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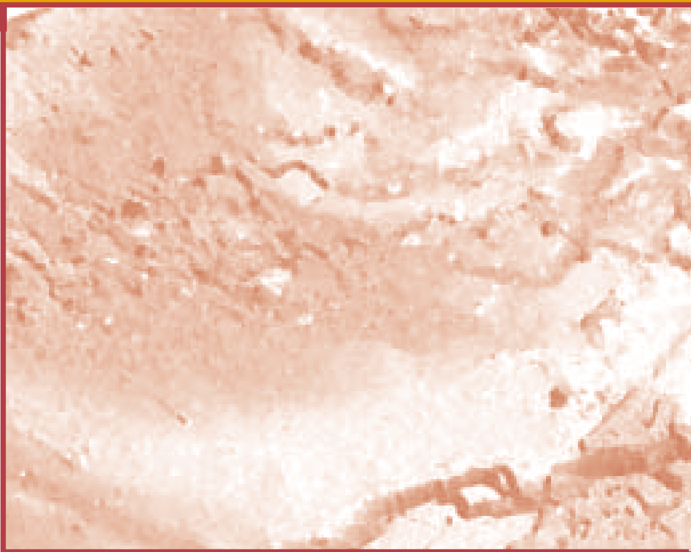

An Integrated SAR, Geological and Geochemical Study

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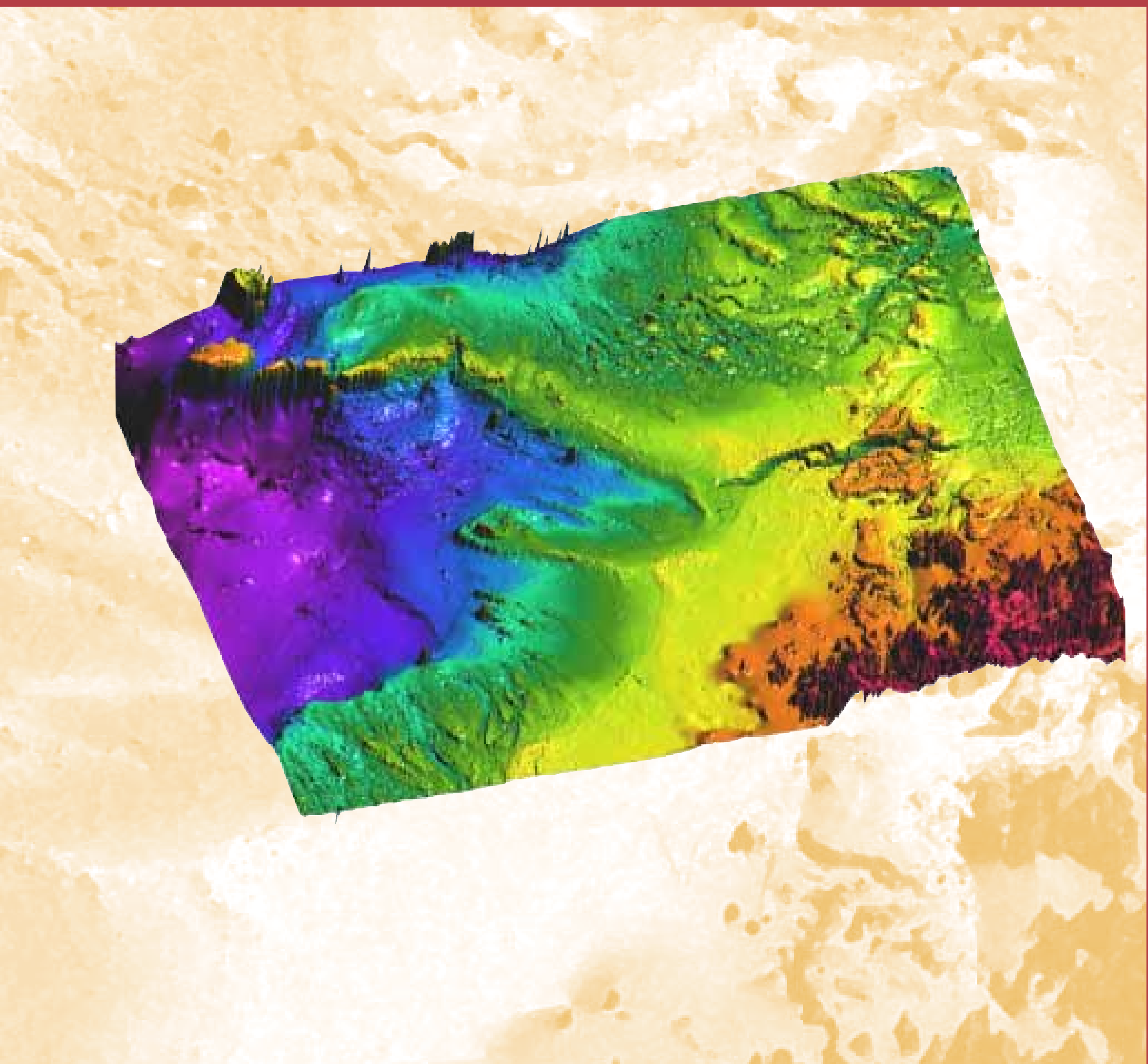

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RECORD 2001/11

Hydrocarbon migration and seepage in the Timor Sea and Northern Browse Basin North-West Shelf, Australia: An Integrated SAR, Geological and Geochemical Study

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- **SAR interpretation**: Nigel Press & Associates (Dr Alan Williams and Maria de Farago Botella) and TREICoL (Dr Geoff Lawrence).
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- **Project Management**: Shawn Burns (RadarSat International).

Summary

The Australian Geological Survey Organisation (AGSO), in collaboration with Nigel Press & Associates, AUSLIG (specifically the Australian Centre For Remote Sensing) and RadarSat International (RSI), has undertaken an interpretative study of hydrocarbon migration and seepage in the offshore Bonaparte and Browse Basins, north-western Australia.

The study used as its framework a total of 55 RadarSat Wide 1 Beam Mode Synthetic Aperture Radar (SAR) scenes, which provide a minimum of double coverage over an area exceeding 365,000 square kilometres. These data were analysed, providing a regional understanding of the key processes of hydrocarbon migration and seepage in the area. The SAR coverage extended from the coastline to abyssal water depths, and covered a range of geological provinces and sub-basins. These ranged from poorly known, deep water frontiers in the outer Browse Basin, the Ashmore Platform and the Timor Trough, to well-explored features such as the Vulcan Sub-basin, the Sahul Syncline and western Sahul Platform. A range of regional to detailed water column geochemical sniffer and Airborne Laser Fluorosensor data, acquired over a number of years, were meshed with the SAR data to provide an understanding of the nature and distribution of hydrocarbon seepage across the region.

The interpretations derived from these independent seepage detection technologies were compared and contrasted, and then integrated with a wide variety of petroleum geological information, including regional seismic data, isopach maps of key reservoir, source and sealing units, and fault maps. This approach has led to a new appreciation of the migration/seepage processes over the entire region. These results are potentially useful to explorers who wish to evaluate aspects of hydrocarbon migration, charge and trap integrity at scales ranging from regional to prospect-specific.

The principal findings of the SAR study were as follows:

- 308 Rank 2 (probable seeps) and 292 Rank 3 seepage-slicks (possible seeps) were detected in the study. In addition, 15 Pollution slicks, 70 Remnant Pollution slicks and 227 Individual Natural Film Slicks (INFS) were interpreted.
- The average slick density (including both Rank 2 and Rank 3 seepage-slicks) is approximately 1 every 1,000 square kilometres, which represents a high slick density compared to most other areas around Australia.
- In general, the slicks fall into distinct geographic groupings, with scattered slicks in between. Major groupings are present in:
    - The Browse Basin, especially on the north-eastern Yampi Shelf and along the basin margin fault system which links the Heywood and Copernicus structures.
    - Along the transition zone between the northern Browse Basin and the southern Bonaparte Basin.

- On the Ashmore Platform, in particular outboard of the Rainbow-1 and Sahul Shoals wells.
- Around the flanks of the Cartier Trough, particularly near the Octavius-Tenacous and Oliver well locations.
- On the Londonderry High, approximately 35 km south-east of Anderdon 1 well location.
- Within the Nancar Trough.
- Within the Rabe and Sabo Blocks and the central Timor Trough.

The SAR results have highlighted the exploration potential (for liquids) of the Caswell Sub-basin in the Browse Basin. In addition, potential new petroleum systems appear to have been identified on the outer Ashmore Platform (outboard of the Rainbow 1 and Sahul Shoals 1 wells) and on the Londonderry High, south-east of Anderdon 1. These systems may relate to either a Permian or Late Triassic-Early Jurassic, carbonate, oil-prone source on the Ashmore Platform and a Palaeozoic (Carboniferous and or Early Permian) source on the Londonderry High.

Introduction

This report presents the results of a study undertaken by the Australian Geological Survey Organisation (AGSO), Nigel Press & Associates, AUSLIG (specifically the Australian Centre For Remote Sensing) and RadarSat International (RSI) on hydrocarbon migration and seepage in the offshore Bonaparte and Browse Basins, north-western Australia (Figures 1 & 2).

The study used as its framework a total of 55 RadarSat Wide 1 Beam Mode Synthetic Aperture Radar (SAR) scenes, which provide a minimum of double coverage (up to five-fold coverage in some areas) over an area exceeding 365,000 square kilometres (Figure 3). These data were analysed, providing a regional overview of the key processes of liquid (condensate and oil) hydrocarbon migration and seepage in the area. The SAR coverage extended from the coastline to abyssal water depths, and covered a range of geological provinces. These ranged from poorly known, deep-water frontiers in the outer Browse Basin, the Ashmore Platform and the Timor Trough, to well-explored features such as the Vulcan Sub-basin, the Sahul Syncline and western Sahul Platform.

The SAR data were used to map areas of liquid hydrocarbon seepage (in time-series) and were then integrated with a number of other key remote sensing data sets from the region, including:

- Water column geochemical sniffer (WaSi) data (~18,000 line kilometres).
- Airborne Laser Fluorosensor (ALF) data. Three types of ALF interpretations have been included, namely:
  - Reprocessed Mark III ALF interpretations from six recent and detailed AGSO surveys (total ~10,500 line kilometres).
  - Interpretations resulting from the reprocessing of BP Mark II legacy ALF data acquired over the region.
  - Original BP interpretations from the BP regional Mark II ALF reports.

The interpretations derived from these independent seepage detection technologies have been compared and contrasted, and then integrated with a wide variety of petroleum geological information, including regional seismic data, isopach maps of key reservoir, source and sealing units, and fault maps.

The goals of this investigation included improving our understanding of hydrocarbon migration and seepage at both the regional and localised scales. Specifically, these goals were to:

- Obtain an understanding of the nature and distribution of hydrocarbon seepage, and assess this in relation to regional prospectivity, particularly in relation to the presence of possible new petroleum systems;
- Improve the understanding of the hydrocarbon potential of frontier basins in the region, particularly those in deep water;
- Evaluate how the seepage characteristics of fault reactivated basins, such as the Bonaparte Basin, differ from those with little fault reactivation, such as the Browse Basin;
- Improve the understanding of how different remote sensing technologies respond to different types and rates of hydrocarbon seepage, thereby leading to an improved remote sensing "tool-kit" for basin evaluation;
- Assess the ability of individual, or combinations of, remote sensing technologies to contribute to an improved understanding of issues such as top seal and fault seal failure;
- Assess the usefulness of remote sensing technologies in environmental management in the region.
- Develop technical approaches which are potentially useful to explorers who wish to evaluate migration, charge and trap integrity at scales ranging from regional to prospect-specific.

The remainder of this report is structured as follows.

Firstly, there is a discussion of the regional geology of the region. Secondly, the results and implications of the respective remote sensing programs are discussed, specifically in the order SAR, followed by sniffer followed by ALF. Finally, an integration of all results is presented, along with a regional synthesis in relation to their exploration implications.

The study comprises two parts. The first part consists of an ArcView GIS format (on CD-1), with the GIS containing all of the data and results listed above, including TIFF files of key SAR scenes. A full interpretative report, containing text, maps and images (Acrobat pdf and MS Word formats), tabulated data of all slicks and ALF anomalies, and a full MS PowerPoint presentation of all salient data, results and interpretations, is contained on CD-2. Higher resolution versions of the seismic lines are also included as image files.

Regional and Petroleum Geology of the Offshore Bonaparte and Browse Basins

The present study spans the boundary between the offshore Bonaparte and Browse Basins, which represent the two most northerly margin-scale compartments of Australia's North-West Shelf (Figure 1). These two basins have had quite different rift and post-rift histories, and hence are discussed separately below.

Bonaparte Basin System

The Bonaparte Basin comprises a system of basin and sub-basin elements which extends from the north-western Australian mainland to the island of Timor (Figure 2). The region is geologically complex, with individual tectonic elements often having strongly divergent orientations and disparate ages. Localised evaporite deposition in the Siluro-Ordovician was followed by a phase of northeast-southwest oriented crustal extension in the Late Devonian-Early Carboniferous (O'Brien et al. 1993; 1996a). This rifting formed the Petrel Sub-basin, the outer two compartments of which now under-pin (what would become in the Late Jurassic) the Malita Graben and Vulcan Sub-basin.

Rifting episodes in the Early Permian and Late Jurassic (O'Brien, 1993; O'Brien et al. 1993) took place on an approximate northwest-southeast azimuth, almost orthogonal to the earlier Devonian-Early Carboniferous phase. The Jurassic rifting resulted in the formation of a number of localised Late Jurassic depocentres, which are traditionally considered to contain the principal oil-prone source rocks in the region. Depocentres formed included the Swan Graben, the Paqualin Graben and the Skua Trough in the Vulcan Sub-basin (Pattillo & Nicholls, 1990), the Nancar Trough in the Sahul Syncline, and the Malita Graben. Following continental break-up in the Late Jurassic (Baxter et al., 1997), a classic passive margin sequence developed. Early Cretaceous marine shales and mudstones, which provide the principal seal for the Mesozoic petroleum traps in the area, progressively gave way to predominantly shelfal carbonate deposition throughout the Tertiary (Pattillo & Nicholls, 1990).

In the latest Miocene/earliest Pliocene (~5-6Ma), the progressive convergence of the Australian and Eurasian plates established an oblique collisional setting. Subsequent uplift of (what is now) the island of Timor, and the associated formation of a localised, proto-foreland basin (the Timor Trough; Figure 2) induced strong flexural stress on the Australian plate inboard from the Timor Trough (O'Brien et al., 1998a,b). The associated extensional fault reactivation of the deeper Palaeozoic and Mesozoic fault arrays produced Mio-Pliocene-aged faults, with displacements ranging from sub-seismic (<20-30 m) to greater than 300 m. This reactivation faulting led to the partial or complete breach of the top and/or fault seal in many previously charged traps, such as East Swan and Avocet (O'Brien & Woods, 1995; O'Brien et al., 1996b; 1998a,b).

At approximately 2.5 Ma, the regional stress regime changed significantly: volcanism and thrusting on Timor island stopped and convergence of Timor and the Australian mainland appears to have ceased (Abbott and Chamalaun, 1981; McCaffrey, 1988; Genrich et al., 1995). The throws on the flexural faults within the Timor Sea reflect this change in regional stress: from about 2.5 Ma, throws on the flexural faults decreased dramatically (O'Brien et al., 1998a,b).

The petroleum exploration history of the region mirrors this geological complexity. The Mesozoic section in the region is highly prospective, as evidenced by the numerous oil and gas-condensate discoveries in and around the Sahul Platform and Sahul Syncline (e.g. Elang, Bayu-Undan, Laminaria, Buffalo) and the Vulcan Sub-basin (Skua, Jabiru, Challis, Tenacious). These traps are all fault-bounded horsts that formed in the Late Jurassic (Pattillo & Nicholls, 1990) and consist of combinations of Mesozoic reservoirs (principally Triassic and Early-Middle Jurassic sands), with Late Jurassic or (more typically) Early Cretaceous top seals. The source rocks are considered to principally comprise Late Jurassic shales deposited within the grabens. However, the Early to Middle Jurassic Plover Formation probably makes a significant contribution in some areas (Edwards et al., 2001).

Balancing this “inherent” prospectivity is the attendant risk of drilling breached traps. The Bonaparte Compartment developed as a wide, low-topographic gradient margin compartment (O’Brien et al., 1999a), and as a result typically has a relatively thin cover of the post-rift (Cretaceous) shales which act as the regional seal. The combination of the thin regional seals (often <100 m thick) with the often significant (>100 msecs displacement) Neogene extensional faulting in the region means that the Bonaparte Basin can be strongly predisposed to fault seal failure and trap breach. In contrast, the Browse Basin to the south combines thick seals with small displacement Neogene faults, and hence the probability of preserving traps is much greater.

Neogene collision also induced rapid Pliocene subsidence in some shelfal areas (see Shuster et al., 1998), with thick Pliocene section present in the Cartier and Nancar Troughs and the Malita Graben. Subsidence was so rapid that it out-stripped sediment supply in these areas, producing localised, relatively deep-water troughs on the shelf. In some cases, such as at the Oliver field on the south-eastern edge of the Cartier Trough, this Pliocene loading increased the maturity of the source rocks significantly, pushing them into the gas window, and causing extensive flushing of the pre-existing oil column (O’Brien et al., 1996b). In the situation seen at Oliver, and also at Montara in the southern Vulcan Sub-basin, the combination of Neogene subsidence and high fault seal integrity within the trap proved almost equally deleterious to fault seal failure - sub-commercial gas accumulations were produced rather than breached traps.

Browse Basin System

The Browse Basin is a Palaeozoic to Cainozoic depocentre situated immediately to the south-west of the Bonaparte Basin in the southern Timor Sea. Covering an area of approximately 140,000 km^2, the Browse Basin was initiated during northwest-directed extension during the Late Carboniferous to Early Permian. Post-rift subsidence was terminated in the Late Triassic by low-strain compression (the Fitzroy Movement) which inverted the syn-rift and early post-rift sequences and produced the prominent northeast-trending anticlinal structures that host the accumulations at Scott Reef and Brecknock.

Crustal extension was recommenced in the Early to Middle Jurassic, culminating in continental break-up and the onset of sea floor spreading in the late Callovian (late Middle Jurassic) at about 155-160 Ma (Ludden, 1992). It is possible that break-up in the Browse Basin may have significantly predated break-up in the Bonaparte Basin, perhaps 20-25 Ma (Baxter et al., 1997). As a result, the Browse Basin appears to lack the thick, fault-controlled Late Jurassic source intervals that dominate in the Bonaparte Compartment.

Post-rift subsidence continued from the Late Jurassic until the Middle Miocene, when compression associated with the collision of the Australian and Eurasian plates reactivated existing structures in the basin. This event formed a series of north-to-northeast-trending, en-echelon anticlines along with the Leveque Shelf (e.g. Lombardina-1).

The Browse Basin has been sub-divided into four sub-basins, the Caswell, Barcoo, Scott, and the Seringapatam Sub-basins (Stagg, 1978; Symonds et al., 1994; Struckmeyer et al., 1998). The Caswell and Barcoo Sub-basins contain in excess of 10 km of sedimentary section, and these sub-basins, along with the flanking shelves to the east, the Yampi and Leveque Shelves, are considered the most prospective for hydrocarbon exploration. The Browse Basin is a proven hydrocarbon province, with giant, but as-yet undeveloped gas and condensate accumulations at Scott Reef, North Scott Reef and Brecknock, located in the west-central part of the basin. Recently, Inpex has also announced a series of massive gas-condensate discoveries within the Browse Basin. These gas-condensate accumulations typically comprise Mesozoic horsts and reservoirs, and appear to have been sourced from Triassic or Jurassic shales. They contrast to the sub-commercial Gwydion-1 and Cornea-1 oil discoveries on the Yampi Shelf, which, along with the oil recovered from Caswell-2 and Kalpytea-1/ST1, appear to have been sourced from Early Cretaceous source rocks (Boreham et al., 1997; Blevin et al., 1998).

Exploration interest in the Yampi Shelf specifically, and the Browse Basin in general, was boosted dramatically by the discovery of the Gwydion oil field on the southern Yampi Shelf in 1995 (Spry and Ward, 1997) and the Cornea field on the northern Yampi Shelf in 1997 (Stein et al, 1998; Ingram et al, 2000). The Yampi Shelf is comprised of a rugose Proterozoic basement ramp which dips to the northwest, away from the flanking cratonic (Proterozoic) Kimberley Block; Cretaceous reservoir-seal couplets are developed around and over basement highs. Dry gas is also reservoired in these traps, suggesting that the source rocks for the oil and the gas are different (O'Brien and Quaife, 1997; O'Brien et al, 1996c, 2000).

Unlike the Bonaparte Basin, the Browse Basin formed as a high-gradient margin. Rapid post-rift subsidence facilitated the deposition of a very thick Cretaceous sequence, which reaches many hundreds of metres in some areas. Moreover, the Browse Basin, lacking a foreland system on its outer edge, has not experienced significant extensional (flexural) reactivation during the Neogene. In contrast, most of the Neogene tectonism within the Browse Basin has been inversional (O'Brien et al., 1999a.b). The combination of thick regional sealing units and little fault reactivation means that fault seal failure is typically not a primary exploration risk within the Browse Basin.

The thick Cretaceous loading within the Browse Basin means that some of the Mesozoic structural plays that have been actively explored within the Bonaparte Basin are actually over-mature within the Browse Basin. In more basinal areas, deep water, Cretaceous fan plays, and other stratigraphic plays, may potentially represent attractive targets.

Bonaparte-Browse Basin Transition Zone

The boundary zone between the Bonaparte and Browse Basins (O'Brien et al, 1993, 1996a, 1999a,b) is a fundamental, north-west trending, Proterozoic lineament or fracture system, which has acted as a long-lived fault relay zone (O'Brien et al, 1996a, 1999a,b). Intense fault-overlap along the transition zone results in this boundary being a long-lived, syn-rift high - that is, individual faults gain displacement away from the fracture zone. It is, therefore, a preferred locus for hydrocarbon migration and accumulation. Differential compaction across these basement-involved relay zones means that such areas are often expressed as northwest-trending, low-relief bathymetric highs. In addition, the fact that the Bonaparte-Browse transition zone is the boundary between a relatively wide and a narrow margin compartment (O'Brien et al, 1999a), makes the south-eastern corner of this transition zone (effectively the northern Yampi Shelf) a focus for regional hydrocarbon migration from the Browse Basin. Transition zones between wide and narrow margins are prime locations for the entry of low-stand silici-clastics into the rift or post-rift margin system. As a consequence, well-developed channel systems are often present along these relay systems. Such channels (as expressed by the present day Penguin Deeps) appear to have been a first-order control on the distribution of the Maastrichtian Puffin Formation in the northern Browse Basin and southern Vulcan Sub-basin.

Examples of hydrocarbon traps located along the Bonaparte-Browse transition zone include Skua, Puffin and Montara. Other traps which, at a first-order, are located in a similar setting to these include Sunrise, Loxton Shoals, Troubadour and Evan Shoals. The Sahul Syncline itself, which contains the Laminaria field, for example, probably represents a crustal-scale relay system which links the Vulcan Sub-basin and the Malita Graben (O'Brien, 1993). On the wider North-West Shelf, the Canning–Browse, Carnarvon–Canning and Carnarvon–Cuvier transition zones appear to be structurally analogous to the Browse–Bonaparte transition and, therefore, may be similarly prospective (O'Brien et al., 1999a).

Evaluation of Seepage and Migration

SAR Data

The study used as its framework a total of 55 RadarSat Wide 1 Beam Mode Synthetic Aperture Radar (SAR) scenes, which provide a minimum of double coverage over an area exceeding 365,000 square kilometres. These data were analysed, providing a regional understanding of the key processes of hydrocarbon migration and seepage in the area. The SAR coverage extended from the coastline to abyssal water depths (Figure 3), and covered a range of sub-basins. These ranged from poorly known, deep water frontiers in the outer Browse Basin, the Ashmore Platform and the Timor Trough, to well-explored features such as the Vulcan Sub-basin, the Sahul Syncline and western Sahul Platform.

The terminology describing the details of the ranking/descriptive scheme for SAR slicks is found in the NPA SAR report on CD-2. The principal findings of the SAR study were as follows:

- 308 Rank 2 and 292 Rank 3 seepage slicks were interpreted in the study. In addition, 15 Pollution slicks, 70 Remnant Pollution slicks and 227 Individual Natural Film Slicks (INFS) were interpreted.
- The average slick density (including both Rank 2 and Rank 3 seepage slicks) is approximately 1 every 1,000 square kilometres, which represents a high slick density compared to most other areas around offshore Australia (O'Brien, unpublished).

The distribution of the seepage slicks interpreted on SAR data is shown in Figure 4. In general, the slicks fall into distinct geographic groups, with scattered slicks in between. Moreover, at a first-order, the majority of the slicks are located in areas where the regional top seal thickness was relatively thin (Figure 5).

Major groupis of seepage -slicks are present in the following locations.

- The Browse Basin, especially on the north-eastern Yampi Shelf.
- The Browse Basin, over the Heywood Shoals and along the basin margin fault system which links the Heywood and Copernicus structures.
- On the Ashmore Platform, south of the Ashmore Reef-1 structure.
- Along the transition zone between the northern Browse Basin and the southern Bonaparte Basin.
- On the Ashmore Platform, in particular to the north-northwest of the Rainbow-1 location.
- On the Ashmore Platform, in particular outboard of the Sahul Shoals-1 well location.

- Within the Nancar Trough, particularly around carbonate banks in the area.
- Within the Rabe and Sabo Blocks, and within the central Timor Trough.

