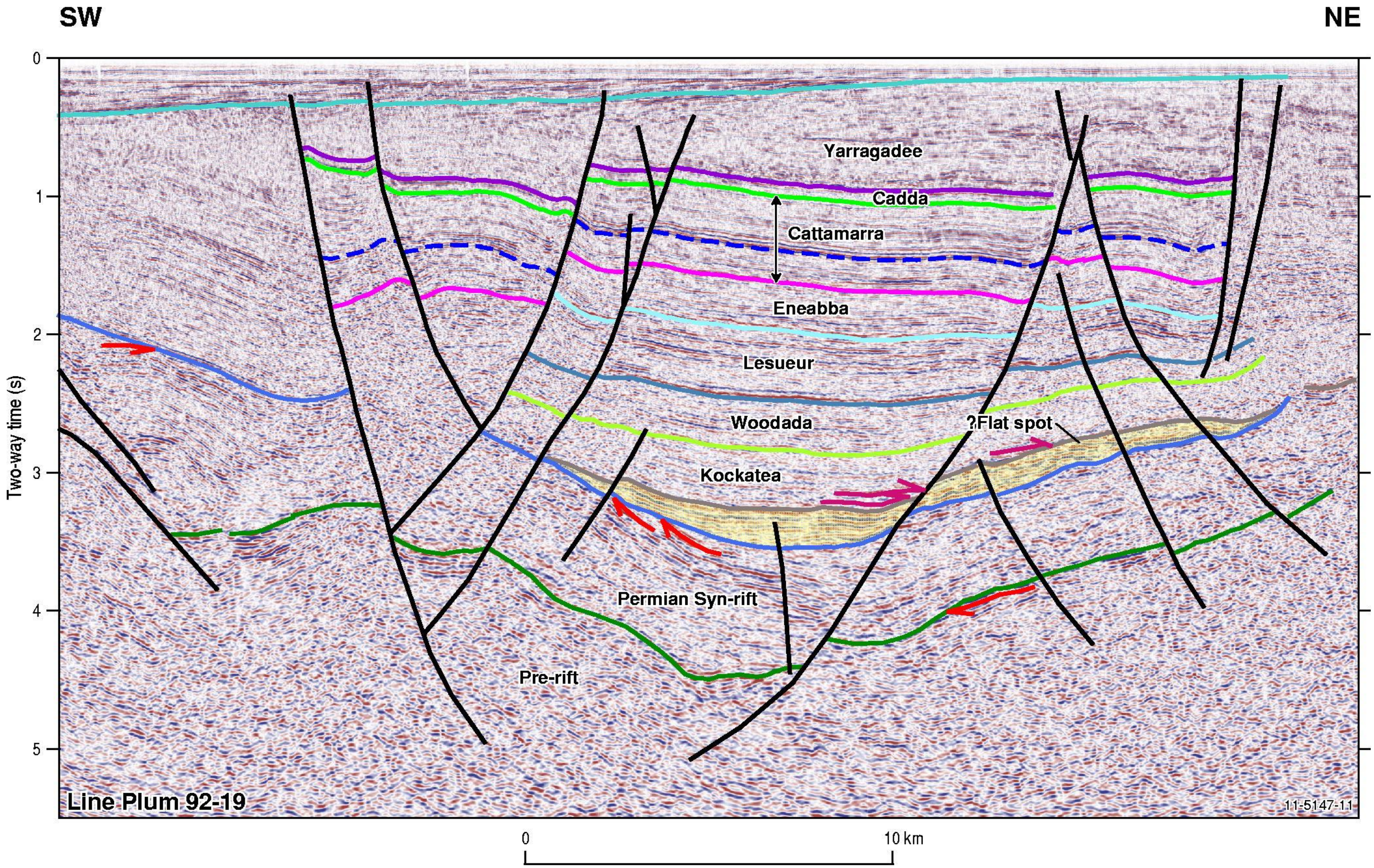

Figure 5. Portion of seismic line Plum 92-19, within the Abrolhos Sub-basin, displaying a thick basinal succession of high amplitude continuous reflectivity interpreted as a lowstand clastic basin fan complex of the Dongara Sequence. Note possible flat-spot near the top of this succession. Location of seismic section shown in Figure 1.