In addition to these clusters of slicks, scattered slicks were detected in the following locations:

- In the Browse Basin, near the Browse Island 1 well location.
- Along the boundary of the Swan Graben, around the Skua oil field.
- In Skua Trough, near the Leeuwin 1 well location.
- On the Londonderry High, ~35 km south-east of the Anderdon 1 well location.
- On the south-eastern flank of the Cartier Trough, near the Hadrian 1 and Cockell 1 well locations, up-dip from the Oliver gas accumulation, and near the Octavius-Tenacious wells.
- Between Allaru 1 well location and the producing Challis oil field and also near the Maple 1 and Paqualin 1 well locations

In addition to these clusters of slicks, a significant number of single slicks are present throughout the study area. Specific descriptions and interpretations of these slicks are as follows.

Dense Clusters of Slicks

North-eastern Yampi Shelf, Browse Basin

The greatest density of slicks in the entire study area was detected on the north-eastern Yampi Shelf, approximately 20 to 100 km inboard of (i.e. east of) the Cornea trend. Here, Rank 2 and 3 seepage-slicks were detected in an east-west to east-northeast trending band over 100 km long and up to 20 km wide (Figure 6). Individual slicks within this cluster are typically linear to cuspate in shape and 500 m to 5,000 m long. These slicks can be seen on seismic lines 165 YST-07 to –11 (see later).

The slicks are located around the inboard edge of the basin and are positioned along a significant and sharp bathymetric break, which is located in water depths of between about 75 and 60 m. This break relates to the basin-ward edge of a prominent basement shelf or platform in the sub-surface, a boundary which loosely defines the edge of the regional Cretaceous sealing unit. As such, it appears that these slicks are related to prolific oil seepage caused by capillary failure at the edge of the top seal (O'Brien et al., 2000, in press). These slicks extend to the north-east, all the way to the Browse-Bonaparte Transition Zone (at the end of seismic line 165YST-17; see later).

Further outboard, slicks are almost absent along the Cornea and Londonderry structural trends themselves, in spite of the fact that the Cornea accumulation contains very significant volumes of oil and gas (Ingram et al, 2000). This absence of slicks may be due to the fact that the top seal capacity over these trends is still sufficiently high to prevent oil leakage through the seal (O'Brien et al., 1998a,b, 2000). Other contributing factors could be related to the inherent character of the oil itself (such as low API gravity, biodegradation and low GOR).

A total of five 'co-registered' SAR scenes were acquired over the north-eastern Yampi Shelf during approximate 3 years period. The interpretation of these 'time-series' data has allowed an evaluation of the "repeatability" of the slicks in the area from one scene to the next. Significantly, prolific oil seepage at the basin edge was detected on only two scenes of these five scenes (Figures 7 & 8). This observation suggests that the seepage along the edge of seal is episodic, with seepage being present for only about 40% of the time.

Interpretation

Prolific oil seepage at the basin edge is almost certainly related to capillary failure of the regional seal. This seepage highlights the presence of a significant liquid petroleum system outboard of the Cornea and Londonderry trends. The "corner" formed by the junction of the Browse and Bonaparte Basins is clearly a major migration focus for hydrocarbons generated within the northern Browse Basin. The observed seepage at the basin edge may be due to a combination of secondary migration from source depocentres and tertiary migration from the Cornea trend, the result of oil being progressively displaced by gas (O'Brien et al., 1998b, 2000). General lack of slicks over the Cornea field itself suggests that the top seal capacity along this trend is likely to be relatively high.

Heywood Shoals and Heywood - Copernicus Fault System, North-Eastern Browse Basin

Slicks are present over several of the carbonate shoals in the area, particularly the Heywood Shoals (Figure 9). These shoals are located on the major, basin-margin fault system and seismic direct hydrocarbon indicators (DHIs), such as gas chimneys, are evident on some seismic lines (see seismic line 130-06) through the structure. These observations (subject to field confirmation) suggest that the Heywood Shoals may have originally formed over a hydrocarbon seep system, a process documented overseas and also hypothesised for other shoals within the Bonaparte Basin (O'Brien, unpublished data). A number of SAR slicks are also present along the fault system which extends between the Heywood 1 and Copernicus 1 well locations, again suggesting that this area is receiving active liquid petroleum charge.

Interpretation

The Heywood Shoals may well be a hydrocarbon-related feature. If it is so, a more detailed evaluation of the well itself and why it failed may be in order (i.e. does it have any up-dip potential etc?). The Heywood Shoals – Copernicus fault system is apparently presently receiving active liquid charge, upgrading the potential of the north-eastern Browse Basin.

Ashmore Platform, South of Ashmore Reef 1 Structure

Slicks are present closely associated with Ashmore Reef. As with the case of the Heywood Shoals, if these slicks are confirmed as genuine oil slicks, then it may be that reef formation was originally related to hydrocarbon seepage.

Browse - Bonaparte Transition Zone

Slicks are present immediately south of the Browse-Bonaparte Transition Zone (Figure 10). These slicks lie along seismic line 175 BBHR-13 (Figure 11). The western-most slicks appear to be related to a carbonate bank system at depth. The more central slicks show no obvious relationship to either seafloor or sub-seafloor structures. These slicks are located approximately 5-20 km south and south-east of the Keeling 1 and Woodbine 1 wells. They could be due to the petroleum system that charged the Keeling structure. Alternatively, they could be associated with stratigraphic traps at the Puffin Formation level, as these low-stand fan deposits thin dramatically through this particular area.

Slicks are also present near the Prion 1 well location, on the north-western flank of the Vulcan Sub-basin (Figure 12 and 13). These slicks are seen on seismic lines 163 VTT-02, 03 and 04 (including over the Haydn prospect, as discussed by O'Brien et al., 1998a). These slicks, which appear from the seismic data to be associated commonly with combinations of seafloor pockmarks/graben, HRDZs, and shallow amplitude anomalies, provide evidence of charge on the western flank of the basin.

Ashmore Platform: NNW of the Rainbow 1 Well Location

Slicks occur closely associated with carbonate banks (particularly the edges of the banks) between approximately 10 and 50 km NNW of the Rainbow 1 well location on the Ashmore Platform (Figure 14). These slicks occur outboard of any of the drilled trends in the region, and are seen on seismic lines 163 VTT-10, 11 and 12 (Figure 15). Given the geology, it would appear inconceivable that these slicks could be sourced from the "traditional" Late Jurassic source rocks (which are absent in this area). Rather, an older source, possibly Early Triassic or older, such as identified by Edwards et al. (2001), could be potentially responsible.

If a hydrocarbon seepage-related origin is confirmed, these slicks point to the presence of an entirely new petroleum system within the Bonaparte Basin, an observation which would open up a new exploration fairway in this region. Given the potential impact, it is recommended that these slicks be confirmed, or otherwise, by sampling at sea.

Ashmore Platform: Outboard From Sahul Shoals Well Location

Slicks occur closely associated with carbonate banks (particularly the edges of the banks) between approximately 12 and 35 km to the north, north-west and north-east of the Sahul Shoals 1 well location on the Ashmore Platform (Figure 14). These slicks occur to the north of any of the drilled trends in the region, and are seen on seismic lines 163 VTT-15, 16 and 17 (Figure 16). As with the slicks outboard from the Rainbow 1 well location, it would appear improbable that the slicks could be sourced from Late Jurassic source rocks. Ann older source, possibly Early Triassic, could be responsible.

If a hydrocarbon seepage origin is confirmed, these slicks point to the presence of an entirely new petroleum system within the Bonaparte Basin, an observation which would open up a new exploration fairway in this region. Given the potential impact, it is recommended that these slicks be confirmed, or otherwise, sampled at sea.

Nancar Trough

A very dense suite of Rank 2 and 3 seepage-slicks, as well as slicks labelled as "Remnant Pollution", are found around the Karmt Shoals in the Nancar Trough area (Figure 17). These slicks have been located over seismic lines 163VTT-34 to 39. Seismic lines 163VTT 34 and 35 provide the best examples of the carbonate bank-slick association in the area (Figure 18).

Previous work by Bishop and O'Brien (1998) had shown that the Karmt Shoals themselves were actually surrounded ("rimmed") by gas-charged, shallow sediments. In addition, gravity cores from this exact same area (Edwards & Hulskamp, 1998) contain significant concentrations of liquid thermogenic hydrocarbons. As such, these facts, and the observation that the slicks interpreted as remnant pollution in this region occur *directly over* the mapped shallow hydrocarbon-charged sediments, have led us to the conclusion that the almost certainly represent prolific natural hydrocarbon seeps (rather than "pollution"). This clearly points to the Nancar Trough being a prolific source of liquid hydrocarbons in the area. The lack of exploration success to date in this region probably relates principally to fault seal failure, as discussed by de Ruig et al. (2000) and Castillo et al. (2000).

Interestingly, slicks are sparse over the Laminaria-Corallina oil fields, immediately to the east of the Karmt Shoals. In fact, the slicks were typically 10-15 km to the west of these fields (Figure19). These data can be interpreted in a number of ways. Firstly, it could be that fault seal failure (a function of the number, displacement and orientation of the Neogene faults, and the regional stress field and the thickness and quality of the regional seal) is much more pronounced within the Nancar Trough area than over the Laminaria-Corallina highs, per se, thereby allowing a much greater abundance of hydrocarbons to seep from the seafloor. This is probably the most likely explanation. Alternatively, it might be that the hydrocarbons in the Laminaria-Corallina structures have a higher API gravity (reported as 59^{o} API by Smith et al., 1996) than those within the Nancar Trough, and hence might produce a more subdued SAR response. Very high API oils tend to have significantly shorter residence times of the surface of the sea (Sivadier & Mikolaj, 1973), thereby militating against detection by SAR.

Irrespective, whilst the SAR did not "bulls-eye" the Laminaria-Corallina fields, it did high-grade the source potential of the adjacent depocentre.

Rabe and Sabo Blocks and Central Timor Trough.

A number of Rank 2 and 3 seepage-slicks were interpreted within the Rabe and Sabo Blocks in Indonesian waters, and also within the central Timor Trough (Figure 20). Whilst no seismic data are available to determine the geological setting of these slicks, their presence does provide some encouragement for the presence of an active petroleum system within these deep water frontiers.

Scattered Clusters of Slicks

Browse Basin

Within the Browse Basin, a number of scattered slicks were interpreted from the SAR imagery (Figure 21). In general, these scattered slicks were located either along fault systems within the Caswell Sub-basin, or around the edges of the depocentre itself.

These observations highlight the exploration and source potential of the Caswell sub-basin. It should be noted that no slicks are directly associated with the Gwydion oil field or surrounds, on the central Yampi Shelf, consistent with a lack of water column sniffer anomalies detected in this region (O'Brien et al., 2000). This lack of seepage appears due to a higher top seal capacity and thickness in the central Yampi Shelf.

Bonaparte Basin

Within the Bonaparte Basin, scattered slicks are present at a number of locations. In the southern Swan Graben, a number of Rank 3 seepage-slicks are present in the vicinity of the Skua oil field (Figure 22). These slicks range from a few hundred metres to up to 4 km in length, and are closely spatially associated with HRDZs in the vicinity of the Skua field (Figure 23). No slicks were observed associated with the East Swan and Eclipse structures further to the north-east, consistent with the breached nature of these traps (O'Brien et al., 1998a, in press).

A significant cluster of Rank 2 seepage-slicks is located along the Callovian fault tips at the south-western end of the Swan Graben (Figure 22). These slicks are present near the Grebe 1 and Snipe 1 wells and could be related to leakage from undrilled traps or secondary or tertiary migration from the southern Swan Graben source rocks or traps.

In the Skua Trough, a cluster of Rank 3 seepage-slicks is present near the Leeuwin 1 well location. The significance of these slicks is unclear, though it is known that the nearby Tahbilk accumulation is "leaky" (Cowley & O'Brien, 2000).

On the Londonderry High, approximately 35 km south-east of Anderdon 1, a cluster of Rank 3 seepage-slicks is present (Figure 24), apparently associated with a large Permian High at the south-eastern end of seismic line 163 VTT-32. . The significance of these slicks is uncertain, given that they are located both a long way from known source depocentres, such as the Skua Trough, the Skua Graben and the Caswell Sub-basin, and are separated from the depocentres by a number of apparent migration barriers. As such, the presence of migrated hydrocarbons on this part of the Londonderry High is difficult to explain. The slicks occur about 60 km to the north-east of a number of Rank 2 and 3 slicks which occur over a fault relay system along the Browse-Bonaparte Transition Zone, and it is conceivable that they could have migrated from there. Alternatively, they may comprise part of a pre-Jurassic (Late Triassic or Early Permian) petroleum system located to the north-east (see Edwards et al., 2001). If this proposal were correct, it would have important exploration implications and should be pursued.

A significant cluster of Rank 3 seepage-slicks is present within 3 to 5 km (slightly up-dip) of the Octavius-Tenacious wells on the south-eastern flank of the Cartier Trough (Figure 25). These slicks may be related to the displacement of oil from the traps themselves, or from adjacent, as yet undrilled traps, via Neogene regional tilting associated with the formation of the Cartier Trough. Alternatively the slicks may be related to leakage associated with fault seal failure.

Another significant cluster of Rank 2 and 3 seepage-slicks was present on the south-eastern flank of the Cartier Trough, near the Hadrian 1 and Cockell 1 well locations, up-dip from the Oliver gas accumulation (Figure 25). These slicks occur through an area where a prominent Neogene extensional fault extends all the way to the seafloor (see seismic line 163 VTT-17). Shallow seismic amplitude anomalies are associated with the slicks, which also tend to be located over small seafloor topographic highs, which have average diameters of about 800-1,000 m (Figure 25). These highs may represent either proto-carbonate banks associated with seafloor seepage vents or possibly some form of gas-escape structure (?massive mud mound-type features).

The most likely explanation for these slicks is that they represent hydrocarbons (oil and probably significant gas) which are either passing through (secondary migration) or being displaced from (tertiary migration) the Oliver structure, which is located down-dip. Fluid inclusion and other data (O'Brien et al., 1996b) have demonstrated that the Oliver trap is being progressively gas flushed from hydrocarbons being generated within the Neogene Cartier Trough. If the tertiary migration model is correct, then these slicks probably represent a small-scale version of the migration processes taking place on the Yampi Shelf, inboard from the Cornea trend. The proposal for a widespread gas-flushing at the present day within the Cartier Trough is supported by the distribution of slicks around the Cartier Trough (Figure 26). Slicks are concentrated around the periphery of the Cartier Trough, perhaps implying a progressive fill-spill model involving an early oil charge and a later gas charge (see O'Brien et al., 1996b).

Some minor, scattered slicks were also observed between Allaru 1 well location and the producing Challis oil field, within the central Vulcan Sub-basin and also near the Maple 1 and Paqualin 1 well locations.

Summary of Exploration Implications of SAR Data

There are several questions which need to be addressed in relation to assessing the implications of the SAR results in relation to exploration prospectivity. These include:

1. What is the distribution of theslicks observed on SAR data?
2. Is this distribution consistent with what is expected?
3. Where is there evidence for new petroleum systems?
4. Where are slicks characteristically absent?
5. Is the absence of slicks due to the fact that the hydrocarbons cannot leak easily (due to high top seal or fault seal capacity etc) or is it due to the more fundamental lack of an active petroleum system?
6. What key additional work is required to better understand the SAR data?

Identified Seepage-Slicks

In general, the majority of the slicks within the study area are present where the regional seal is thin (Figure 5). This is evidenced in particular on the Yampi Shelf, inboard from the Cornea oil field. It is also true over the wider Bonaparte Basin. The Bonaparte Basin is, in the main, characterised by a combination of relatively thin regional seals and significant displacement Neogene faults, which favours leakage.

The majority of slicks detected within the Browse Basin appear to be related to hydrocarbons generated within the Caswell Sub-basin. This is probably also true of the slicks detected in the far northern Browse Basin, near the Keeling and Woodbine wells.

In the Bonaparte Basin, a number of the significant seepage-slick clusters can be related to “traditional” Late Jurassic source rock depocentres. Significant “Late Jurassic-related” seepage is located at the fault tips of the south-eastern Swan Graben, and around the Skua oil field and related structures. Valid traps in and around these areas would be well-placed to receive a liquid hydrocarbon charge

The greatest cluster occurs within the Nancar Trough, where there is evidence for prolific seepage. Another area with evidence for significant “Late Jurassic-related” seepage is along the south-eastern edge of the Cartier Trough, specifically along the Octavius-Tenacious trend and also up-dip from the Oliver accumulation.

The slicks present within and around the Nancar and Cartier Troughs probably reflect the fact that the Neogene subsidence in these areas has been significant, which has reinvigorated the petroleum systems, leading to active oil and gas-condensate expulsion at the present day. Clearly, the prolific seepage within the Nancar Trough points to the fact that there is significant secondary oil migration taking at the present day, with large numbers of thick and long slicks developed across the depocentre. The presence of these slicks is consistent with other hydrocarbon indicators within the trough, such as ALF anomalies and gas chimneys around the Karmt Shoals, as reported by Bishop and O'Brien (1998). It is likely that the hydrocarbon seepage in the Nancar Trough is actually due to two related processes. The trough now contains a very active petroleum system, which has been invigorated by Pliocene subsidence and sediment loading. However, the extensive faulting associated with the Neogene tectonism Neogene has resulted in low fault seal integrity and hence numerous pathways for seepage. Moreover, the presence of a large palaeo (i.e. pre-Neogene) oil column at Ludmilla-1 within the Nancar Trough (de Ruig et al., 2000) indicates that this liquid petroleum system was active prior to the Neogene, and also suggests that at least some of the observed slicks could be due to tertiary migration.

Clearly, whilst the Nancar Trough is highly prospective in relation to the viability of the oil charge, both pre- and post-Neogene, the key exploration risk in the area is fault seal integrity. Unreactivated, or largely unreactivated, pre-Neogene hosts would still represent attractive targets, as would any stratigraphic traps (e.g. Puffin Formation equivalent fan sands etc). Any relatively high integrity, post-Neogene traps (if present), which could be partly related to combinations of Neogene tilting and faulting, for example, would also been able to receive an active charge. It does not appear that the Nancar Trough is expelling as much gas at the present day as is the Cartier Trough, perhaps due to a difference in the age of the source and/or its current depth of burial. As such, gas-flushing is probably not a significant risk within the Nancar Trough.

The SAR and geological data suggest that the central Cartier Trough is a region of high fault seal integrity (i.e. there are no slicks and virtually no significant Neogene faults), whereas the flanks are characterised by both a significant amount of seepage and high displacement Neogene faults. Given that the Cartier Trough is expelling significant amounts of gas at the present day (O'Brien et al., 1996b; Kennard et al., 1999), it may be that this gas is driving a "front" of oil from charged traps around the margins of the Cartier Trough, thereby producing the observed clusters of slicks (particularly where Neogene faults are present). Nevertheless, valid traps somewhat up-dip of these areas would be well-placed to receive a liquid hydrocarbon charge at the present day.

The greatest concentrations of slicks within the Bonaparte Basin, however, actually occur in areas well outside the Late Jurassic depocentres. These clusters of slicks may point to the presence of new petroleum systems, and hence may represent, at least at the regional scale, the most significant aspect of the SAR results. Two key clusters of slicks appear to be closely associated with carbonate banks on the outer Ashmore Platform, outboard from the Rainbow 1 and Sahul Shoals 1 well locations respectively. These slicks, if confirmed as being due to thermogenic hydrocarbons, point to the presence of a new petroleum system in the area, which is at this stage undrilled. Perhaps the most likely source horizon that could be responsible for these slicks would be the proposed Late Triassic-Early Jurassic, outer margin carbonate source that has apparently charged the Sunrise gas-condensate field and the Buffon well (Edwards et al., 2001). It is possible that the slicks observed within the Timor Trough were also sourced from this horizon.

Another key cluster of slicks was located south-east of the Anderdon 1 well on the Londonderry High. These slicks, if confirmed as thermogenically-sourced, point to the possibility of long-range migration from a Palaeozoic (?Early Permian) petroleum system to the north-east, perhaps analogous to the Keyling Formation within the Petrel Sub-basin (Edwards et al., 1997).

A key recommendation of this study is that these identified seepage-slick clusters on the Ashmore Platform and the Londonderry High be pursued. Additional SAR acquisition, to determine repeatability, or lack thereof, of the seepage, should be undertaken in the first instance. Sampling of the slicks at sea is desirable and feasible.

Areas Where Seepage-Slicks Are Absent

The deep water, outer Browse Basin contained very few slicks. Slicks were absent over the Scott Reef-Brecknock area, major gas-condensate accumulations. This lack of SAR slicks may be due to a general absence of oil-prone (?Late Jurassic) source rocks in the outer Browse Basin - that is, gas or gas-condensate generation dominates (e.g. Scott Reef), with attendant lacking or muted SAR response, because gas evaporates quickly, so that slicks do not form or are ephemeral (ivadier & Mikolaj, 1973). Alternatively, the top seal capacity in the outer Browse Basin may be very high, negating seepage over wide areas (fault seal is not usually a problem within the Browse Basin). A combination of gas and gas-condensate charge, and high top seal capacity, is also possible.

Slicks were also absent over much of the Sahul Platform, perhaps due to either gas-prone charge or perhaps fault seal failure (trap breaching) or water washing effects (Newell et al., 1999).

Virtually no slicks were detected over the north-eastern Londonderry High, that is, the Eider Horst and surrounds. This is in spite of the fact that this area clearly received significant charge prior to the Neogene, as evidenced by the significant palaeo-column within the Avocet structure (O'Brien et al., 1996b, 1999b). It therefore appears that the source for this region, namely the Echo Syncline or parts of the Sahul Syncline, is now exhausted, or (less likely) that the Eider Horst is now in a migration "shadow".

Some of the known oil accumulations in the Bonaparte Basin also produced no strong, direct SAR response. Examples of traps with no directly attributable, attendant slicks included Cornea, Laminaria-Corallina, Jabiru and Challis. As discussed previously, however, the SAR data did effectively bulls-eye the Cornea and Laminaria-Corallina trends via the presence of massive slick clusters within 10-15 km of the fields. In contrast, the Skua, Octavius-Tenacious and Oliver accumulations were all identified by the SAR technology.

Water Column Geochemical Sniffer Data

The geochemical sniffer data included in this report were acquired during six surveys which took place between 1990 and 1998 (Figure 27). The first five of the surveys (Surveys 94, 97, 99, 100 & 176) were acquired using the vessel RV Rig Seismic, whereas the final survey, Survey 207, was acquired in 1998 using the vessel *TSMV Pacific Conquest*. Details of these surveys are listed below in Table 1. Individual detailed interpretation reports are available for each of these surveys, while a summary CD, which contains all reports, interpretations and digital analytical data, is also available (Morse, in press).

It is not the purpose of this report to repeat the detailed evaluation of the sniffer survey data, as this has already been presented within these reports or in subsequent derived publications. Rather, only the key results of these surveys are discussed in this section. In a later section of this report, which presents an integration of the SAR, sniffer and ALF data, some of the sniffer data are discussed at length.

Sniffer Methodology

The sniffer data were acquired using an AGSO purpose-built system, which comprised a towed, 2.5 m long 'fish' from which bottom-water was pumped through a hollow nylon tube (wrapped with a stainless steel braid) into the geochemical laboratory on the ship. The towed-fish was typically deployed within 10-15 m of the seafloor to minimise dispersion from the potential sources of seepage. Light hydrocarbons were extracted from seawater in an evacuated chamber and analysed by gas chromatographs connected in parallel. Total hydrocarbon concentrations were measured every 30 seconds (or, at a ship speed of 5 knots, a distance of about 30 m on the seafloor). The light hydrocarbons (C_1-C_4) were measured every 2 minutes (~240 m intervals on the seafloor), and C_5-C_8 were measured every 8 minutes (~ every 1,000 m on the seafloor).

Hydrocarbon anomalies are identified by comparing the measured light hydrocarbon concentrations to the local 'background' concentrations. A variety of geochemical cross-plots can then be used to determine whether the anomalies are actually due to hydrocarbon seepage, the hydrographic structure in the water column, or *in situ* biogenic production. If the anomaly is related to seepage, additional cross-plots are used to determine the source of the seepage (thermogenic gas versus gas-condensate versus oil-prone, or biogenic gas).

Water column anomalies can be classified according to their elevation above local background concentrations. For example, strong anomalies are defined as those where some, or all, of the C_1-C_4 hydrocarbon concentrations increase more than an order of magnitude above background; moderate anomalies have hydrocarbon increases five-to-ten-fold above background and weak anomalies have hydrocarbons increase less than five-fold above background.

Table 1. Details of the water column geochemical sniffer surveys used in the present study.

Survey Number	Year Acquired & Total Kms	Region Covered	General Description	Relevant Reports & Publications
94	1990 1,800 km	Arafura Sea	Regional survey.	Survey Report: Bickford et al. (1992a)
97	1990 2,730 km	Vulcan Sub-basin to Eider Horst	Regional survey.	Survey Report: O'Brien et al. (1992) Papers: O'Brien & Woods (1995); O'Brien et al. (1998)
99	1991 3,466 km	Sahul Syncline; Malita Graben; northern Petrel Sub-basin	Regional survey.	Survey Report: Bickford et al. (1992b)
100	1991 2,540 km	Central to southern Petrel Sub-basin; Malita Graben; Sahul Syncline	Regional survey.	Survey Report: Bishop et al. (1992
176	1996 3,535 km	Yampi Shelf; northern Browse Basin; Vulcan Sub-basin; Sahul Platform	Regional survey with detailed grids in northern Browse Basin and southern Vulcan Sub-basin.	Survey Report: Wilson (2000) O'Brien et al. (2000) O'Brien et al. (in press)
207	1998 4,788 km	Yampi Shelf; Vulcan Sub-basin; Northern Carnarvon Basin; south-western Canning	Detailed grids on Yampi Shelf and in southern Vulcan Sub-	Survey Report: Wilson (1999)

		Basin	basin; regional lines elsewhere.	

Sniffer Results

The discussion of the results of the sniffer surveys have been broken down into several geographic provinces, namely:

- Yampi Shelf and Northern Browse Basin,
- Vulcan Sub-basin, including the Eider Horst,
- Sahul Syncline, Sahul Platform and Malita Graben,
- Petrel Sub-basin and
- Arafura Sea.

Yampi Shelf & Northern Browse Basin

The water column geochemical sniffer data in this area comprised a number of Survey 176 (1996) and 207 (1998) lines which were acquired on the Yampi Shelf and in the far northern Browse Basin (the Haydn survey area). For the simplicity of discussion, only the results of Survey 176 will be mostly used in the following discussion. There was, however, very good agreement between the location and nature of hydrocarbon seeps detected by both surveys.

YAMPI SHELF

On the Yampi Shelf, a targeted water column geochemical sniffer program was carried out over the Gwydion-1 well and surrounds, and also over the Londonderry-1 and Cornea trends.

In the Gwydion area, 340 km of data were acquired during Survey 176 over the Gwydion field (Gwydion survey) and along a structural trend approximately 30 km west of the Gwydion field (Gwydion West survey). Background methane values of approximately 4 ppm methane and 0.016-0.018 ppm ethane were typically measured throughout the region, suggesting that minimal amounts of hydrocarbons are migrating to the seafloor at the present day. Weak ethane anomalies were detected on two shot-points about 1 km west of the Gwydion 1 well location. In addition, weak ethane anomalies were also detected at two shot-points on the Gwydion West survey. The geological significance of these anomalies is unclear.

An overlay of the sniffer profile on seismic line YST 165-03 is shown on Figure 28a. The prominent amplitude anomaly associated with the Gwydion-1 well is clearly seen, though no hydrocarbon anomalies were present over this accumulation within the water column. The lack of water column anomalies in this area is probably due to the fact that the regional seal here is thick, which has effectively prevented the seepage of hydrocarbons to the seafloor (O’Brien et al., 1996c, 1998b, 2000).

Two regional sniffer lines were acquired over seismic lines 165YST-4 and –5 during sniffer survey 207. These lines were located half-way between the Gwydion survey lines and the lines in the Londonderry-Cornea area. No significant hydrocarbon anomalies were detected on either of these lines.

A grid of sniffer data was acquired over and between seismic lines 165YST-07 and –12, which extends over the Londonderry and Cornea structural trends. This acquisition revealed the presence of areally extensive gas seepage (O'Brien et al, 1996c, 2000; O'Brien and Quaife, 1997). This seepage extended from around the Cornea trend on YST 165-08 (inboard from the Londonderry-1) well, for approximately 25 km to the east-southeast of the Londonderry 1 and Cornea 1 exploration wells (Figure 29). The most intense seepage is located inboard of most of the mapped amplitude anomalies, gas chimneys and HRDZs (Figure 29). An area of particularly intense seepage extends over an area 5-6 km across, with methane values peaking at 300 ppm (75-100 times background). Ethane peaked at over 2 ppm in the same area.

The composition of the seep gas is very dry, averaging about 0.8% wet gas (% wetness = $[\{C_2\text{-}C_4\}/\{C_1\text{-}C_4\}*100]$) over the full range of methane concentrations (Figure 30a). The seep gas's molecular composition (high ethane/ethylene ratio) and the $\delta^{13}C$ ratio of its methane (average –42.45) demonstrate that the seep gas is of thermogenic (rather than biogenic) origin. The fact that the hydrocarbon wetness did not increase with progressively increasing methane concentrations indicates that the seep gas is sourced by a gas-prone, or over-mature source, rather than an oil-prone source (O'Brien et al, 1996c). Plots of the concentration of ethane and propane versus methane for the seep gases (Figure 30b) show that there is a simple linear relationship between the methane concentration and the concentration of ethane and propane. This simple relationship suggests that there is just one source for the gas within the seeps on the Yampi Shelf.

The composition of the seep gas (0.8% wet, $\delta^{13}C$ = -42.45) is remarkably similar to that of gas recovered from the reservoir within the Cornea-1 well (2.2 % wet, $\delta^{13}C$ = -40.60; Shell, personal communication, 1999). As such, it is likely that the reservoir gas in the Cornea Field and the seep gas have been generated from the same source rock. This source rock is probably of quite different age (older) and maturity (much more mature) than the Valanginian source rocks which generated the oil reservoired in Cornea-1 (Blevin et al, 1998; Ingram et al., 2000). It is also likely that both source rocks are continuing to generate hydrocarbons at the present day (Spry and Ward, 1997; Blevin et al, 1998; Boreham et al., in press).

The sniffer data from the Londonderry-Cornea area are overlain over the YST seismic lines in Figures 28b-g. These overlays allow a direct comparison between the underlying geology and the position and intensity of the seeps within the water column.

On line YST 165-07, the regional seal (Late Aptian to Turonian interval) thins sharply onto the basin margin near the Cornea-1 well location (Figure 28b). In spite of this, and the fact that Cornea-1 intersected a significant amount of hydrocarbons (Ingram et al, 2000), no significant hydrocarbon anomalies were detected. There is, however, a significant disturbance of the topography seafloor is present directly over Cornea, and also to the southeast of the field.

A distinct series of areally restricted seeps with well-defined shapes were detected on line YST 165-08, which runs through the Londonderry-1 well location and over the Cornea trend (Figure 28c). These anomalies are present where the regional seal thins onto the margin, with the most prominent located directly above seismically prominent gas chimneys present in the sub-surface. The sniffer data reveal that these chimneys typically produce water column anomalies which are 2-5 times background (up to a maximum of ~17 ppm methane). Consequently, whilst chimneys can appear spectacular on seismic data (Figure 31; see also Stein et al., 1998), they are relatively insignificant in contributing to the overall flux of hydrocarbons to the seafloor, and into the water column, at least at the present day. Similarly, the data suggest that even quite low amounts of gas can produce substantial seismic amplitude effects. Significantly, there is no evidence within the sniffer data of the seepage of wet, oil or oil-related gases, even directly over the Cornea trend. Clearly, dry (<1% wet) gas is by far the predominant seep gas, perhaps because of its high mobility, particularly when compared to the heavy, biodegraded oil which is present within the Cornea field (Ingram et al, 2000).

By far the greatest amount of seepage, both geographically and in terms of concentration, is present on line YST 165-09 (Figure 28d). Methane concentrations within the bottom waters increase progressively from background levels of 3-4 ppm to a maximum of 300 ppm methane near shot-point 2,000 (CDP 3000). The progressive increase in the methane contents between shot-points 3,000 and 2,500 mirrors the thinning of the regional seal. A massive increase in seepage was detected immediately associated with where the seal pinches out against a prominent basement high (at shot-point 1,700; CDP 2,600). Margin-ward of this bald basement high, the gas contents of the bottom waters show an exponential decrease, suggesting that loss of gas from the system is completely out-stripping resupply via migration. This region corresponds broadly to the apparent pinch-out edge of the regional seal.

Seismically, the massive gas seepage above the basement high is defined only by a zone of moderately poor coherency and attendant lack of continuity. No well-defined amplitude effects or gas chimneys are present, in spite of the massive gas fluxes through the sequences above the bald high. The best seismic signature of the seepage appears to be a very prominent seafloor amplitude anomaly (Figure 28d). This anomaly accurately maps the location of the most intense seepage, and may relate to enhanced biological activity and carbonate cementation associated with oxidation of seep gases. This amplitude anomaly is located in water depths ranging between about 100 and 80 m.

If the high seafloor amplitudes on line YST 165-09 are due to the presence of seep-related carbonate hard-grounds, then the processes responsible for their formation may be analogous to those documented for HRDZ formation in the sub-surface. It must be remembered, however, that over the last 300,000 years or so, this part of the shelf (100-80 m water depth) would have been sub-aerially exposed (as a result of eustatic sea-level variations) for about 30-50% of the time. As such, these seeps have alternated regularly between a submarine and sub-aerial environment, with significant implications for the type of diagenetic processes that may have taken place.

Line YST 165-10 is a striking example of the control that basement topography exerts on hydrocarbon seepage in this region (Figure 28e). Four localised seeps, which vary from about 18 to 27 ppm methane (5-7 times background) occur directly over topographically prominent basement highs. The regional seal either thins dramatically, or is absent altogether, over these highs. As such, the highs apparently act as hydrocarbon catchments around which seepage is focussed.

Hydrocarbon concentrations within the bottom waters drop dramatically between seismic lines YST 165-10 and –11 (Figure 28f). Methane contents are consistently 1.5-2 times background along the line, with an apparent very weak anomaly being localised over a prominent basement high which pierces the seal.

Line YST 165-12 shows very little evidence of gas seepage (Figure 28g), and apparently marks the northern limit of active seepage in this area. Significantly, shallow seismic amplitude anomalies are also virtually absent north of this line (Figures 29 and 32).

Water column geochemical sniffer data have identified characteristic styles of seepage on the Yampi Shelf. Where the regional seal is thick, such as around the Gwydion-1 well on the southern Yampi Shelf, or in the more basinal areas, seepage within the bottom waters tends to be either absent, or at very low levels. In contrast, in the Londonderry-Cornea area, levels of gas seepage ranged from low to very high. Again, the principal control on the amount of seepage appears to be the thickness and quality of the regional seal. Laboratory Mercury-Air capillary pressure data acquired on core plug material at the base of the Albian shale package in Cornea South–1 (Ingram et al., 2000) indicated a capillary seal capacity, computed at equivalent depth, equal to a 55 m column of gas, or a 157 m oil-only column (22 API oil saturated with gas). The closure in the Cornea structure is only slightly greater than the computed maximum column height for a gas phase. These petrophysical observations, combined with the seismic DHIs and sniffer results, support a model in which gas is continually bleeding through the seal. The gas chimneys tend to be located at the apices of topographically prominent tilt blocks, probably because seal capillary failure at that point is facilitated by thinner and perhaps sandier sealing facies. In spite of their obvious seismic character, the gas chimneys show generally low rates of present day seepage and effectively represent point sources of hydrocarbons. The greatest amounts of seepage are found around topographically prominent basement highs, around which the seal thins significantly or is absent. These highs appear to act as hydrocarbon catchments which focus seepage around them. As such, they represent ideal locations over which to capture a snapshot of the hydrocarbon charge across the area.

It appears that low rates of hydrocarbon seepage, such as those seen around the chimneys, can produce very prominent seismic amplitude effects in the shallow section. In contrast, the areas of most intense seepage are not easily defined seismically, and are best identified by a prominent amplitude anomaly at the seafloor.

The seeps detected by the sniffer invariably were composed of dry, thermogenic gas, with wet gas contents of less than 1% typical. This gas was probably sourced from an over-mature, possibly gas-prone source rock, and almost certainly represents an older source to that which has sourced the oil in the Gwydion and Cornea fields. No evidence was seen in the sniffer data of the heavy, biodegraded oil which is reservoired in Cornea. This may in part relate to the fact that dry gas has a much higher mobility than heavy oil, and hence can leak through the sealing facies much more easily.

Clearly, gas flushing represents a key exploration uncertainty on the Yampi Shelf. If gas flushing is an active process, then the fact that the fault displacements decrease to the north-east of Londonderry 1 and Cornea 1, into the basement fracture system/relay zone which separates the Timor and Browse Compartments, means that a natural remigration fairway exists through this area. If traps are present within this zone, and they have adequate top seal capacity, then they may represent an attractive exploration target (O'Brien et al, 1996c).

NORTHERN BROWSE BASIN (HAYDN SURVEY AREA)

No significant amounts of methane or ethane, or hydrocarbon wetness anomalies, were detected in the bottom waters throughout the Haydn survey area, which is located approximately 110 km north-northwest of the Londonderry-Cornea survey area. The minor variations in the methane and ethane concentrations present can be attributed to biologic activity in the water column, or to variations in the depth of the sniffer tow-fish (O'Brien et al., 1998a). There was also no evidence of hydrocarbon seepage over the Keeling gas accumulation, which has a prominent HRDZ over it (O'Brien & Woods, 1995). The Keeling structure previously contained a 33 m oil leg, was breached during the Neogene faulting, and later resealed. The trap has accumulated 24 billion cubic feet of gas in the last five million years (O'Brien et al., 1996b). Clearly, the absence of leakage over this field shows that it is now effectively a high integrity trap (HIT).

Vulcan Sub-basin - Eider Horst

In the Vulcan Sub-basin – Eider Horst area, three generations of sniffer data are available. These are:

1. Regional data acquired in 1990 during Survey 97.

2. Detailed to semi-detailed data acquired during Survey 176 in 1996. Detailed sniffer surveying was undertaken in the Skua-East Swan area in the southern Vulcan Sub-basin, as well as over the Talbot Field.
3. Semi-detailed to regional data acquired during Survey 207 in 1998.

The regional Survey 97 program discovered a number of hydrocarbon anomalies. These were located in two key areas, namely in and around the Skua Field, and along the Browse-Bonaparte Transition Zone, between the Crux 1 and Conway 1 wells (Figure 33). In addition, an anomaly was identified about 20 km north-east of the Cygnet 1 well. Anomalies around the producing Jabiru and Challis Fields were detected when the sniffer tow-fish was very near the surface, and are hence attributable to discharge from these facilities.

All of the around Skua and along the transition zone anomalies in both groups were moderately weak and consisted principally of methane and ethane enrichments, though some anomalies in the Skua group also had moderate propane enrichments. The anomalies were also characterised by significantly greater ethane enrichment as compared to methane. The anomalies around Skua show a progressive increase in hydrocarbon wetness with increasing methane (O'Brien et al., 1992), which suggests an oil-prone source and is consistent with the nature of the Skua accumulation itself. In contrast, the relationships between the methane concentration and hydrocarbon wetness for the transition zone anomalies are significantly different from those for the anomalies spatially associated with the Skua field. Hydrocarbon wetness does not increase with increasing methane concentration, indicating that the source of the anomalies is gas/condensate prone. Similarly, the methane/ethane ratio is higher in the anomalies associated with the transfer fault than with those directly associated with the Skua field. These anomalies do, nevertheless, provide strong evidence for an active charge system in this as-yet-undrilled part of the fault relay zone.

There were three other hydrocarbon anomalies detected during the survey (apart from those within the two groups discussed above). A very weak minor ethane anomaly was present near the Cartier 1 well on the Ashmore Platform (Line 28). Another very weak ethane (and THC) anomaly was detected on Line 36 near the East Swan 1 well, on the eastern edge of the Swan Graben. In addition, a very weak ethane (with minor methane) anomaly was encountered on Line 37, between the edge of the Paqualin Graben and the Rainbow 1 well on the Ashmore Platform. Significant propane enrichments were also noted on Lines 43 and 46, over the Sahul Shoals. These anomalies occurred through the same general area as the significant seepage-slicks discussed earlier. The very subdued nature of all of these anomalies prevents us from determining whether they are due to thermogenic seepage from the seafloor, or are related to some other process. However, both of the anomalies on Lines 36 and 37 were accompanied by minor increases in the ethylene concentration, which might indicate that they are of biogenic, rather than thermogenic, origin.

Consistent with the SAR results, no water column geochemical anomalies were found in the north-eastern part of the Vulcan Sub-Basin survey area, in the vicinity of the Eider Horst.

Large, residual oil columns were encountered in drilling a number of wells in this area, such as Avocet 1A & 2 (Whibley & Jacobson, 1990; O'Brien & Woods, 1995) and it is believed that these traps were breached during the Neogene fault reactivation associated with plate convergence. One interpretation of the lack of water column geochemical anomalies over these traps is that the structures are not presently receiving charge from the Echo and/or Sahul Synclines. This would imply either that the source rock is spent, or that the structures are now in a migration shadow, perhaps due to structural or subsidence changes which have taken place since the Late Miocene. In either case, the observations support the proposal that the structures were charged prior to collision (i.e. pre-Late Miocene). If the structures are indeed not being charged at present, then it would be necessary to drill only structures that were charged before the mid-Miocene and that have not been breached since. The probability of a viable post mid-Miocene charge appears to be remote in this area.

Detailed sniffer surveying between the Skua Field and East Swan structure in 1996 (Survey 176) confirmed the initial results obtained in Survey 97 (O'Brien et al., 1996d, 1998a, in press). In contrast to the earlier survey, line spacings were reduced to 500-1,000 m (Figure 34). In the south-western part of the area (around Skua-Swift) several moderate to strong, localised anomalies are present in the methane, ethane and wetness data. These anomalies are ethane-rich and geochemically 'wet', with a zone of ethane enrichment extending northwards to near Birch 1, and southwards past Swift 1. Ethylene and propylene (biologic indicators) were absent. Maximum methane and ethane concentrations exceeded 30 ppm and 1.5 ppm respectively in this area, from background values of approximately 3-4 and 0.02-0.03 ppm respectively. Hydrocarbon wetness increased progressively with methane (wetness was typically 5-8%), consistent with an oil-prone source for the significant anomalies. In general, these intense water column anomalies also occurred close to the HRDZs mapped in the area.

In contrast to the Skua-Swift region, the entire East Swan-Eclipse area is dominated by low levels of (generally) geochemically "dry" hydrocarbons, which may relate to a low level charge of over-mature hydrocarbons migrating from the Sawn Graben at the present day (O'Brien et al., 1998a; in press).

Some sniffer data were also acquired over the Talbot Field, though no significant anomalies were detected.

<u>Sahul Syncline, Sahul Platform & Malita Graben</u>

Regional sniffer acquisition programs were undertaken in the Sahul Syncline, Sahul Platform (Sunrise-Troubadour area) and Malita Graben during Surveys 99, 100 and 176.

SAHUL SYNCLINE

No significant hydrocarbon anomalies were detected in the Sahul Syncline (survey lines 99/001-010, 99/026 and 100/06). Weak but anomalous ethane and propane concentrations (ethane to 0.081ppm) were observed over a distance of approximately 1,000 m immediately around and to the south-east of the Kite 1 well location. Whether this general lack of anomalies is due to a spent charge or inadequate migration fairways, is at this stage, unclear.

SAHUL PLATFORM

The only data available around the Sahul Platform were acquired during Survey 176. A total of seven strike lines were acquired on an approximate 4 km grid around and inboard from the Troubadour well location. No significant hydrocarbon anomalies were detected in the water column. Given the active charge in the region, it appears that the seal capacity in this area is high.

MALITA GRABEN

There were no strong hydrocarbon anomalies detected in the Malita Graben, though several weak hydrocarbon anomalies were detected (see Bickford et al., 1992b & Bishop et al., 1992 for a detailed discussion). A weak but extensive THC, ethane and propane anomaly was detected over 200 shot-points (approximately 60 km), starting 15 km south-west of the Gull 1 well. A weak total hydrocarbons (THC) and methane anomaly was detected to the east of Curlew 1, although no anomaly was detected over the well itself. Several other weak anomalies were found in and around the Malita Graben.

Overall, the geochemical sniffer data from the Malita Graben suggest that the area is presently one of limited hydrocarbon seepage, either because an active petroleum system within the graben is lacking, or because of migration fairways are limited.

PETREL SUB-BASIN

Regional sniffer survey data within the Petrel Sub-basin were acquired during Surveys 99 and 100. More water column anomalies were detected within the Petrel Sub-basin than were encountered in the Malita Graben. Massive (up to 220 times background) and relatively localised seepage was detected directly over the Petrel 1 and 1 A well locations, with a large plume extending to the south-east. This seepage is probably principally the result of a leaky well head or sub-sea completion, as the Petrel 1 well blew out during drilling in 1969. Some natural seepage from the accumulation itself cannot be discounted.

A number of repeatable anomalies were also detected over and around the Tern gas-condensate accumulation (Bickford et al., 1992b & Bishop et al., 1992). The composition of these anomalies is consistent with leakage from a condensate source, and it is likely that these anomalies represent natural seepage associated directly with the Tern gas field.

A number of quite “wet” geochemical anomalies were encountered in the southern Petrel Sub-basin (line 100/01), with relatively high propane and butane concentrations measured, suggesting the presence of an oil-prone source. Other scattered, weak anomalies were also measured on lines 100/02 and 100/S2.

ARAFURA SEA.

A total of approximately 1,800 km of regional sniffer data were acquired during Survey 94 in 1990 (Bickford et al., 1992). In general, the Arafura Sea was characterised by low levels of hydrocarbons in the bottom waters. Seven areas of anomalous light hydrocarbons, which were distinct from the local background concentrations, were detected during the survey. The anomalies were generally very weak (<5 fold background), with some persisting over less than 10 km (e.g. lines 96/2, 4, and 6) whereas others appeared to represent broad trends of increased concentration which extended over tens of kilometres (e.g. lines 94/8 and 9). The anomalies appear to fall into two classes.

The first class of anomalies (survey lines 94/2, 4 and 6) is characterised by elevated concentrations of total hydrocarbons (THC), methane and trace amounts of ethane. These anomalies all have elevated concentrations of ethylene (i.e. unsaturated hydrocarbons) and, as such, probably result from *in situ* generation in the water column via microbial activity, rather than thermogenic hydrocarbon seepage from the seafloor. A hybrid interpretation, involving weak thermogenic seepage which stimulates biogenic activity in the water column, is possible, but not considered likely.

The second class of anomalies was present on survey lines 94/8 and 9. These anomalies consisted of elevated concentrations of THC, methane and ethane (with trace propane), with the highest concentrations being measured near the Money Shoals 1 and Kulka 1 wells. These increases in saturated hydrocarbons, albeit very weak, were not accompanied by increases in the concentration of unsaturated hydrocarbons. As such, they may represent genuine thermogenic hydrocarbon seepage.

Cross-plotting the methane concentration versus the hydrocarbon wetness for all of the anomalies in the Arafura Sea indicated that all anomalies were from “dry” sources (either dry thermogenic gas or biogenic gas).

Overall, the geochemical sniffer data from the Arafura Sea suggest that the area is principally one of very limited seepage, either because of limited charge volume or because of limited present day vertical migration (due to either a lack of Neogene extensional faulting or the presence of a high quality regional seal).

Airborne Laser Fluorosensor Data

Three types of **Airborne Laser Fluorosensor** (ALF) data and interpretations have been included in this report. These data types were as follows.

1. **BP Legacy ALF Interpretations**. The original BP interpretations from the BP regional Mark II ALF survey reports. The fluors picked from the three BP interpretation reports which covered the study area have been included in the GIS as DBF and shape-files. In addition, the text component of these reports has been scanned and is included in CD II as PDF files. The reports used were:
    - The Bonaparte and West Timor Sea Basins (Williams & Mackintosh, 1990). These data were acquired in 1989.
    - The Browse Basin Survey (Williams & Mackintosh, 1990), which was acquired in 1989.
    - The Timor Gap Survey (Walker, 1991), which was acquired in 1991.

Scanned versions of these original BP interpretation reports have been included in the “ALF” folder on CD-2

2. **Reprocessed BP Legacy ALF Data**. Interpretations resulting from the digital reprocessing of these four BP Mark II ALF survey data. This reprocessing was undertaken by Signalworks Pty Ltd, under contract to AGSO (Cowley, 2001a-d). The results of the data reprocessing have been sub-divided into four provinces, namely the Timor Gap (Cowley, 2001a), Timor Sea (Cowley, 2001b), Bonaparte Basin (2001c) and Browse Basin (2001d). The four interpretation reports have also been included in the “ALF” folder on CD-2.

3. **Reprocessed AGSO Mark III ALF Data**. Six recent and detailed AGSO Mark III ALF surveys (total approximately 10,500 line kilometres) have also been reprocessed by Signalworks, under contract to AGSO (Cowley, 2000a-g). These surveys were all relatively areally restricted but covered a range of three representative geological provinces, including the Yampi Shelf, the northern Browse Basin - southern Vulcan Sub-basin, and Nancar Trough - Sahul Syncline. These seven reports are located in the “ALF” folder on CD-2

ALF Results

Results of the ALF surveys for the various data types were as follows.

BP Legacy ALF Interpretations

The Bonaparte and Timor Sea Surveys were flown by BP between May and August 1989. In total, 14,445 km of data were recorded in the “Bonaparte Basin” (considered by BP to represent the Petrel Sub-basin and flanking shelves), whereas 7,463 km of data were acquired over the "Timor Sea" (effectively the Vulcan Sub-basin, the adjacent Ashmore Platform and Londonderry High and the Sahul Syncline (Figure 35). 219 ALF anomalies or fluors were interpreted by BP in these data (Figure 36), comprising 135 from the Bonaparte Basin and 84 within the Timor Sea. 65 of these fluors were interpreted to be directly attributable to hydrocarbon seepage (Williams & Mackintosh, 1990), with the remaining 154 being interpreted as "weak" anomalies which may or may not be directly related to seepage.

The fluors were both scattered and clustered. Fluors were scattered throughout the Vulcan Sub-basin, with no obvious relationship to known structure except, perhaps, for a virtual absence of fluors within the central Cartier Trough. Three distinct clusters of fluors occurred within the Bonaparte Basin. These were at the south-western end of the Malita Graben, near the Kite and Ascalon wells, in the central Bonaparte Basin, immediately south of the Gull and Curlew wells, and on the Darwin Shelf about 100 km south of the Heron 1 well location. The fluors in the central Bonaparte Basin are located in the relay zone between the Tern and Curlew Compartments of the Petrel Sub-basin (O'Brien et al., 1993, 1996), whereas the other two fluor clusters are probably controlled by leakage at the end of the migration fairway.

The Timor Gap Survey was flown in 1991 and comprised 34,606 km of data along 49 survey lines. BP interpreted 75 fluors as possibly related to seepage (Walker, 1991). It should be noted that virtually all of these anomalies occur along two groups of adjacent survey lines (Figure 36), in the south-western and the central Malita Graben, away from any existing well control. It is possible, given the apparent strong line-bias, that these two clusters could be related to acquisition artefacts.

The Browse Basin Survey was flown in 1989, and comprised 2,185 km which were acquired along six survey lines. 16 fluors of possible seep-related origin were interpreted from these data, of which only 2 were considered "good indicators of petroleum seepage" (Williams & Mackintosh, 1990), with the remaining 14 described as "weak". These fluors fall into two clusters, one around the Scott Reef trend and the other approximately 20-35 km west of Caswell 1. These former group fluors could relate to leakage from the Scott Reef accumulation, whereas the latter might be related to generation within the Caswell Sub-basin.