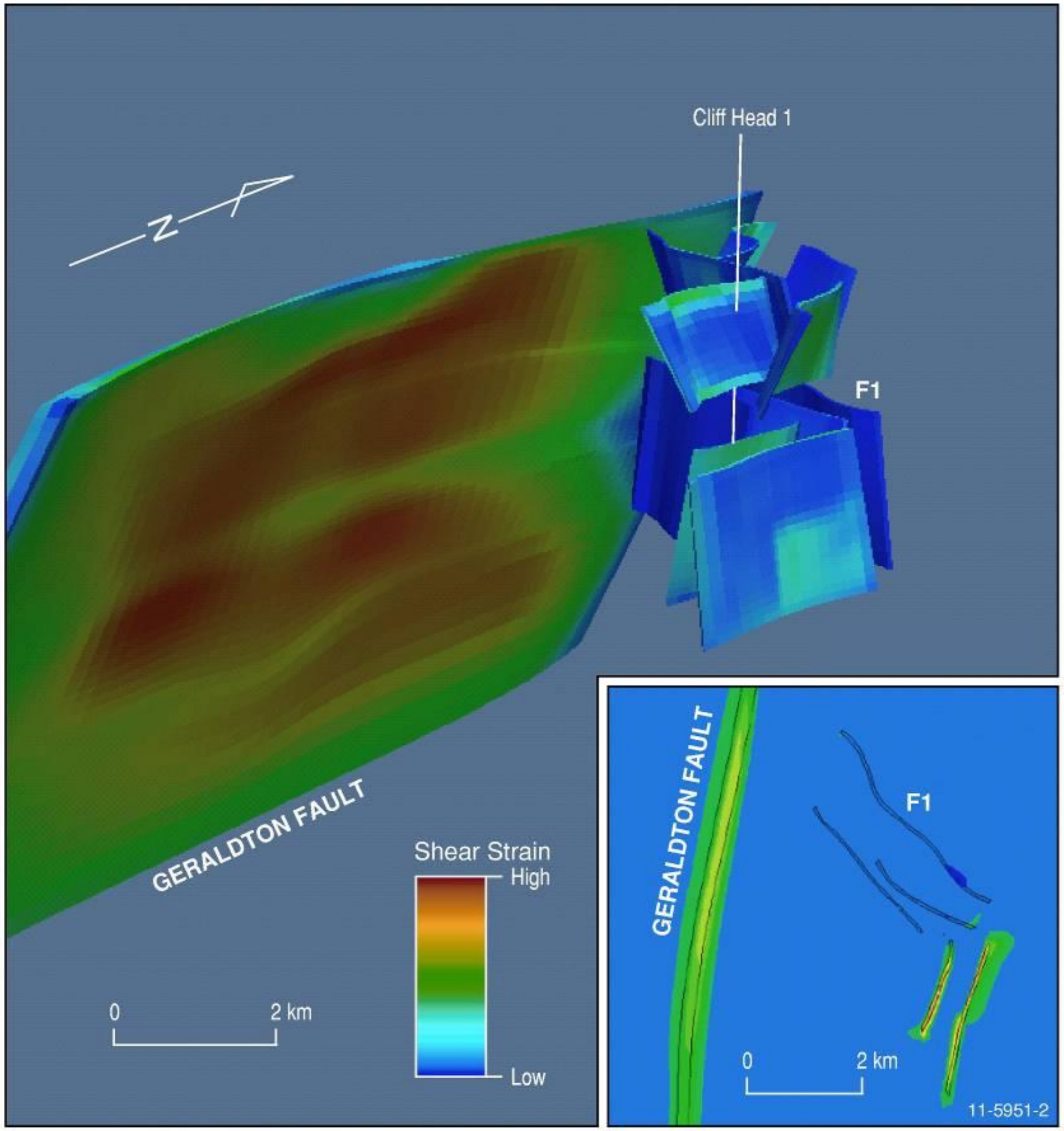

Figure 6. 3D and 2D strain distribution showing the shielding effect of the Geraldton Fault, for NW-SE extension, on the Cliff Head field. Cliff Head trap bounding fault is labeled F1. Inset shows Cliff Head-1 trajectory into structure. Note the low strain modeled on NW striking trap bounding faults. See Figure 1 for location.