There were subtle differences in the wavelengths of the detected anomalies within the different areas. For example, fluors within the Vulcan Sub-basin and surrounds were predominantly blue to green (perhaps suggesting an oil source). Similar fluors were detected at the western end of the Malita Graben and over parts of the Petrel Sub-basin. In contrast, the fluors that clustered within the central Bonaparte Basin were classified as Indigo (Williams & Mackintosh, 1990), which may possibly be attributed to a more condensate-prone source. This would be consistent, of course, with the hydrocarbons in the Tern and Petrel accumulations, which were sourced from the Permian.

Reprocessed BP Legacy ALF Data

The full reports based upon the reprocessing of the three BP Mark II ALF surveys are contained in the "ALF: folder in CD-2. In general, there was both broad agreement and significant differences between the fluor distributions interpreted by BP (above) and the interpreted fluor distributions derived from the reprocessing. Summaries of the reprocessed results are listed below, with details provided within the individual reports.

The biggest fluors obtained during the reprocessing were clustered immediately around the Jabiru Field, and probably relate to production waters rather than natural seepage. These fluors were so large that they "suppress/swamp" the much smaller natural fluors to such an extent that they have been omitted from the interpreted data. The reprocessing of the Timor Sea Survey, excluding the Jabiru fluors (Figure 37) revealed groups of fluors, most of which were heavily line-biased. Clusters occurred south-west of the Jabiru and Challis Fields, and to the north-east, along the Sahul Syncline. Scattered fluors, some large, also occur on the Ashmore Platform, south-west of Sahul Shoals 1. If only large fluors are included (Figure 38), then the same sort of pattern remains.

Reprocessing of the Timor Gap Survey (Figure 39) revealed a general absence of large fluors, with the principal clusters of fluors located in the southern part of the survey area, in the Malita Graben. As such, there was reasonable agreement between the original BP interpretations and the fluors picked in the reprocessing. Again, strong line-bias was evident in some of the data.

The reprocessed Browse Basin survey (Figure 40) revealed that the Scott Reef area produced a strong ALF response, with significant other fluors scattered between Scott Reef and the Caswell wells. It may be that the very strong fluors over Scott Reef relate to fluorescence associated with the reef, though it could also be due to hydrocarbon seepage. Again, the reprocessed data provides more information than did BP's original interpretations, but generally agrees.

Reprocessed AGSO Mark III ALF Data

A total of six AGSO ALF Mark III surveys, which were acquired through study area in the mid- to late 1990s, were reprocessed (Figure 41). These surveys are relatively high resolution (in terms of line spacing) and were also acquired with a much improved acquisition system relative to the BP Mark II surveys. The reprocessing allows the results obtained on all of these different surveys to be compared in a meaningful way.

The results of this reprocessing are in the GIS and are also provided in six survey reports, and a summary interpretation report, in the "ALF" folder on CD-2.

Interpretation data (an interpreted fluor map) for each survey for each of the AGSO ALF surveys are summarised on the following pages. A more detailed integration of the ALF data with the regional geology is present later in this report, in the section which deals with the integration of the remote sensing methods. Table 2 shows selected parameters for the ALF surveys analysed in the AGSO project. The fluor density value is the number of fluors picked from every million spectra (fluors per million spectra). This value should be used with caution as it is affected by the interpretation effort and data quality (i.e. the laser intensity), as well as the actual number of fluors present at the time of the survey.

The large fluor density value is the number of fluors having F/R (Fluor/Raman ratio) greater than 0.30 picked from every million spectra (large fluors per million spectra). This measure is much more reliable because the large fluors can be picked consistently.

Table 2. Summary of the results obtained during reprocessing of AGSO ALF surveys.

Survey Name	Km Flown	No. Spectra	No. Fluors Interpreted	Fluor Density (ppm)	Large Fluor Density (ppm)
AC/P8	1,490.1	1,040,856	249	239	43
AC/P16	412.9	290,337	111	382	176
Haydn	2,438.0	1,529,484	21	14	3
Yampi	3,148.4	2,149,037	132	61	20
Browse	488.7	343,563	57	165	3
Skua	2,419.2	1,569,513	183	117	107

The results of the AC/P8 ALF survey, around the Laminaria and Corallina Fields in the Timor Sea, are summarised on Figure 42. A number of large fluors are present in the area, though relatively few are developed directly over the fields themselves. In fact, these trends appear almost as “shadow” zones, where fluors are generally absent. This may be due to relatively high seal capacity directly over the fields. There is a very strong anomaly near the Buffalo Field.

The results of the AC/P16 survey, which was acquired in the Nancar Trough around the Karmt Shoals, are presented in Figure 43. A number of strong fluors were present, though none were developed over the Karmt Shoals themselves. It may be that the seepage is taking place around the edges of the shoals, with the shoals themselves acting as an impermeable barrier to migration.

The results of the Skua ALF survey are shown in Figure 44. Three prominent clusters of fluors, often containing very large fluors, are present: immediately around the Skua Field itself, south-west of the East Swan wells, and around and south-east of the Eclipse 1 well. Unlike the situation in the AC/P8 survey around Laminaria and Corallina, the ALF data in the Skua survey has clearly delineated the field itself. In addition, it appears to have identified breached migration fairways, such as those south-west of East Swan and near Eclipse 1.

The Haydn survey (Figure 45) was acquired in the far northern Browse Basin. This survey was characterised by a low number of fluors compared to the other surveys. These fluors were also generally weak, with one exception. The largest fluor is located very close to the undrilled Haydn structure, which contains a prominent HRDZ on its eastern bounding fault (O'Brien et al., 1998a). The low density of fluors in this area could be due to either a lack of condensate or oil charge, or the fact that the regional seal in this area is quite thick, with minimal Neogene fault reactivation (O'Brien et al., 1999a,b).

The Yampi ALF survey (Figure 46) was acquired from immediately outboard of the Londonderry-Cornea trends, inboard to the south-east, past the regional "edge-of-seal". The central part of this area is dominated by strong gas seepage, as discussed previously, and by O'Brien et al. (2000). The ALF anomalies have clearly defined the oil-prone Cornea trend, with fluors being absent through the area of dry gas seepage, as would be expected. The edge of regional seal, a zone of significant, but intermittent seepage on the SAR data, was not a zone of high ALF anomalies on this data set. In summary, the ALF data accurately defined the field at this location.

The Browse ALF survey was a small survey acquired through the area of defined gas seepage. It was acquired prior to the much larger Yampi ALF survey. The results (Figure 47) concur with those obtained during the Yampi survey.

Three of the six surveys acquired by AGSO contained known oil fields. These fields were Laminaria-Corallina, Buffalo, Skua and Cornea. The reprocessed Mark III ALF data identified three of these fields, namely Buffalo, Skua and Cornea. The Laminaria-Corallina fields were the exception, for reasons which are not clear. It could be that these fields do not leak appreciably (because of high seal capacity) or could be that the very light nature of the hydrocarbons in them means that seeps on the surface of the sea do not persist for long. Numerous fluors were detected immediately to the south-west of Laminaria-Corallina, which clearly indicate the presence of a working source and migration system. As such, it may be that the absence of fluors over Laminaria-Corallina is best explained by relatively higher seal integrity over these fields, compared to both the surrounding geology and the previously mentioned fields (Buffalo, Skua and Cornea).

The large fluor density values listed in Table 2 could be used, in a qualitative to semi-quantitative sense, to rank the risk in relation to the presence of an active petroleum system in the respective regions (Cowley, 2000g). This approach suggests that the ranking is, from highest confidence to lowest confidence:

1) AC/P16 (Nancar Trough),
2) Skua (southern Vulcan Sub-basin),
3) AC/P8 (Laminaria-Corallina-Buffalo area),
4) Yampi Shelf (Cornea area),
5) Haydn (northern Browse Basin), and
6) Browse (Yampi Shelf area, over known dry gas seep).

Integration of Remote Sensing Technologies

One purpose of this study was to examine the relative response of different remote sensing technologies to different types and rates of hydrocarbon seepage. At a regional (sub-basin) scale, only the SAR and the BP Legacy Mark II ALF data cover sufficient area to be truly comparable. At a detailed scale, combinations of SAR, ALF plus or minus sniffer are available for the AC/P8 and –16 (Nancar Trough-Laminaria-Corallina), Skua to East Swan (southern Vulcan Sub-basin) and Yampi Shelf (Cornea) areas.

Regional Scale

At a regional scale, there is no clear relationship between location of slicks interpreted on SAR data and either scattered or clustered ALF fluors, as interpreted on the BP Legacy Mark II data (Figure 48). For example, the Mark II data did not record anomalies through the Nancar Trough, in spite of the fact that that area is one of considerable present day seepage. Moreover, areas of highly clustered Mark II fluors, such as the western end of the Malita Graben, contained few slicks. A comparison between BP's Mark II interpretation and AGSO's reprocessed Mark III data (Figure 49) in the southern Vulcan Sub-basin also shows that the number of fluors recorded on the Mark III data is two orders of magnitude less than that those interpreted from the Mark III ALF data through the same area. Until a better understanding is obtained as to what is controlling the actual distribution of the Mark II fluors, no further comments can be made.

Detailed Scale

Nancar Trough-Karmt Shoals-Laminaria-Corallina Region

The relationships betweenslicks (in light blue) and Mark III ALF anomalies (in red) are shown in Figure 50. Only ALF anomalies with a Fluor/Raman ratio of greater than 0.3 are shown as large red circles. In this region, there is a good correlation, both in relation to the spatial location and the density, of the slicks and the ALF fluors, consistent with the area being one of high present day seepage. The ALF fluors appear to extend further to the north-east, towards Laminaria-Corallina, than the slicks. If seal capacity is improving in that direction, and hence seepage is decreasing, then this may be because ALF is a generally more sensitive tool than SAR at detecting smaller amounts (both volumetrically and areally) than SAR. Neither SAR nor ALF had strong responses over the Laminaria or Corallina Fields themselves.

Southern Vulcan Sub-basin

The southern Vulcan Sub-basin, between Skua and East Swan, is an area of significant hydrocarbon seepage. In this region, Mark III ALF fluors (Figure 51) are clustered around the field itself, and then in bands south of East Swan and near Eclipse 1. Slicks also cluster around Skua, but are absent further to the north, as are water column sniffer (ethane) anomalies. These observations suggest that where relatively high volumes of hydrocarbons are leaking from a charged accumulation, such as around the Skua Field itself (O'Brien et al., 1998a, in press), then SAR, ALF and sniffer can all detect the seepage. Where seepage rates are lower, either because it is simply a migration fairway or because the traps have already been breached, such as in the northern Swan Graben, then only ALF easily detects the seepage. Insufficient volumes of liquids are present to produce a SAR response.

Yampi Shelf

The results of an integrated SAR, ALF and sniffer acquisition program over the Yampi Shelf are summarised in Figure 52. Most of the significant ALF anomalies are located directly over the Cornea trend. A few smaller fluors are located over the edge of regional seal, and there are associated with large oil slicks detected by SAR. In contrast, most of the sniffer anomalies are comprised of dry gas, and these are located approximately half-way between the outboard ALF anomalies and the inboard slicks. There are very few to no slicksor ALF anomalies associated with the massive dry gas seepage.

The ALF anomalies are located directly over the Cornea field. This, combined with the observation that gas chimneys are common over the Londonderry-Cornea trends (O'Brien et al., 2000), suggests that these ALF anomalies might be due to oil coatings on gas bubbles which formed in the reservoir as dry gas migrates through the oil leg. The bubbles might burst as they reach the surface, producing small oil slicks. This phenomenon has also proposed to explain ALF anomalies over the Skua Field (O'Brien et al., 1998a, in press).

The significant offset between the location of seeping dry gas and the oil slicks detected by SAR appears to be reflecting the differences in the relative mobility of gas and oil, controlled by differential seal capillary failure. The viscous, Valanginian-sourced biodegraded oil has migrated much further inboard, and only leaks to the seafloor once the seal is virtually gone (O'Brien et al., 2000). In contrast, the Palaeozoic/Early Mesozoic-sourced gas 'breaks through' the seal sooner because of its much higher relative mobility. As a consequence, dry gas seeps are developed in more basin-ward locations. It appears probably that the seepage in the area is controlled by a combination of (probably low rates and volumes) of secondary migration from basinal source rocks and (probably high rates and volumes) of tertiary migration of oil and gas displaced from accumulations (such as the Cornea trend) along the margin. This model is summarised on Figure 53, which is a schematic across the Yampi Shelf.

Synthesis

At a regional scale, SAR appears to be effective at delineating the presence of an active liquid petroleum system in this area. It has identified the end-points of the migration catchments in the Browse Basin (i.e. the Yampi Shelf) and also the Vulcan Sub-basin (south-western end of the Swan Graben). It has also highlighted areas such as the Browse-Bonaparte Transition Zone. It also clearly identified the very active, leaky petroleum system in the Nancar Trough, as well as the possible presence of several new petroleum systems, such as those on the outboard Ashmore Platform, as well as south-east of Anderdon 1. The SAR data also highlighted the Skua and Cornea oil fields, and provided a broad anomalous “bulls-eye” south-west of Laminaria-Corallina. Nevertheless, it is clear that SAR does notdetect dry gas and it appears as though there are fewer slicks in areas which are characterised by light oils and gas-condensates. This is to be expected, because gas evaporates quickly at the sea surface, so that slicks do not form or are ephemeral (Sivadier & Mikolaj, 1973).

Detailed Mark III ALF data successfully highlighted three of the four oil fields/trends in the study area: Buffalo, Skua and Cornea, whereas it did not respond strongly to Laminaria-Corallina. As such, we propose that ALF appears to be best used at a prospect scale, where it may be able to rank the prospectivity of one structure versus another.

The water column geochemical sniffer can detect a complete range of hydrocarbons, from dry gas to oil, and also allows full characterisation (molecular and isotopic) of the seep gases. Nevertheless, the sniffer is best used at a semi-detailed scale (line spacings of 1-4 km) and needs to be closely integrated with the geology.

A hierarchy of tools clearly exists. Regional studies with SAR can highlight areas which can then be followed up with sniffer and/or ALF, and finally, seabed coring. The relative responses of the various tools, as determined in this study for various rates and types of seepage, are summarised in Figures 54, 55 and 56.

Summary

This study covered significant parts of the Timor Sea and Browse Basin and detected 308 Rank 2 and 292 Rank 3 seepage-slicks, as well as 15 Pollution slicks, 70 Remnant

Pollution slicks and 227 Individual Natural Film Slicks (INFS). The average slick density (including both Rank 2 and Rank 3 seepage-slicks) is approximately 1 every 1,000 square kilometres, which represents a high slick density compared to most other areas around Australia. It is in fact about 13-15 times higher than in the offshore Canning Basin, and about 100 times higher than in the Great Australian Bight.

The majority of seepage-slicks mapped on SAR data in the region occur where the regional seal is thin. This is evidenced in particular on the Yampi Shelf, inboard from the Cornea oil field, and also in the Bonaparte Basin which is characterised by a combination of relatively thin regional seals and significant displacement Neogene faults. It is clear that areas such as the edge of the regional seal, the up-dip limit of the migration fairway, or other areas where the seal is generally thin or faulted, or both, provide the best opportunity to characterise the migration characteristics of an area. High rates of seepage are unlikely to occur from traps with thick, high quality seals, for examples, and relatively high rates of leakage are probably necessary to produce a strong SAR response.

Major groupings of slicks were present in:

- The Browse Basin, especially on the north-eastern Yampi Shelf and along the basin margin fault system which links the Heywood and Copernicus structures.
- Along the transition zone between the northern Browse Basin and the southern Bonaparte Basin.
- On the Ashmore Platform, in particular outboard of the Rainbow-1 and Sahul Shoals wells.
- On the Londonderry High, south-east of Anderdon 1.
- Around the flanks of the Cartier Trough, particularly near the Octavius-Tenacious and Oliver well locations.
- Within the Nancar Trough.
- Within the Rabe and Sabo Blocks, and within the central Timor Trough.

The SAR results have highlighted the exploration potential (for liquids) of the Caswell Sub-basin in the Browse Basin. In addition, seepage-slicks possibly related to either Late Triassic or Permian petroleum systems have been interpreted on the outer Ashmore Platform (outboard of the Rainbow 1 and Sahul Shoals 1 wells) and on the Londonderry High, south-east of Anderdon 1.

A key recommendation of this study is that these identified slick clusters on the Ashmore Platform and the Londonderry High be pursued. Additional SAR acquisition, to determine repeatability, or lack thereof, of the seepage, should be undertaken in the first instance. Sampling of the slicks at sea is desirable and feasible.

The deep water, outer Browse Basin contained very few seepage-slicks. Slicks were absent over the Scott Reef-Brecknock area, major gas-condensate accumulations. This lack of slicks may be due to a general absence of oil-prone (?Late Jurassic) source rocks in the outer Browse Basin - that is, gas or gas-condensate generation dominates (e.g. Scott Reef), with attendant lacking or muted SAR response. Alternatively, the top seal capacity in the outer Browse Basin may be very high, negating seepage over wide areas (fault seal is not usually a problem within the Browse Basin). A combination of gas and gas-condensate charge, and high top seal capacity, is also possible.

Slicks were also absent over much of the Sahul Platform, perhaps due to either gas-prone charge or perhaps fault seal failure (trap breaching) or water washing effects (Newell et al., 1998).

Virtually no seepage-slicks were detected over the north-eastern Londonderry High, that is, the Eider Horst and surrounds. This is in spite of the fact that this area clearly received significant charge prior to the Neogene, as evidenced by the significant palaeo-column within the Avocet structure (O'Brien et al., 1996, 1999). It therefore appears that the source for this region, namely the Echo Syncline or parts of the Sahul Syncline, is exhausted, or (less likely) that the Eider Horst is now in a migration "shadow".

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We thank the many personnel for participated in the Rig Seismic surveys which acquired much of the sniffer data over the years.

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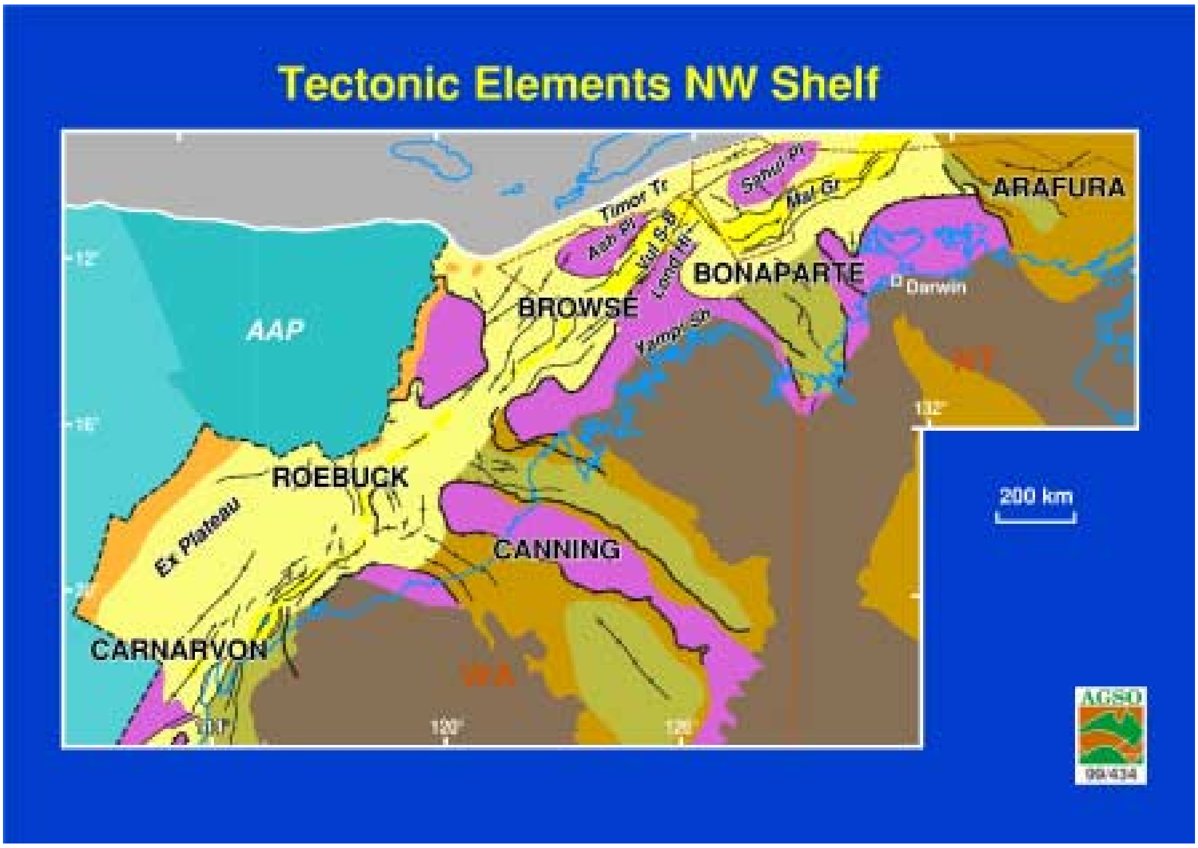

Figure 1. Tectonic elements of the North-West Shelf, Australia.

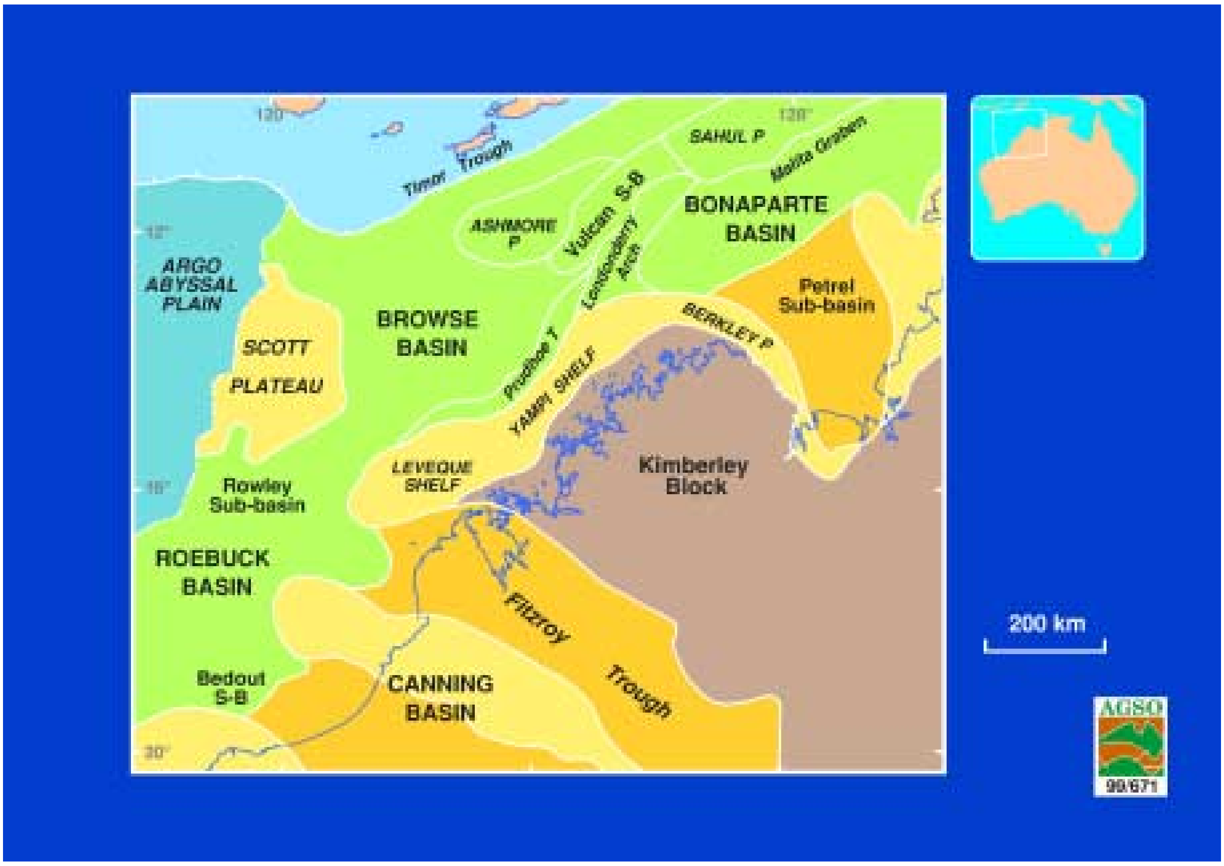

Figure 2. Location map, showing tectonic elements within the Browse and Bonaparte Basins.