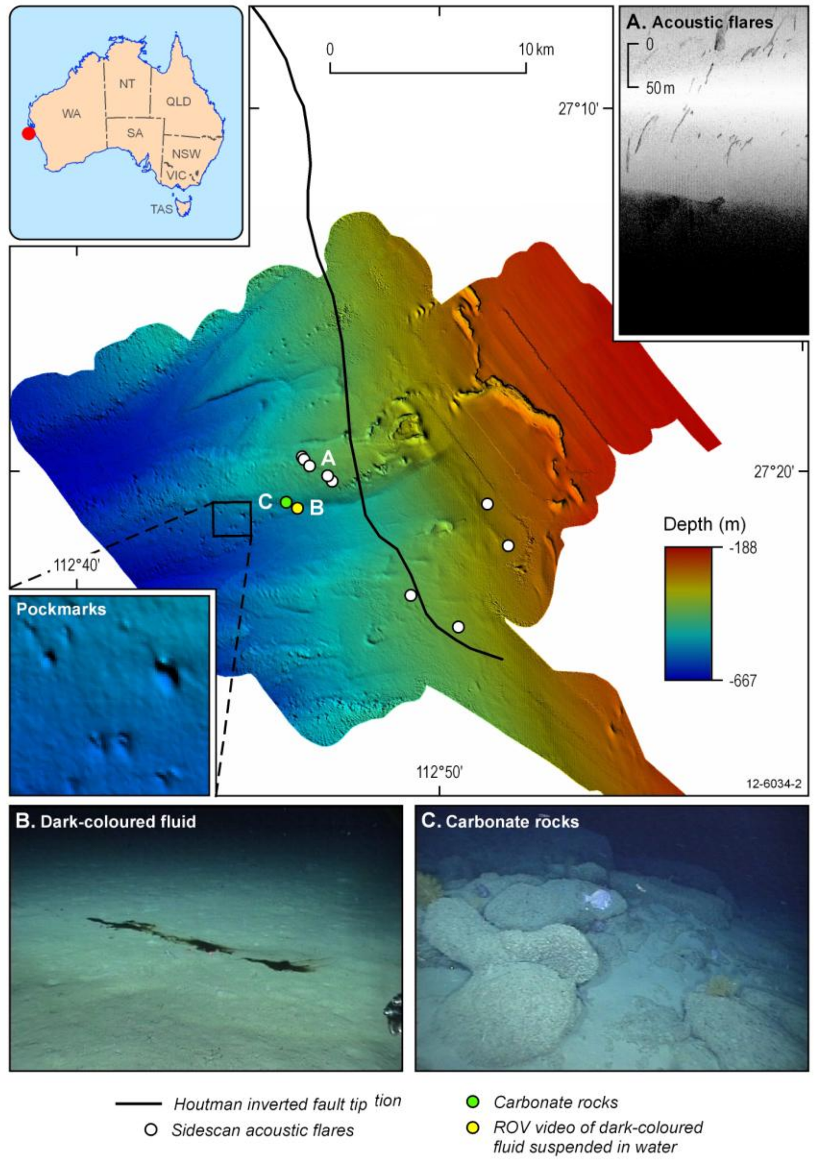

Figure 7. Integration of data over potential seepage site: multibeam bathymetry over Area H revealing pockmark (1-10 metres deep and 10-100 metres wide) fields, small mounds, and escarpments (up to 20 m); A) Hydroacoustic flares detected in sidescan sonar data; B) Dark-coloured fluid on the seabed and suspended in water in video footage from the ROV; C) Carbonate blocks in video footage from the ROV. Laser point in ROV images 10 cm apart. See Figure 1 for location.