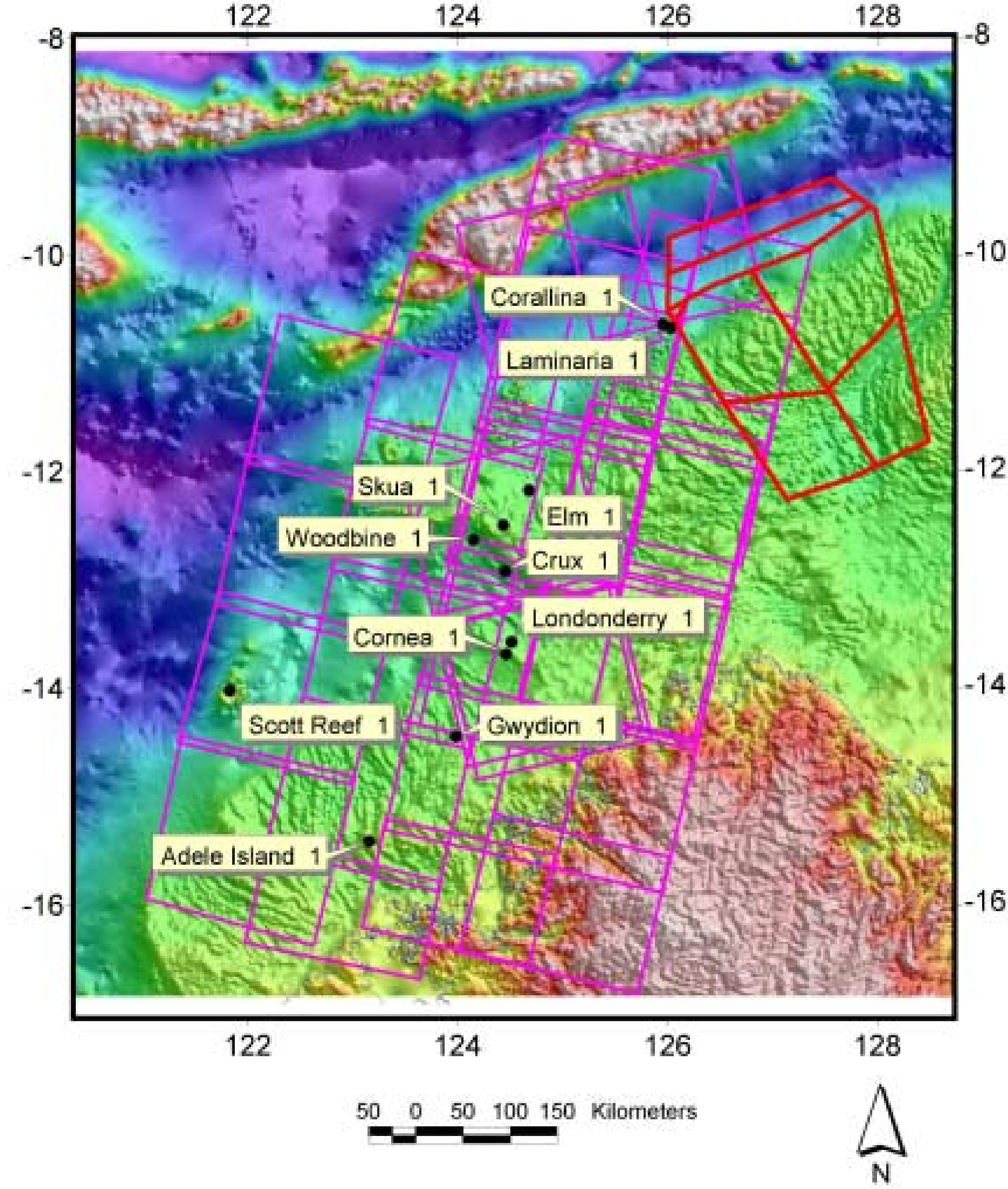

Figure 3. Location map showing area of study, with extent of coverage of SAR data (purple). Zone of Cooperation and key wells indicated.

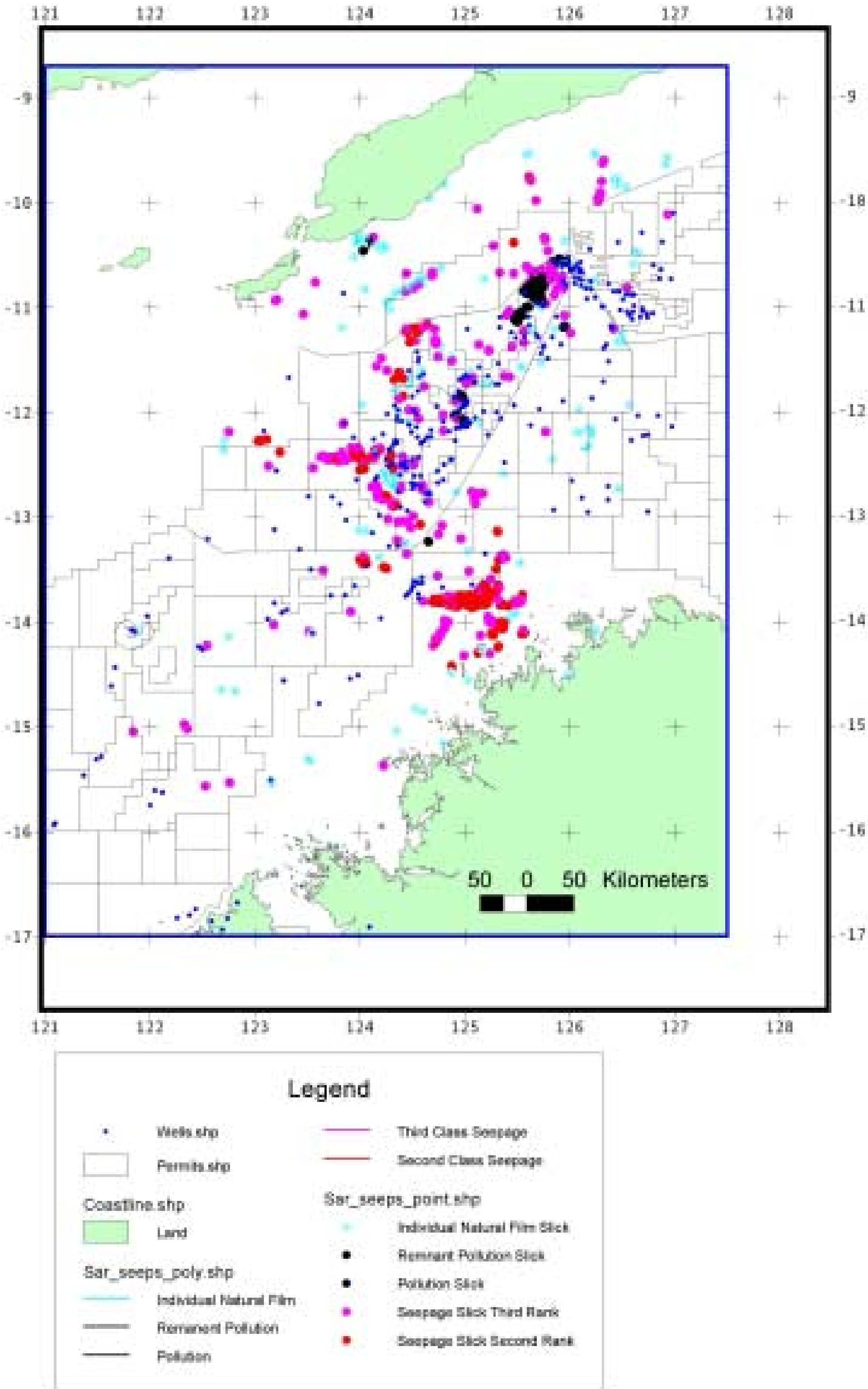

Figure 4. Distribution of slicks mapped on SAR data in the study area, north-western Australia.

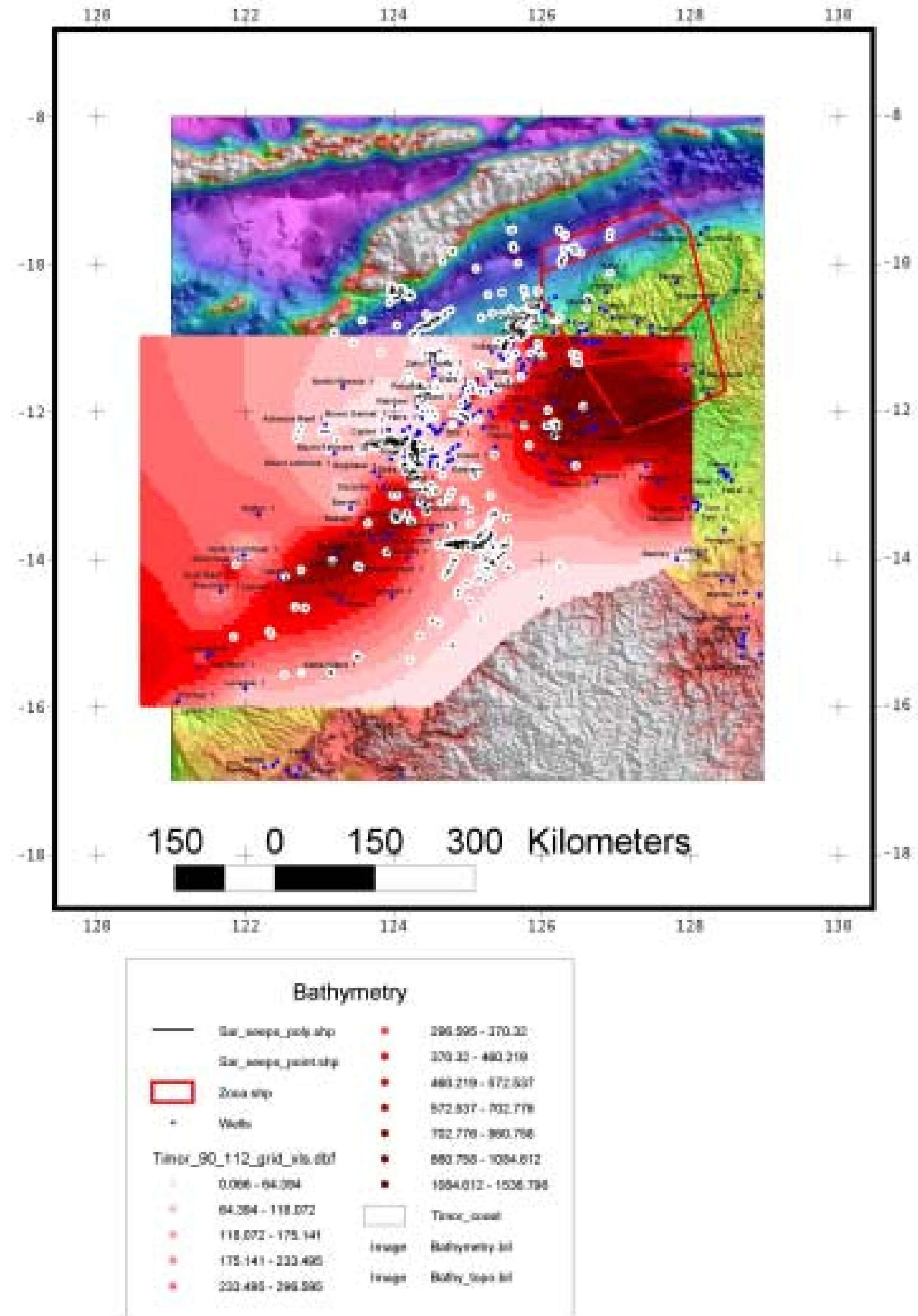

Figure 5. Seepage slicks in the study area, posted on top of regional seal thickness and bathymetry.

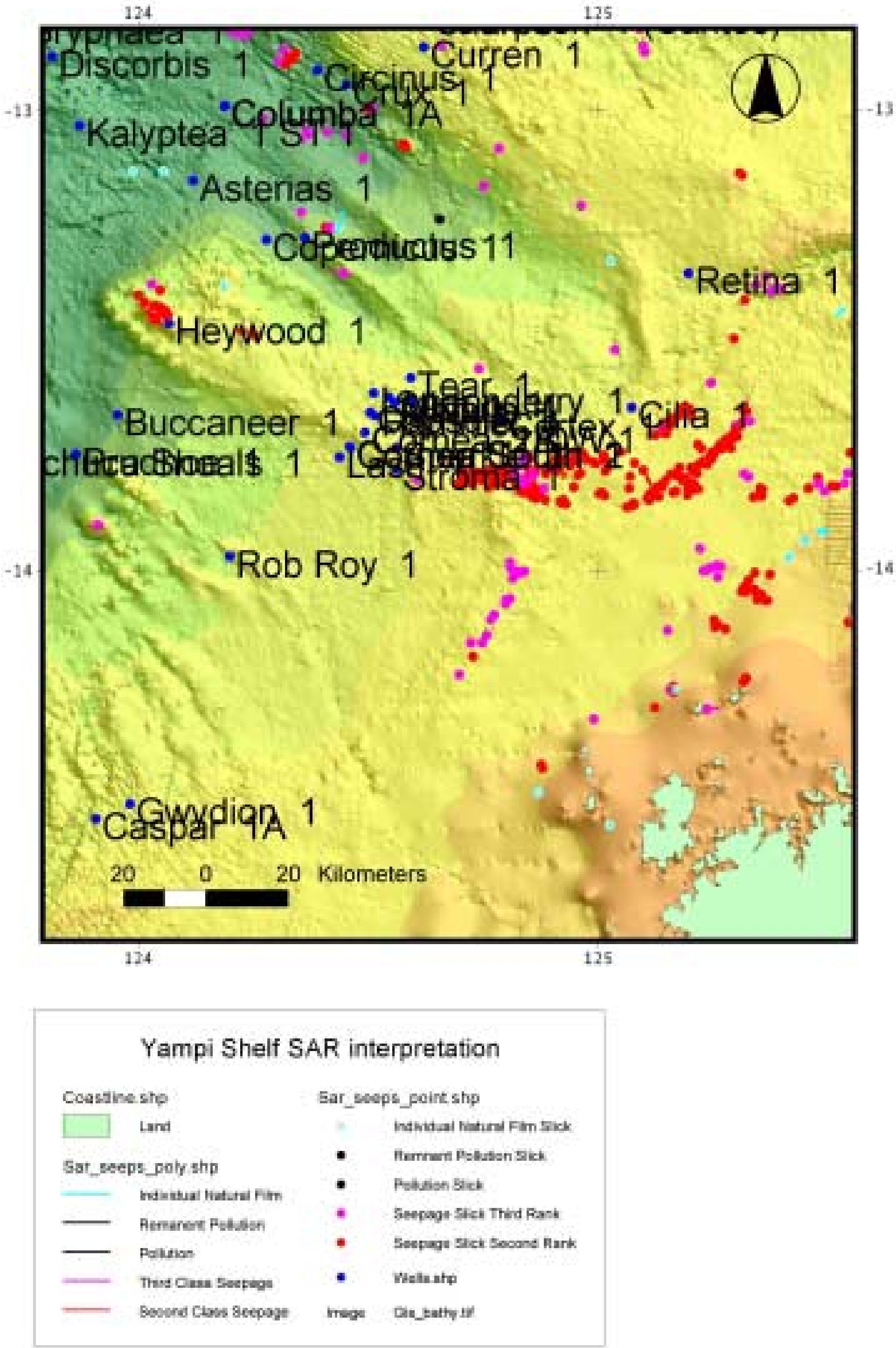

Figure 6. Slicks, northern Yampi Shelf, north-western Australia.

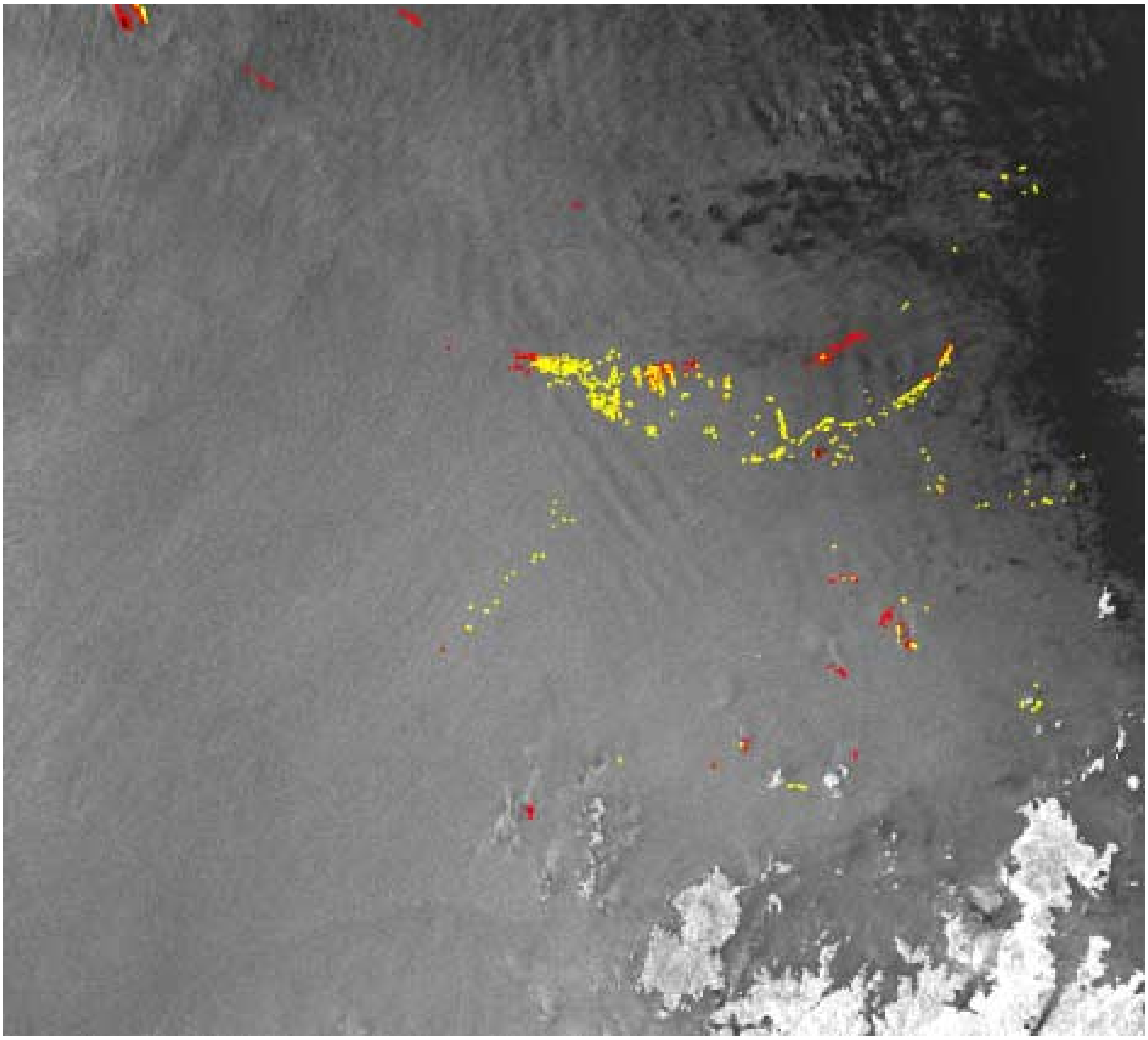

Figure 7. Composite SAR interpretation, showing variation in location of Slicks detected on the inboard Yampi Shelf. Two different dates are shown in red and yellow.

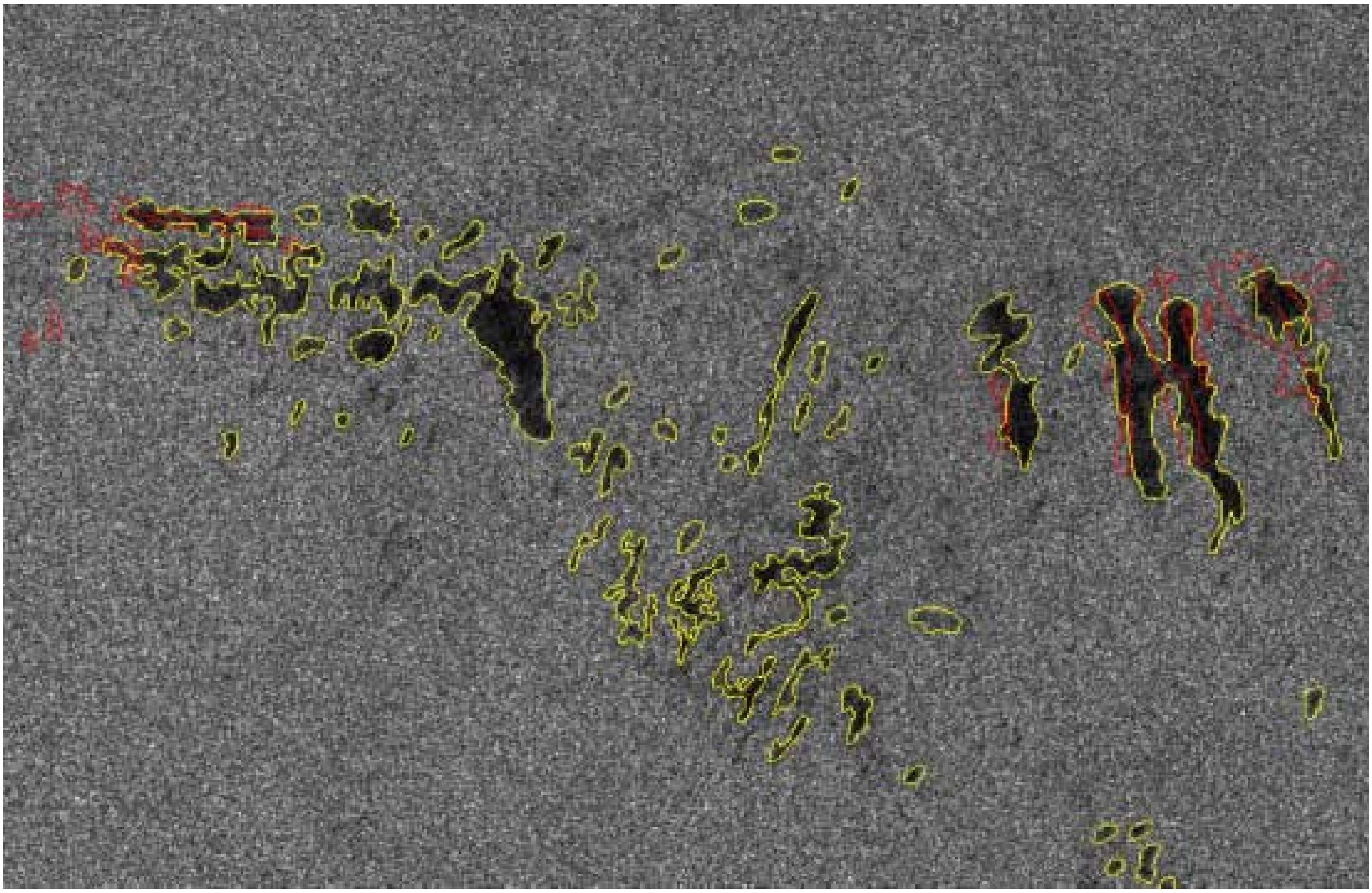

Figure 8. Zoomed in version of Figure 7. Composite SAR interpretation, showing slicks detected on two different dates (yellow and red) at the edge of regional seal, Yampi Shelf.

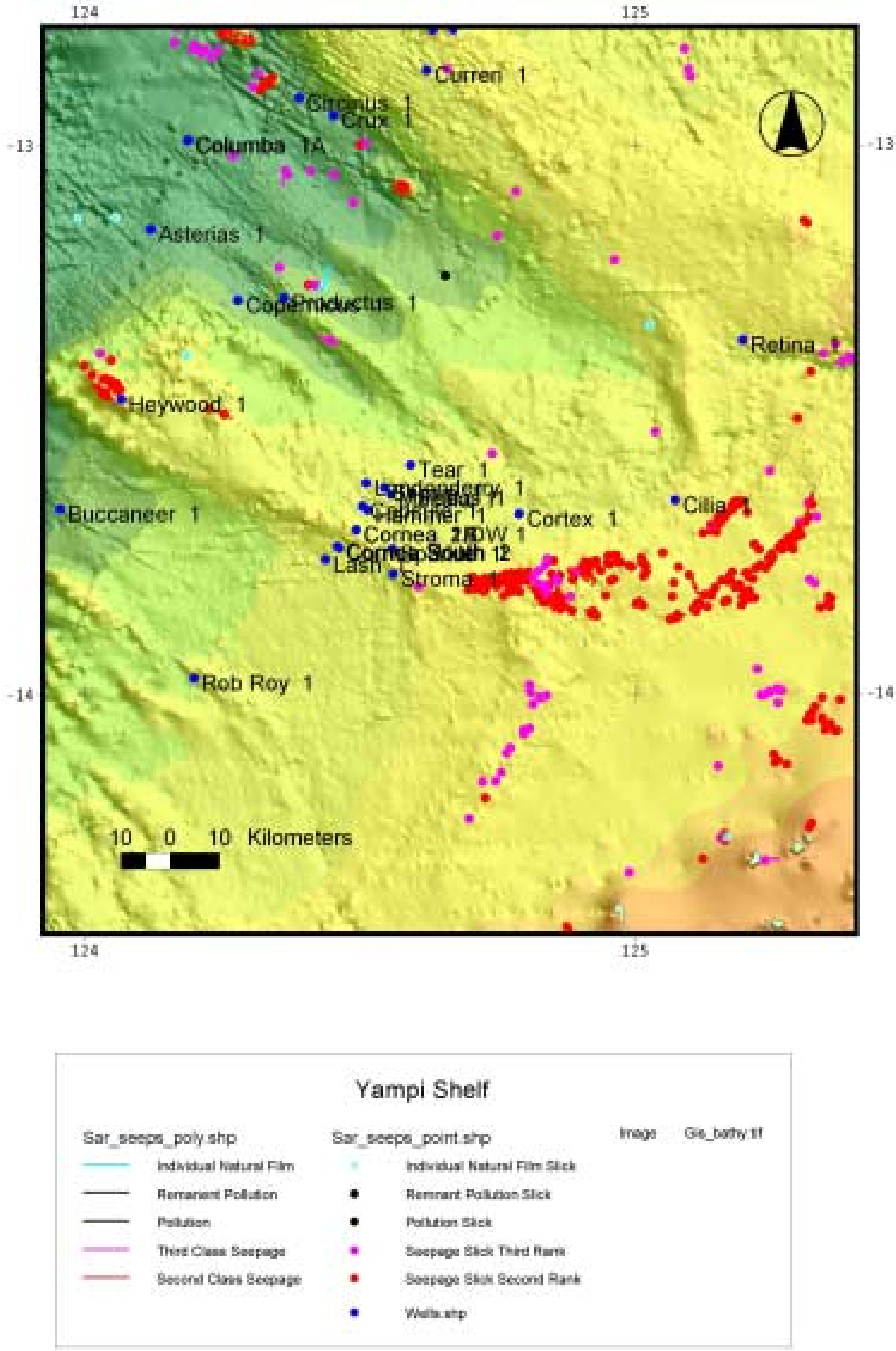

Figure 9. Slicks, northern Yampi Shelf, north-western Australia. Prolific slick development over the Heywood Shoals and along the Heywood-Copernicus fault system.
Red = Rank 2 slicks; Pink = Rank 3 slicks; Light Blue = INFS.

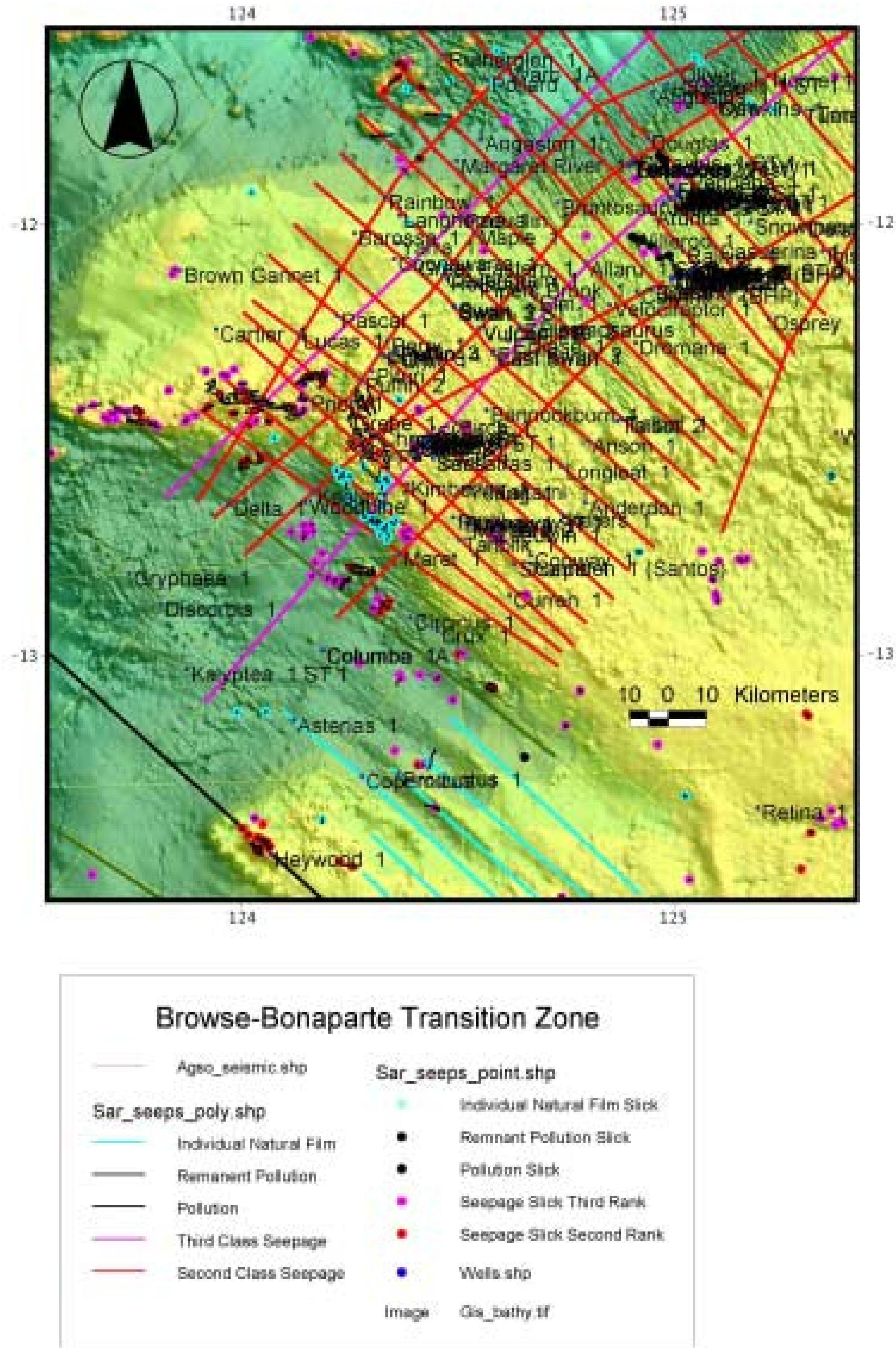

Figure 10. Slicks along the Browse-Bonaparte Transition Zone, north-western Australia. Prolific slick development over the Heywood Shoals and along the Heywood-Copernicus fault system. Red = Rank 2 slicks; Pink = Rank 3 slicks; Light Blue = INFS.

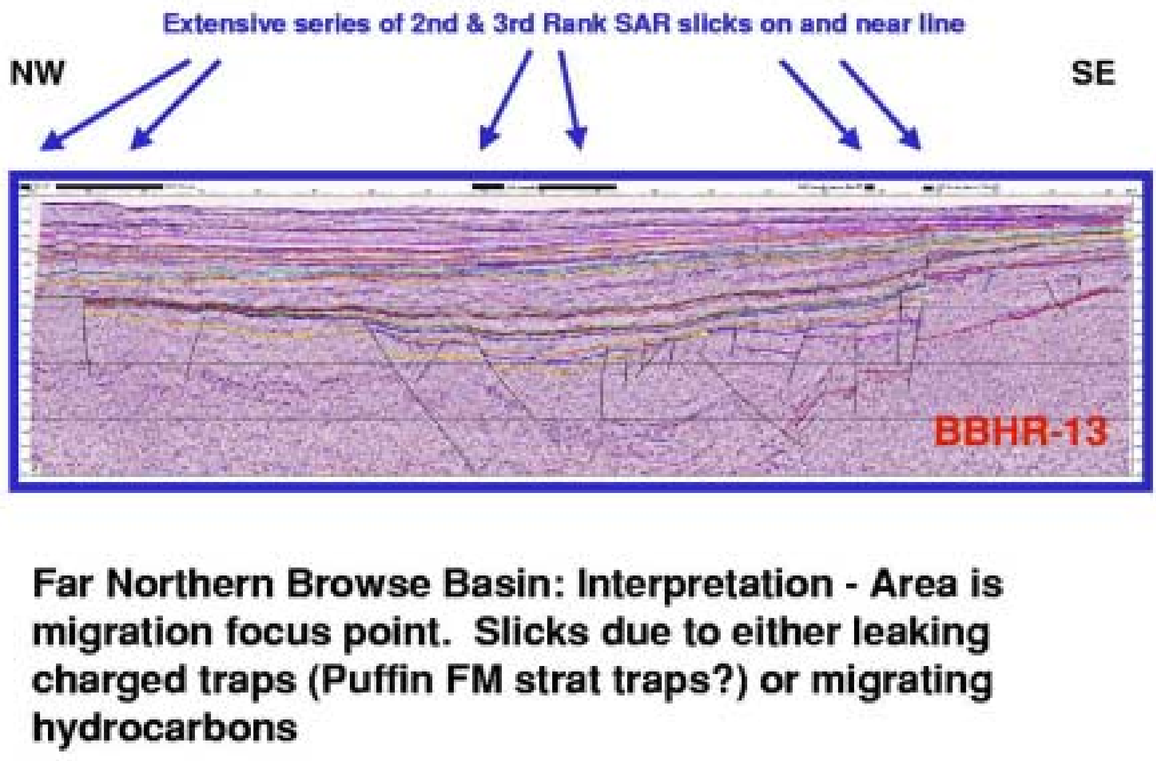

Figure 11. Seismic line 175 BBHR-13, showing Slicks in the far northern Browse Basin.

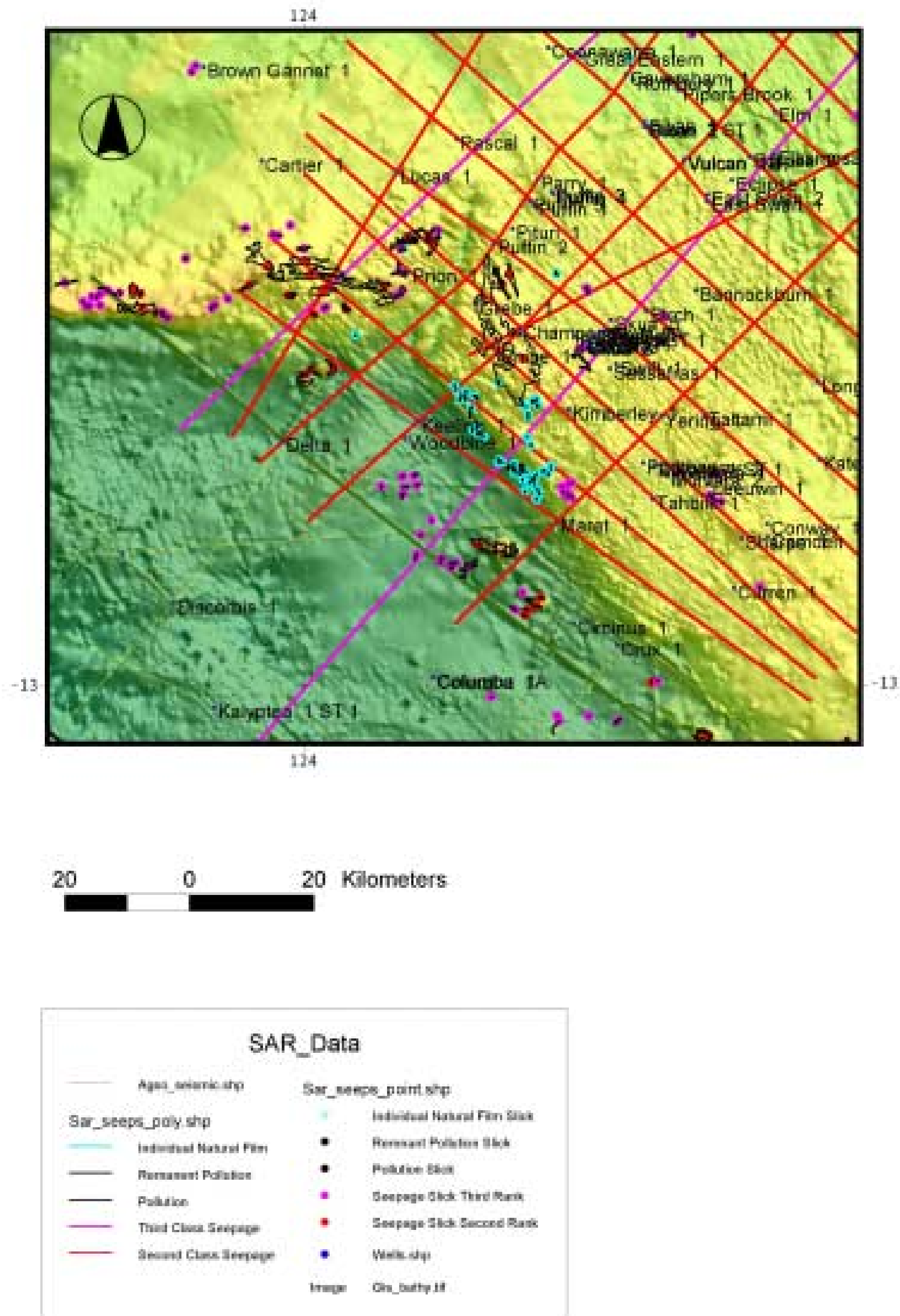

Figure 12. Slicks along the Browse-Bonaparte Transition Zone, north-western Australia. Prolific slick development over the Heywood Shoals and along the Heywood-Copernicus fault system. Red = Rank 2 slicks; Pink = Rank 3 slicks; Light Blue = INFS.

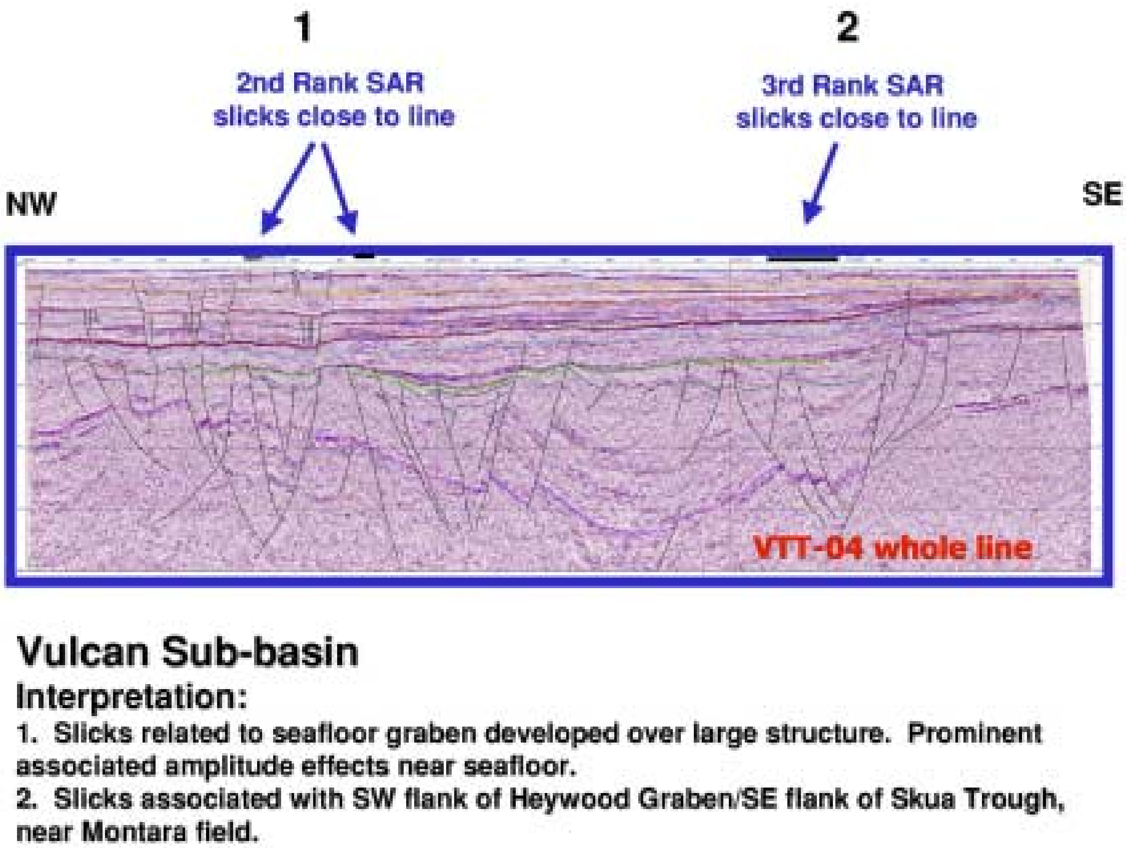

Figure 13. Seismic line 163 VTT-04, showing Slicks along the Browse-Bonaparte Basin Transition Zone.

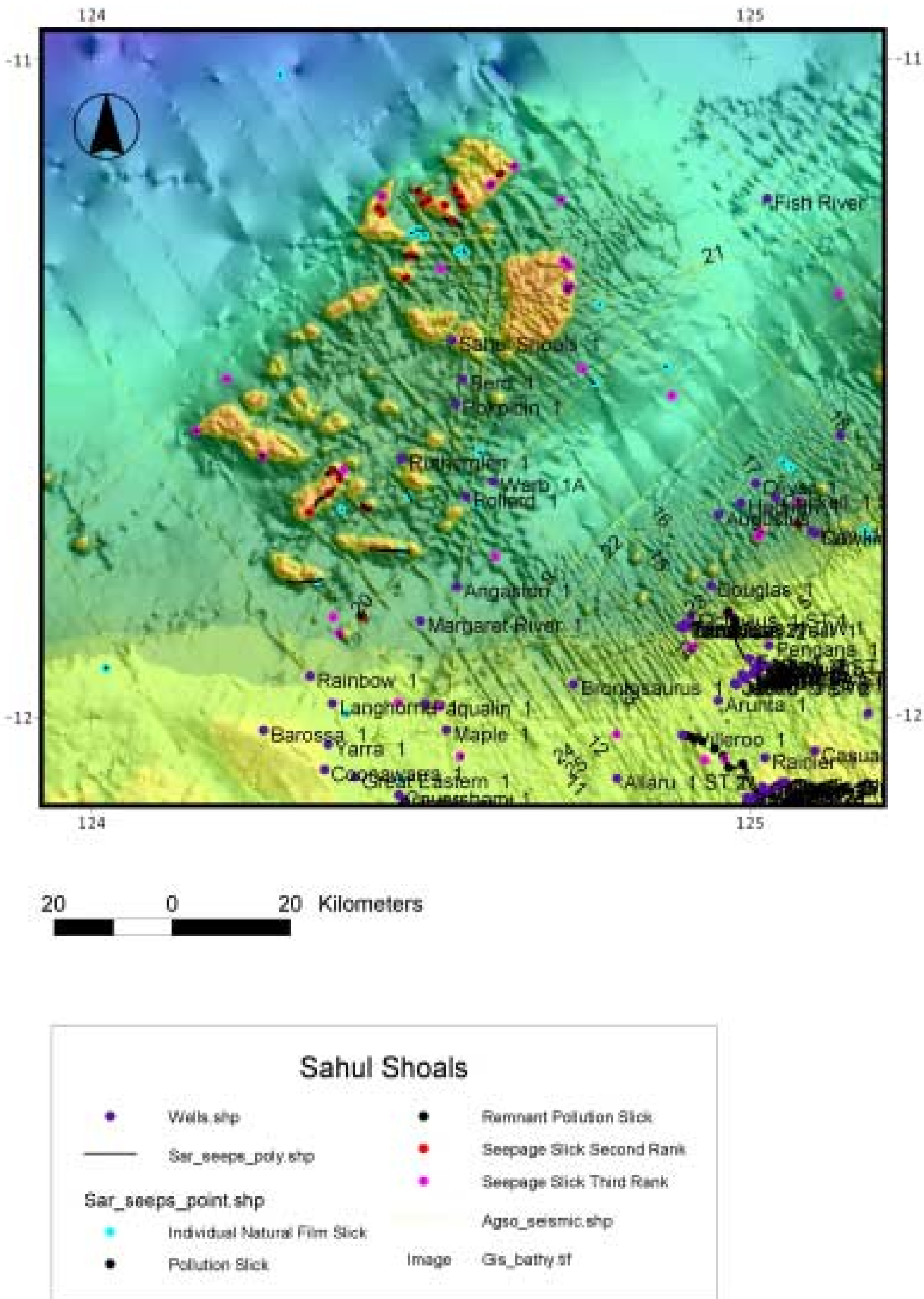

Figure 14. Slicks developed over carbonate bank systems on the Ashmore Platform. Red = Rank 2 slicks; Pink = Rank 3 slicks; Light Blue = INFS.

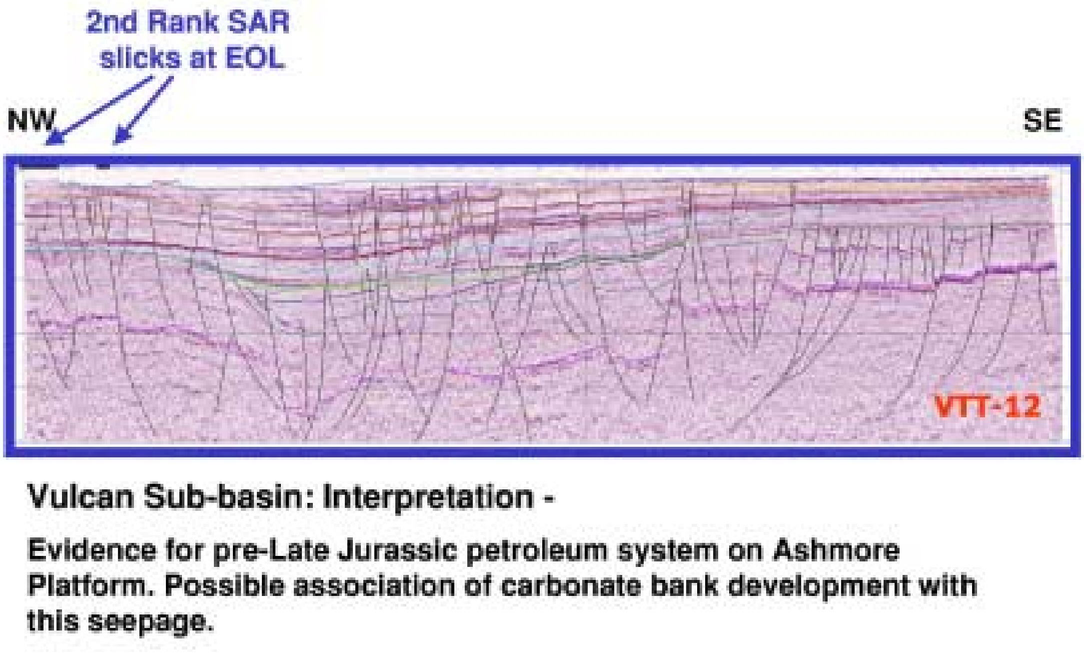

Figure 15. Seismic line 163 VTT 12 showing Slicks developed over carbonate bank systems on the Ashmore Platform.

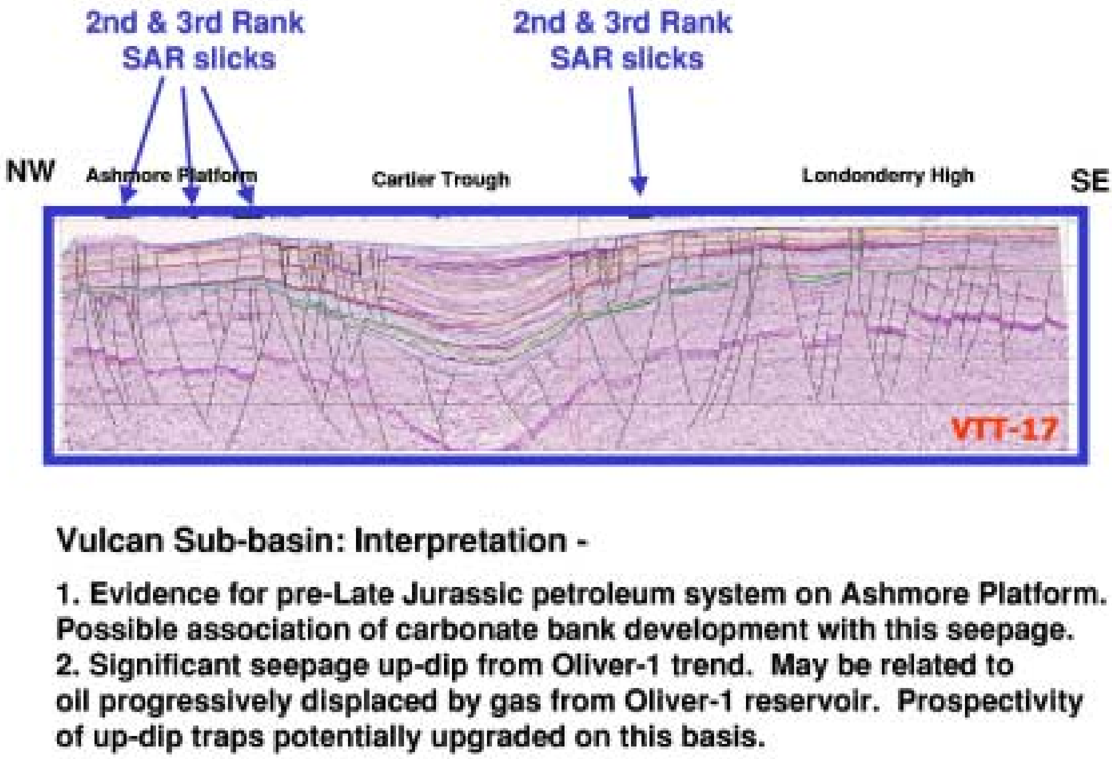

Figure 16. Seismic line 163 VTT17 showing Slicks developed over carbonate bank systems on the Ashmore Platform.

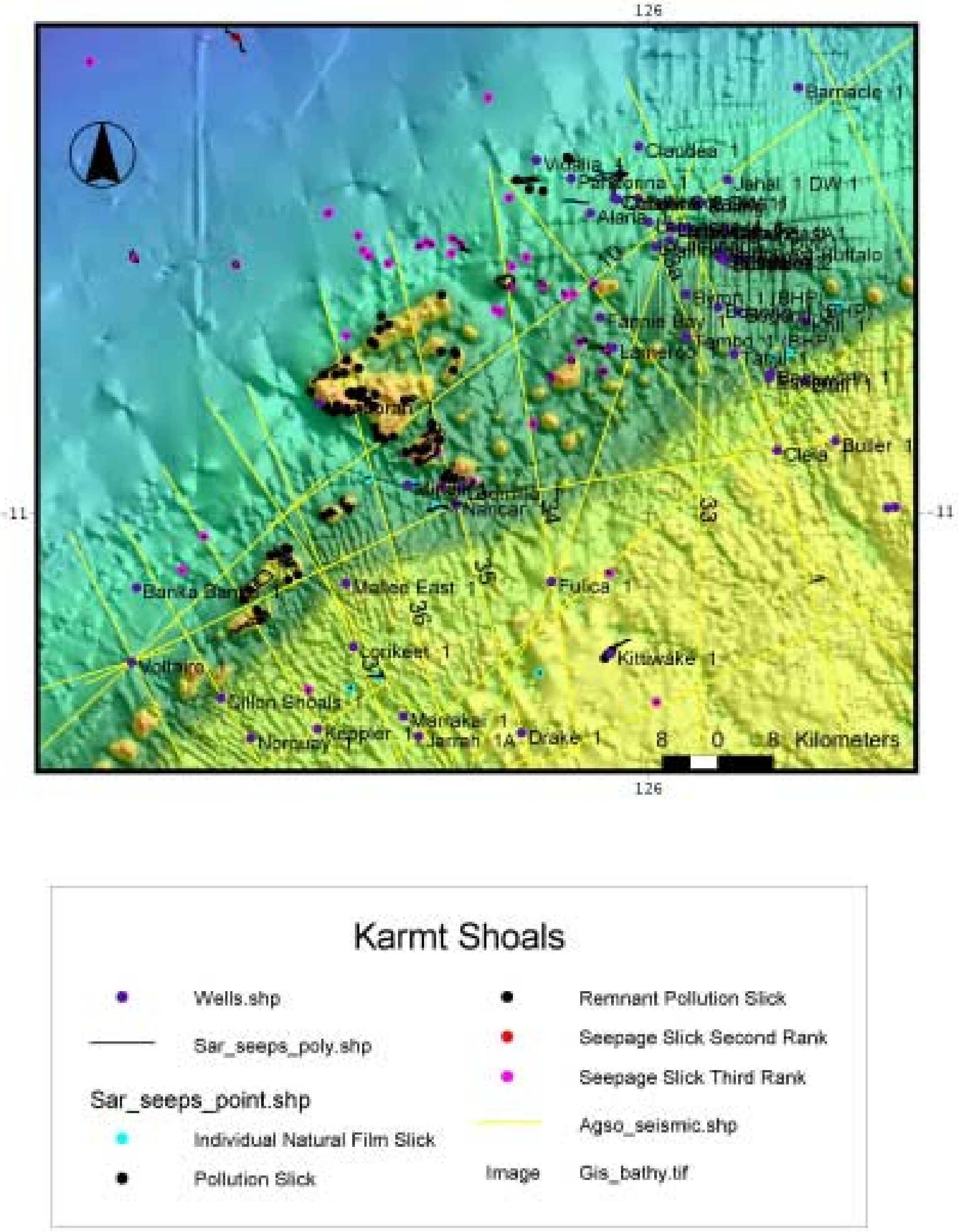

Figure 17. Slicks around the Karmt Shoals, Nancar Trough. Red = Rank 2 slicks; Pink = Rank 3 slicks; Black = Remnant Pollution; Light Blue = INFS

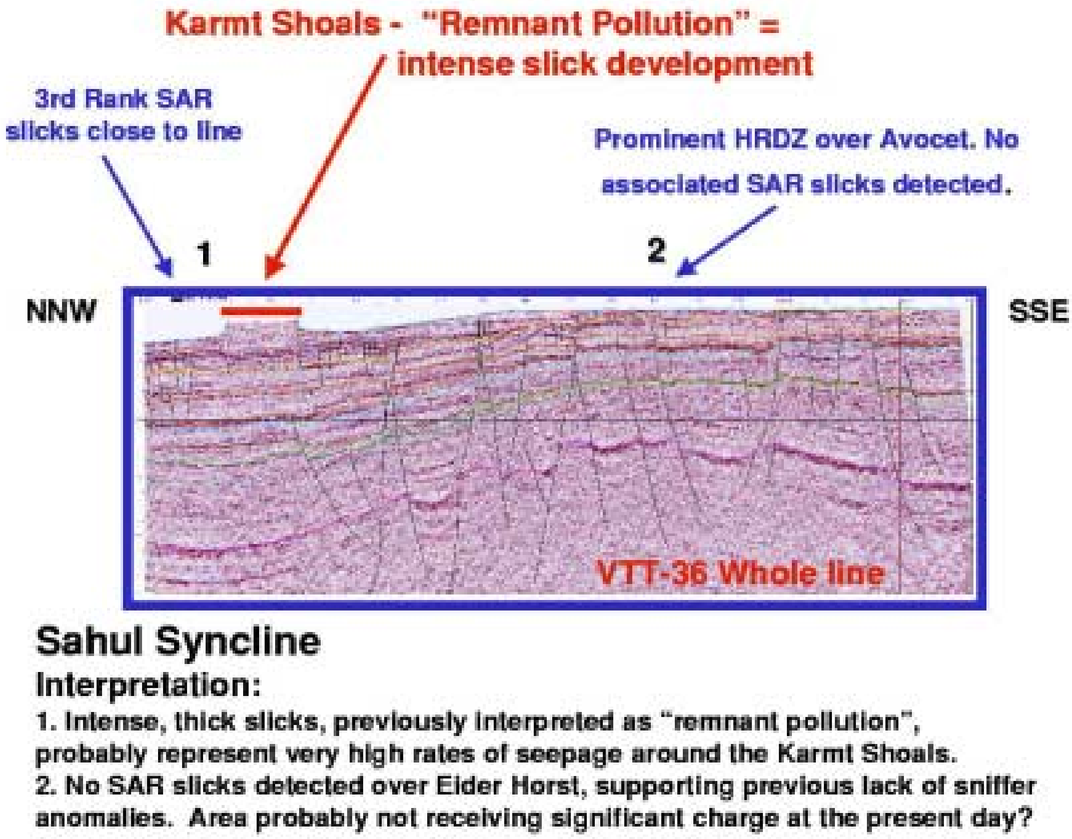

Figure 18. Seismic line 163 VTT-36, showing "remnant pollution", which equates to probably prolific seepage, over carbonate banks in the Nancar Trough.

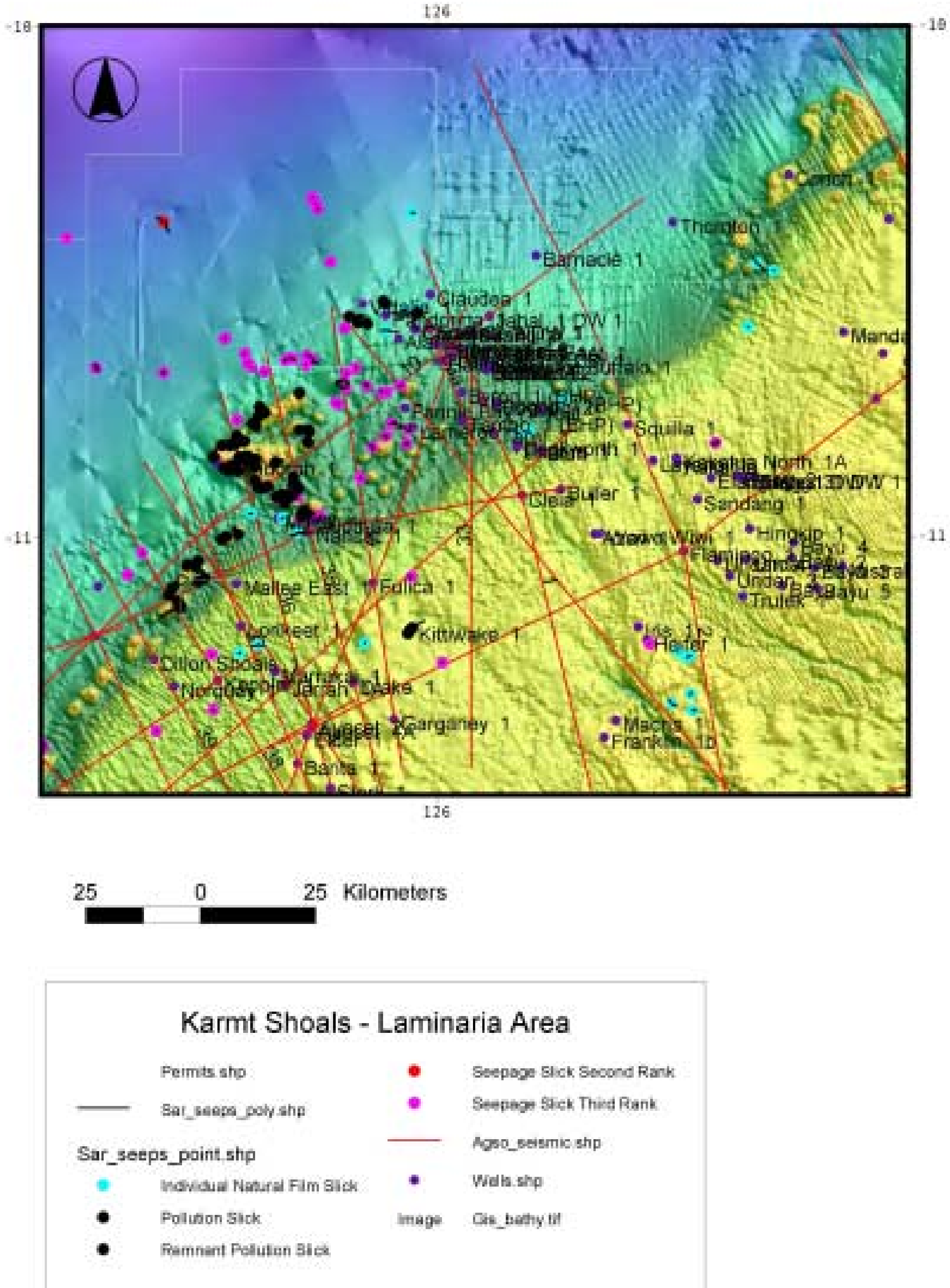

Figure 19. Slicks around the Laminaria Field. Red = Rank 2 slicks; Pink = Rank 3 slicks; Black = Remnant Pollution; Light Blue = INFS

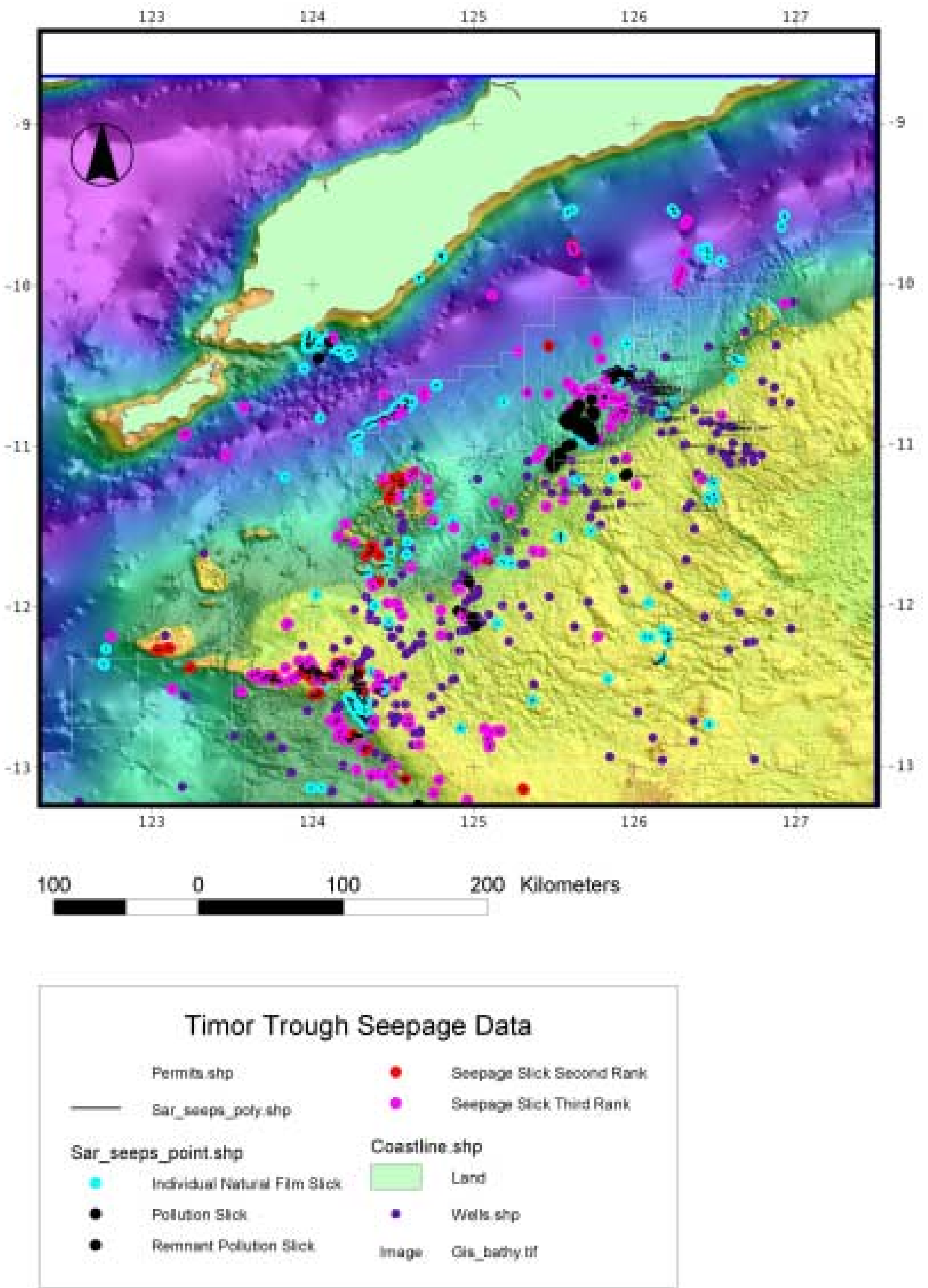

Figure 20. Slicks are present in the Rabe and Sabo Blocks and the central Timor Trough.

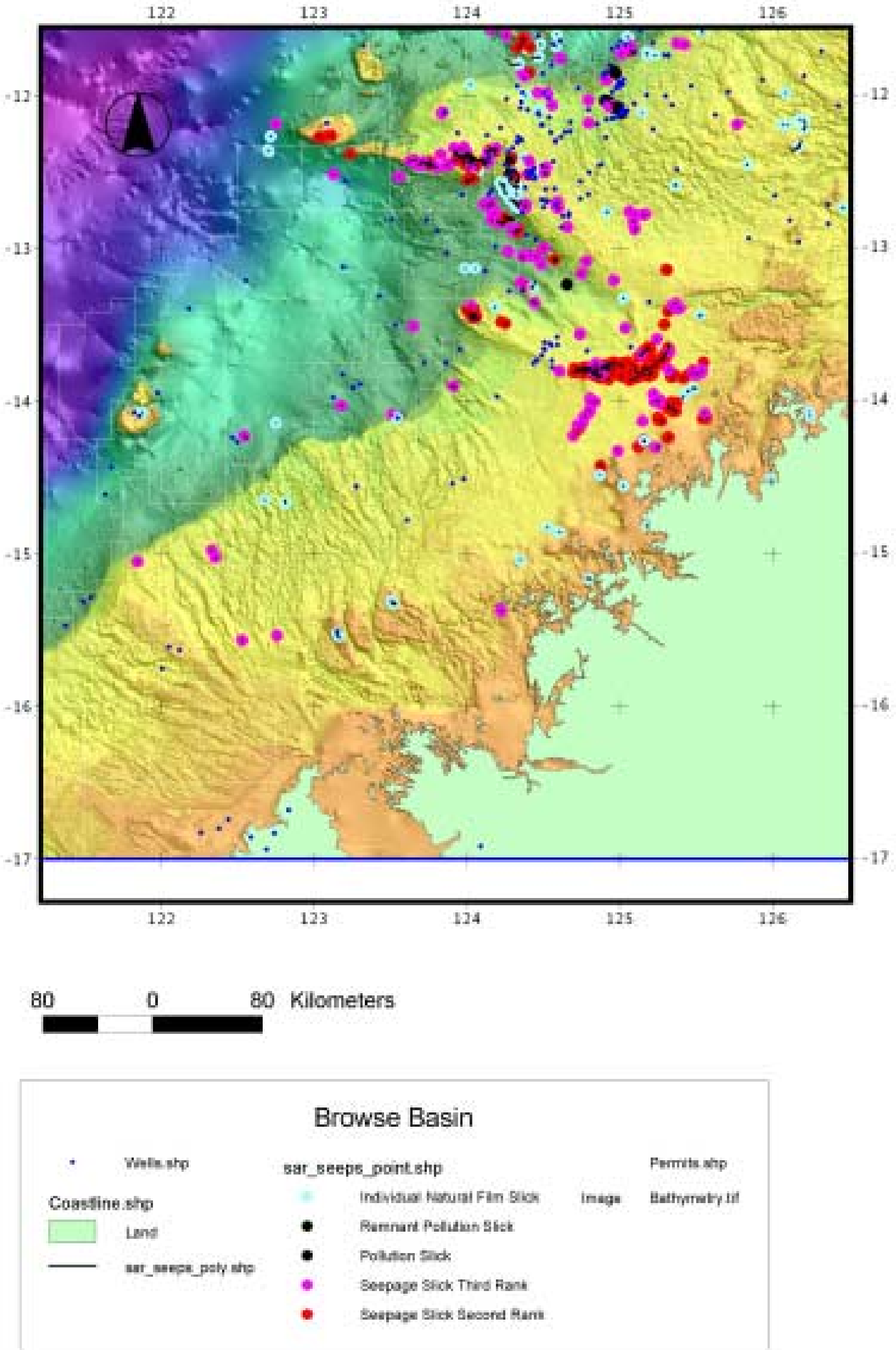

Figure 21. Scattered clusters of Slicks within the Browse Basin. Red = Rank 2 slicks; Pink = Rank 3 slicks; Black = Remnant Pollution; Light Blue = INFS

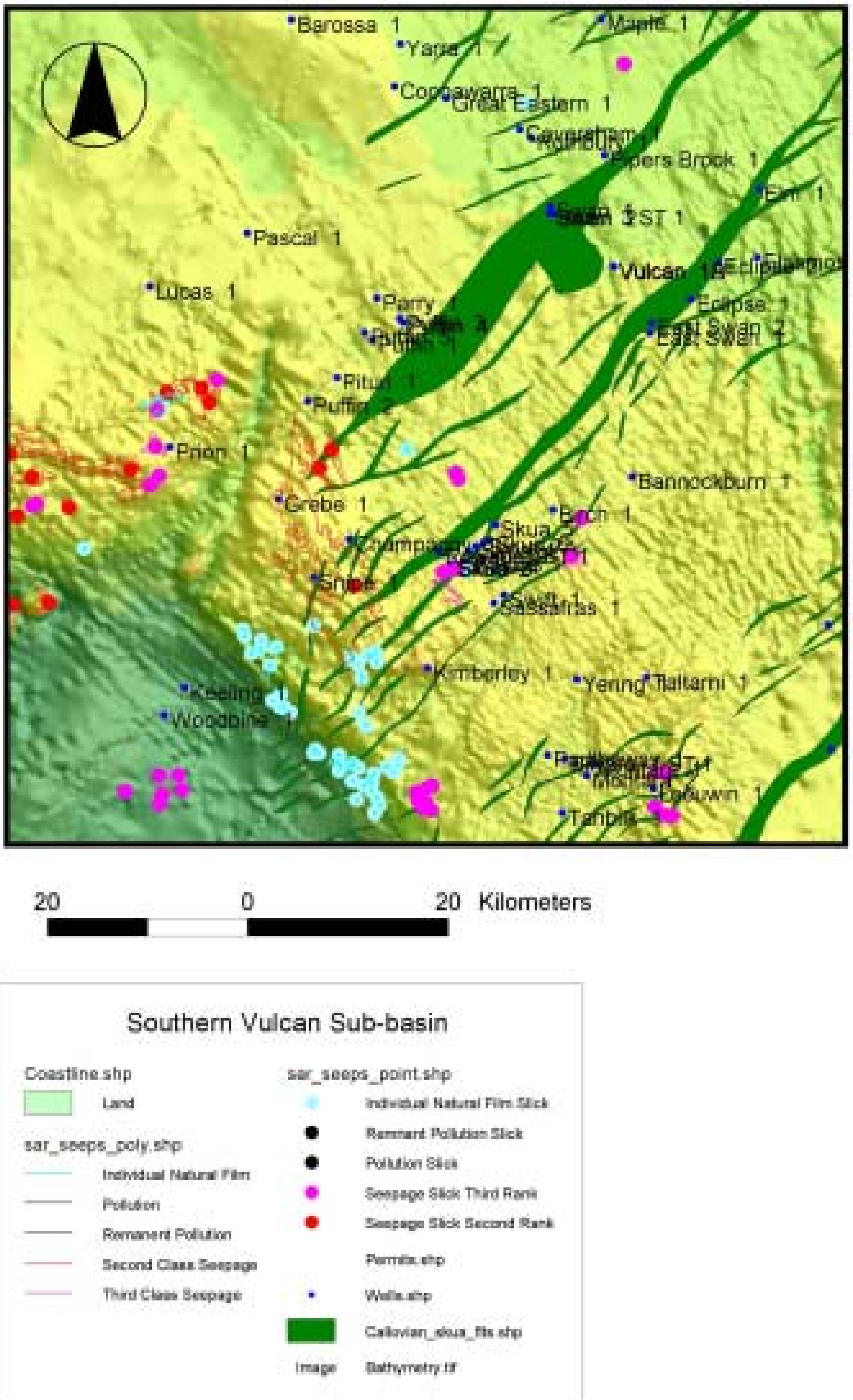

Figure 22. Slicks around the Skua Field, southern Vulcan Sub-basin. Callovian faults shown. Red = Rank 2 slicks; Pink = Rank 3 slicks; Black = Remnant Pollution; Light Blue = INFS

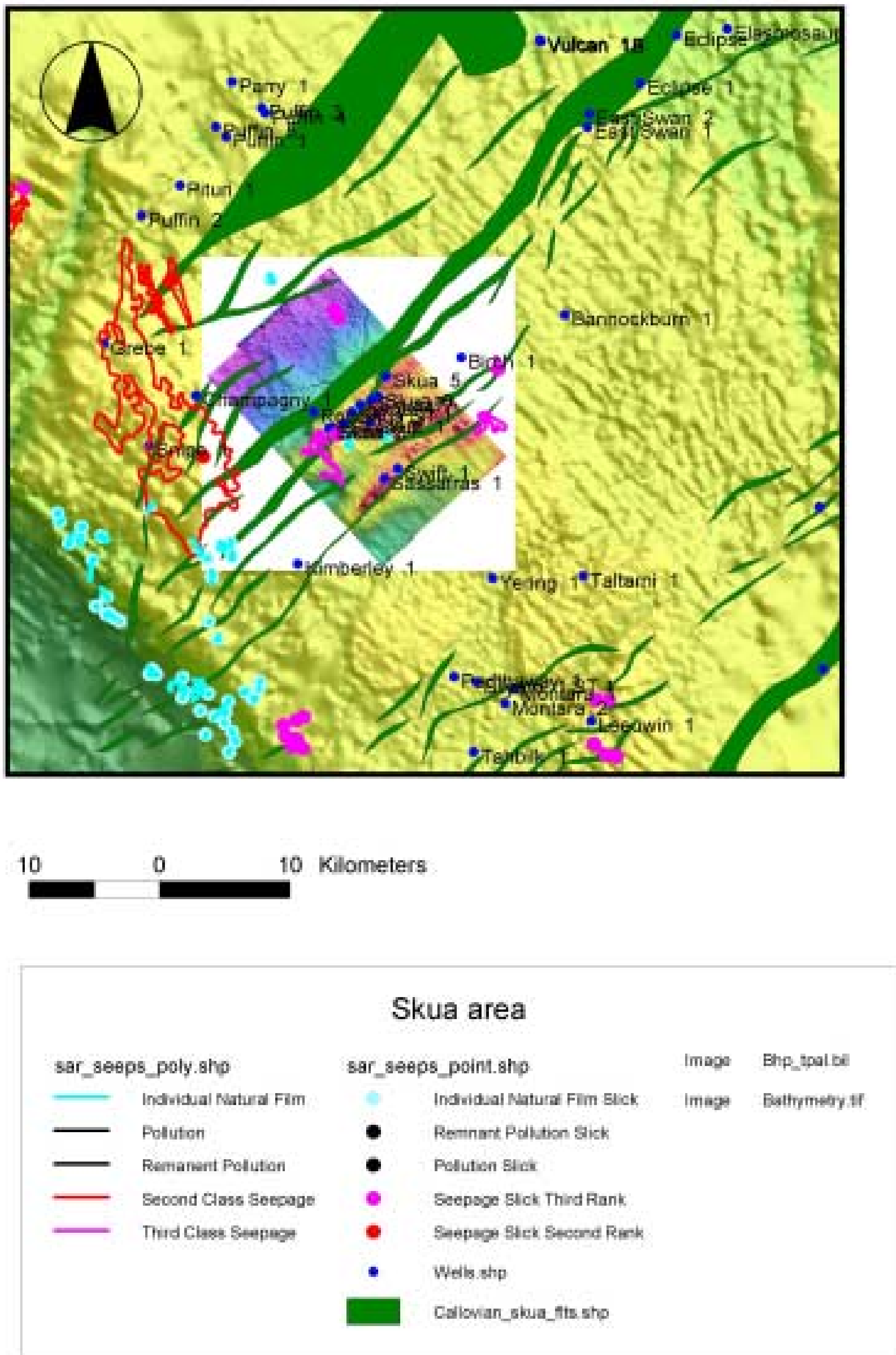

Figure 23. Slicks around the Skua Field, southern Vulcan Sub-basin, shown in relation to Top Paleocene TWT horizon image. HRDZs (leakage zones) visible on TWT image. . Callovian faults shown. Red = Rank 2 slicks; Pink = Rank 3 slicks; Black = Remnant Pollution; Light Blue = INFS

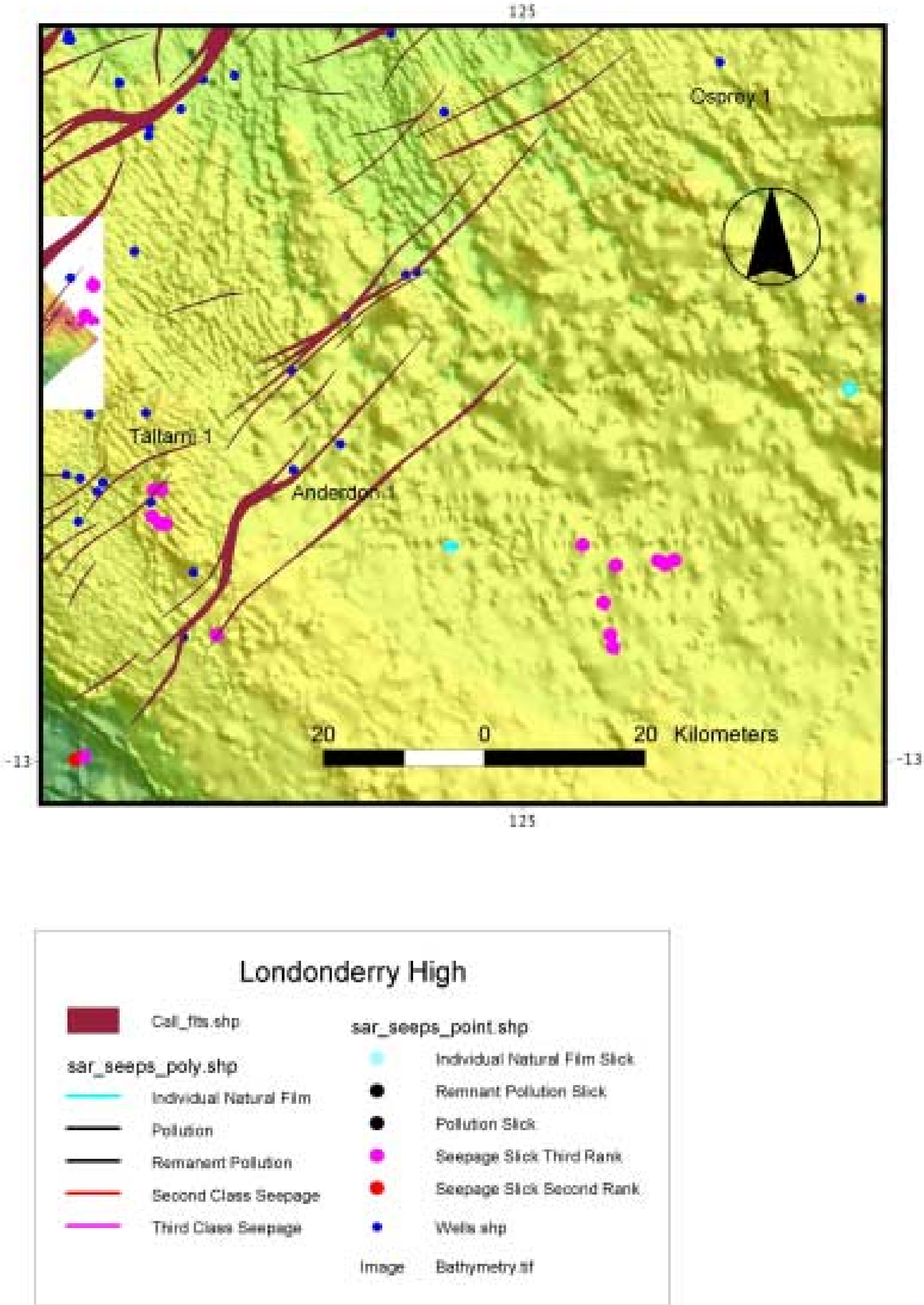

Figure 24. Slicks on the Londonderry High, ~35 km south-east of Anderdon 1 well location. Red = Rank 2 slicks; Pink = Rank 3 slicks; Black = Remnant Pollution; Light Blue = INFS

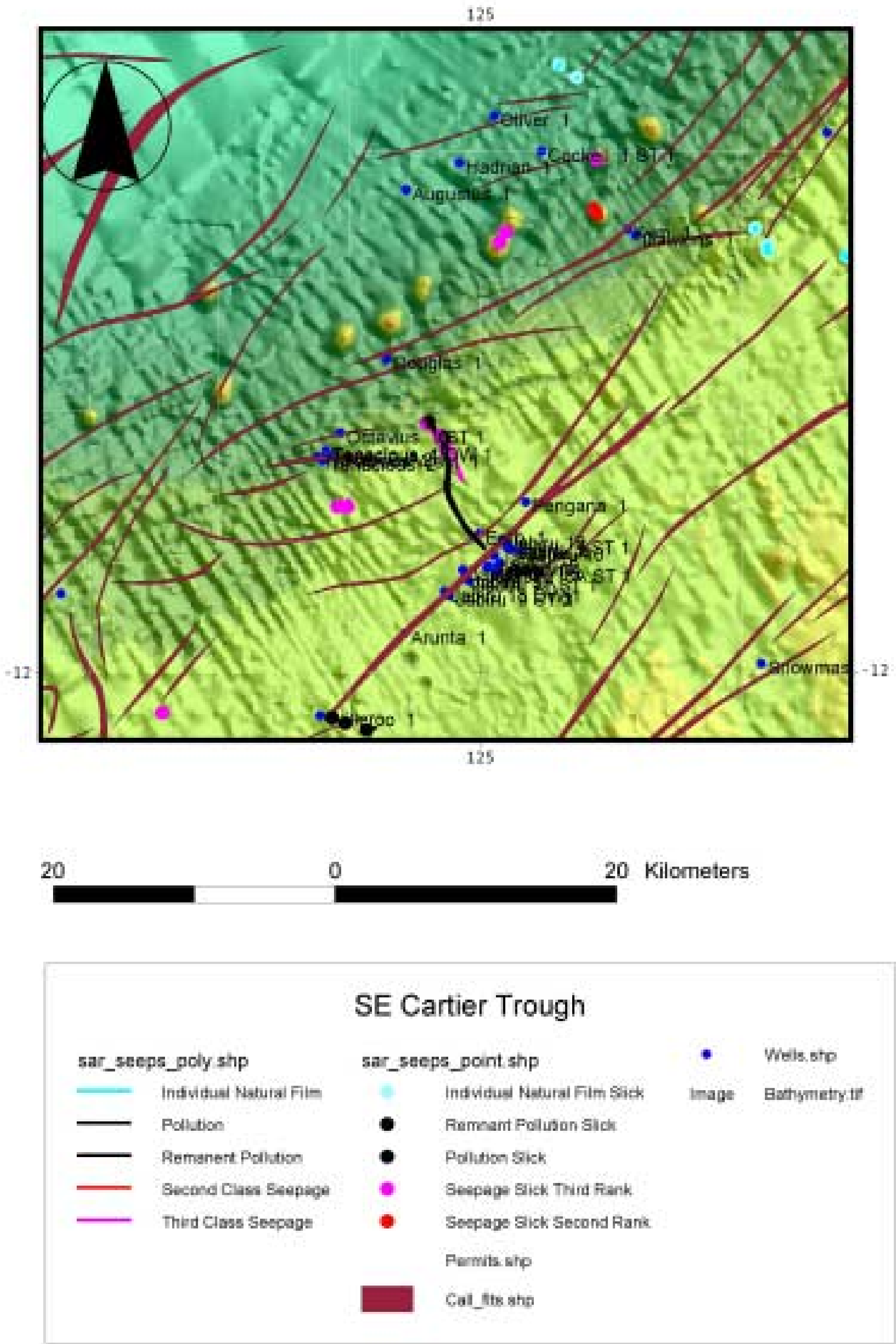

Figure 25. Slicks up-dip from the Octavius-Tenacious accumulations and the Oliver Field. Callovian faults shown. Note association of slicks with seafloor topographically-positive features (build-ups, mud volcanoes?). Red = Rank 2 slicks; Pink = Rank 3 slicks; Black = Remnant Pollution; Light Blue = INFS

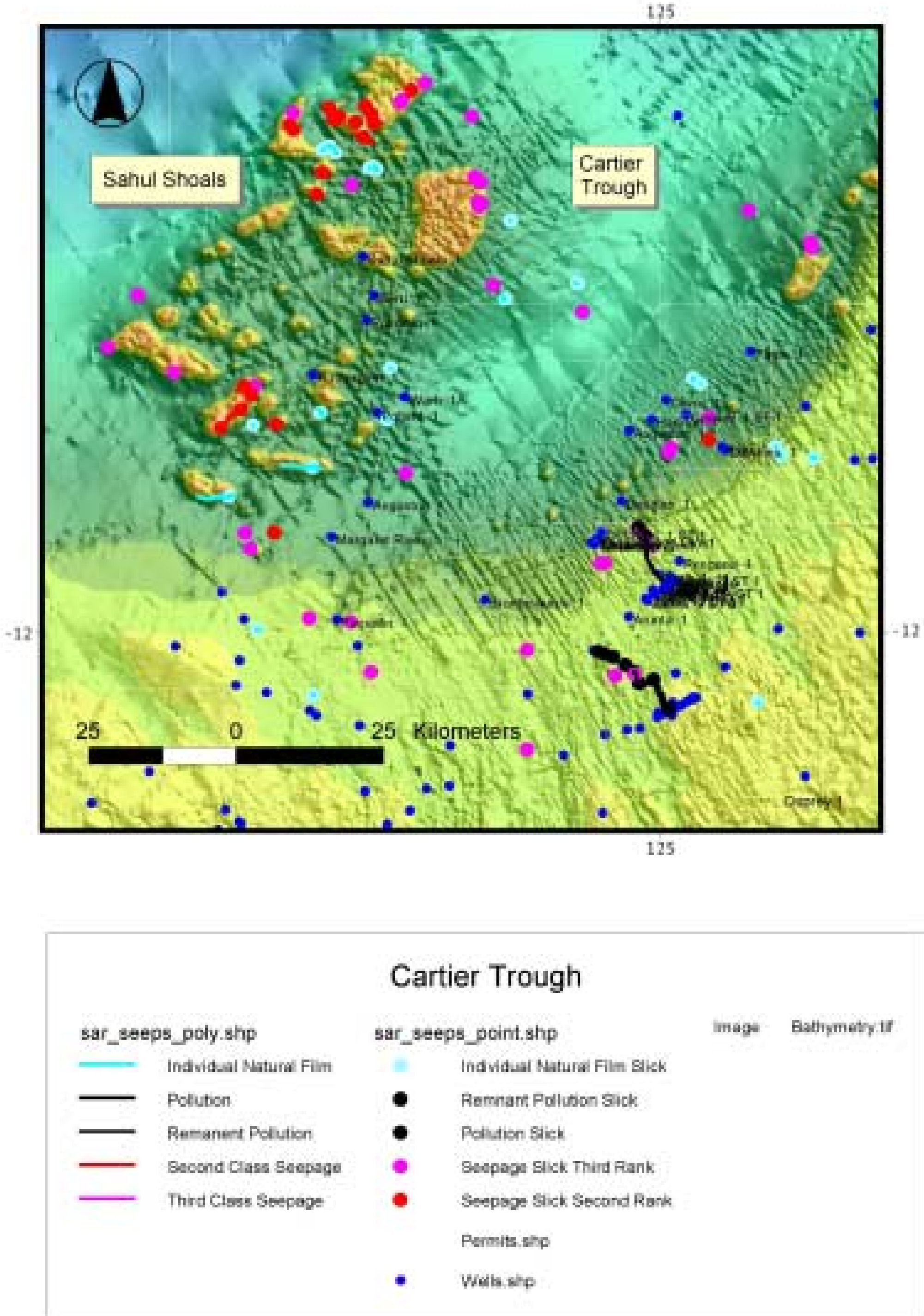

Figure 26. Slicks around the periphery of the Cartier Trough, suggesting active migration from depo-centre and leakage at edge. Red = Rank 2 slicks; Pink = Rank 3 slicks; Black = Remnant Pollution; Light Blue = INFS

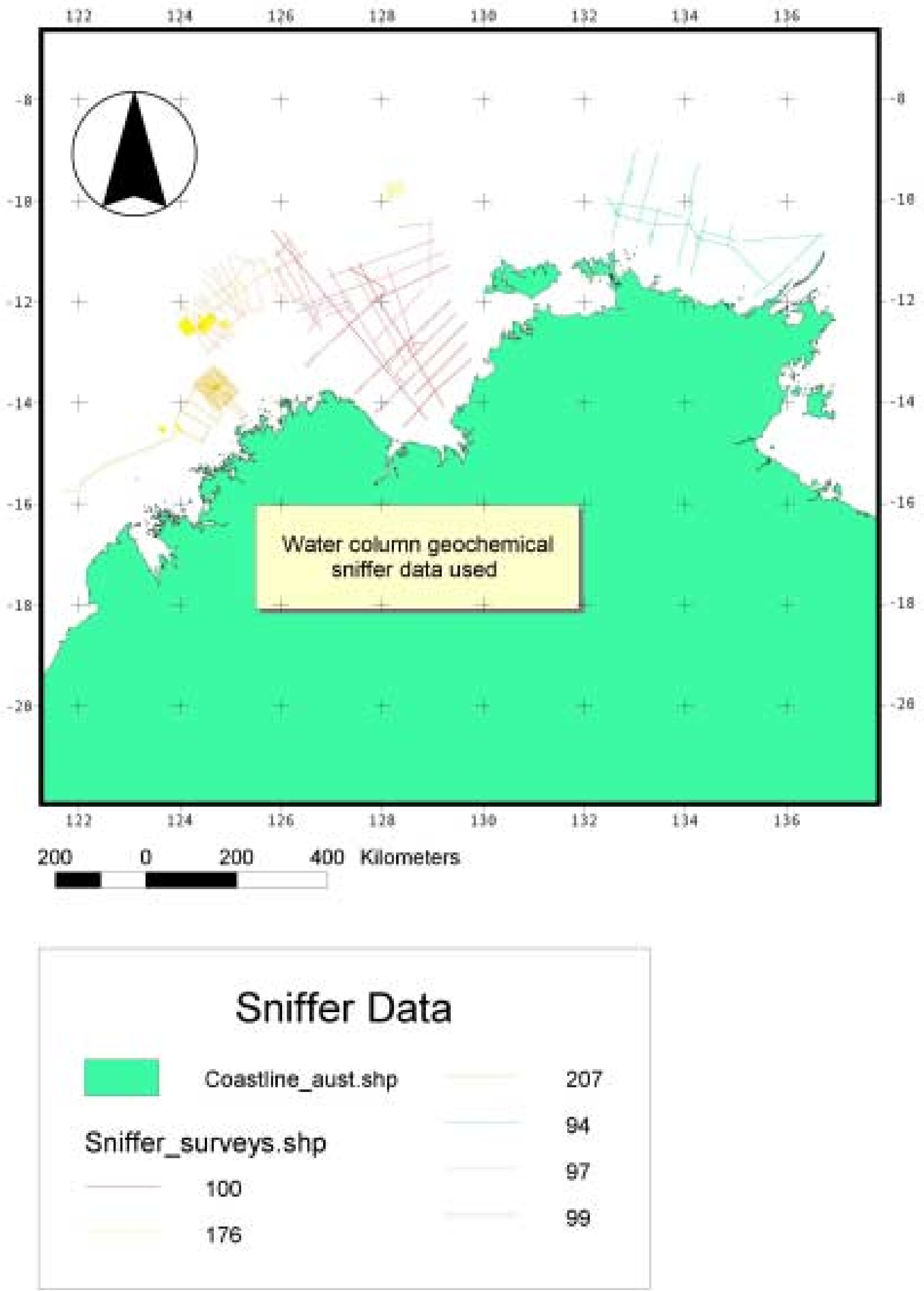

Figure 27. Map showing location of water column geochemical sniffer lines used in the present study.

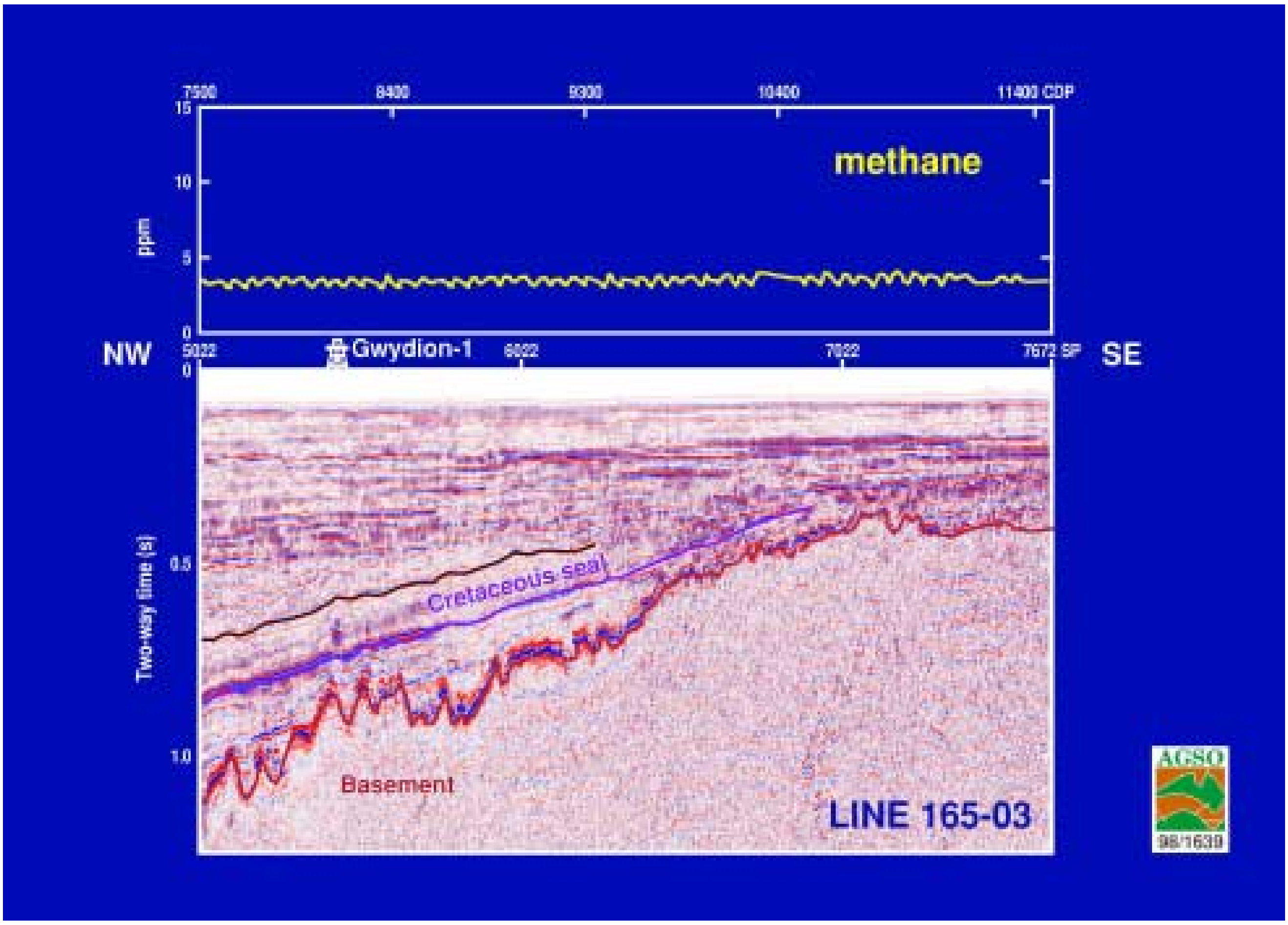

Figure 28a. Water column geochemical sniffer profile (methane) overlain on regional seismic line YST 165-03 from the Yampi Shelf.

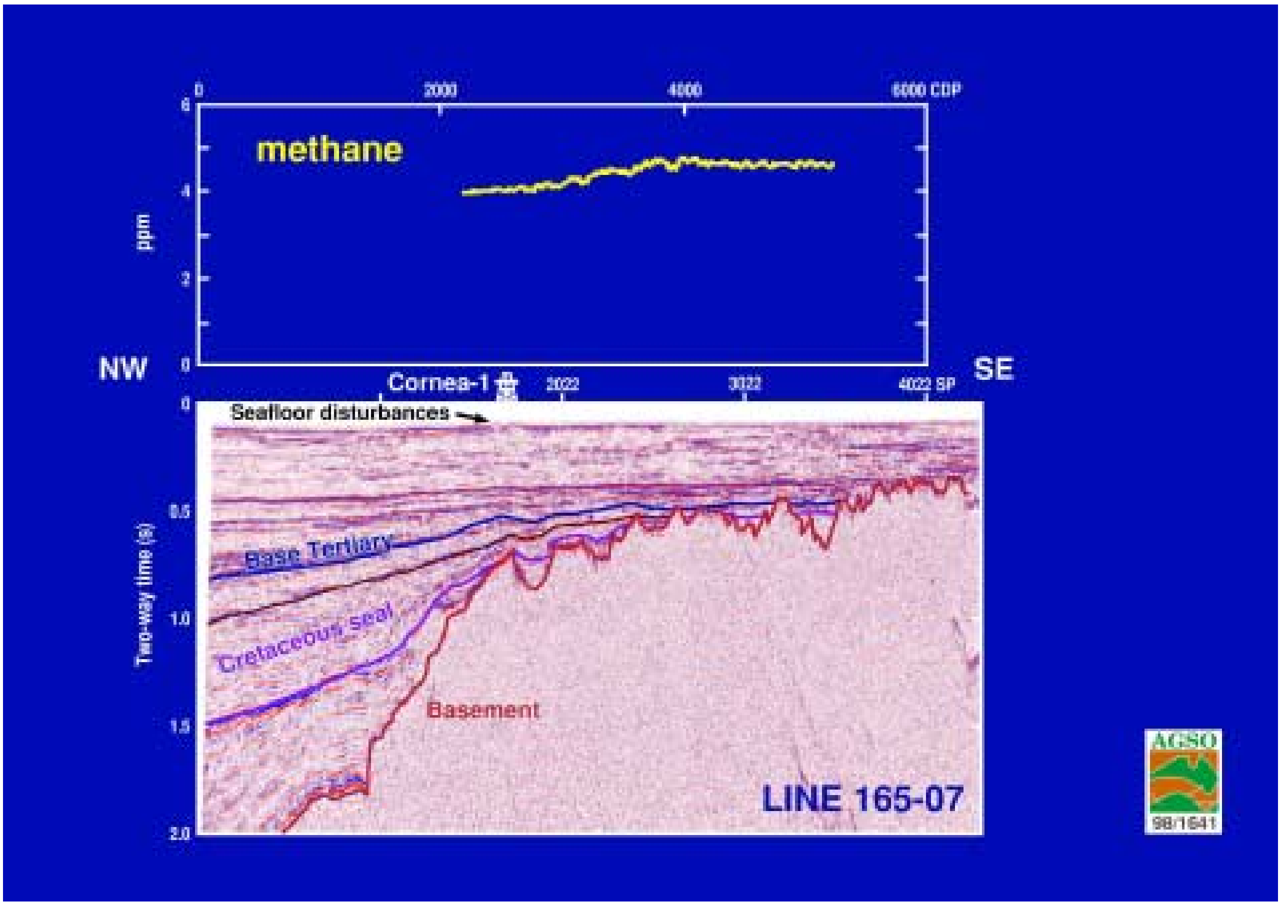

Figure 28b. Water column geochemical sniffer profiles (methane) overlain on regional seismic line YST 165-07 from the Yampi Shelf.

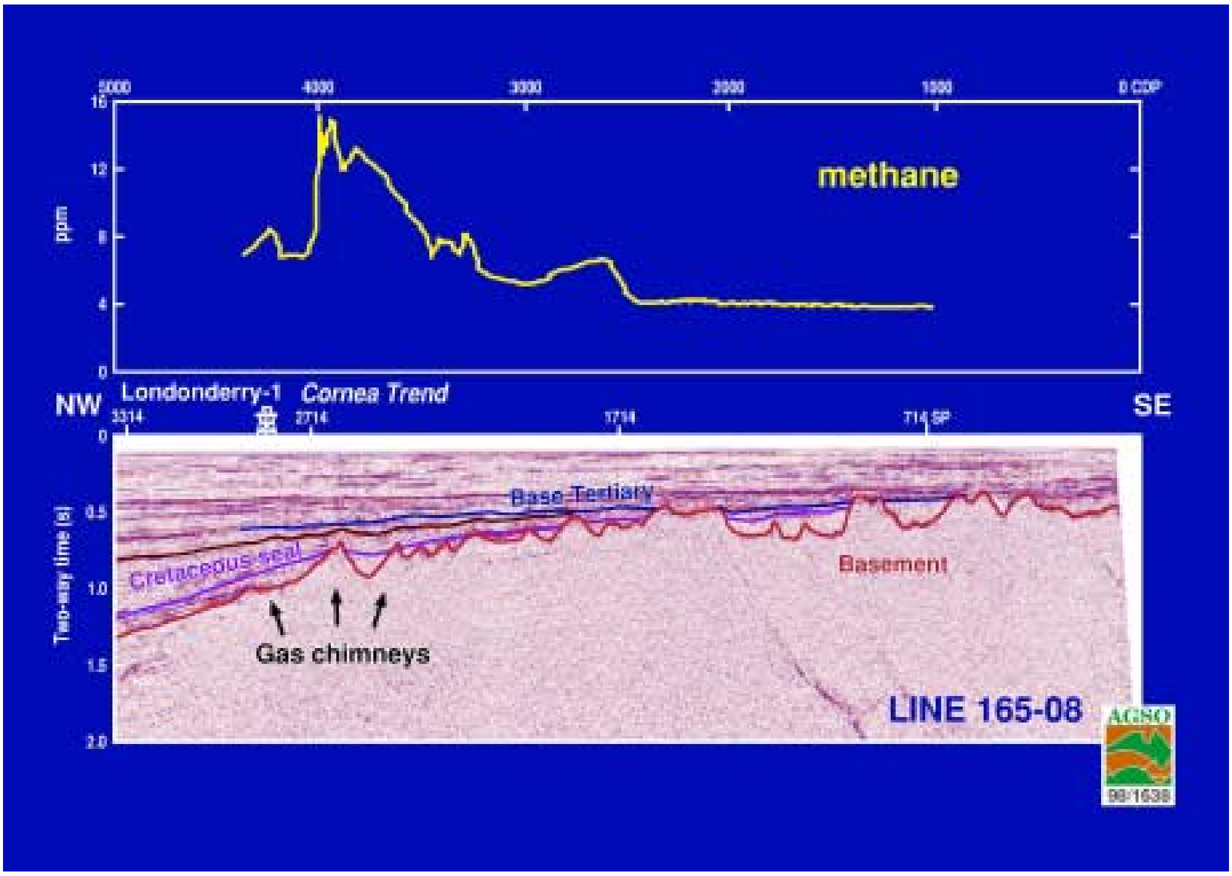

Figure 28c. Water column geochemical sniffer profiles (methane) overlain on regional seismic line YST 165-08 from the Yampi Shelf.

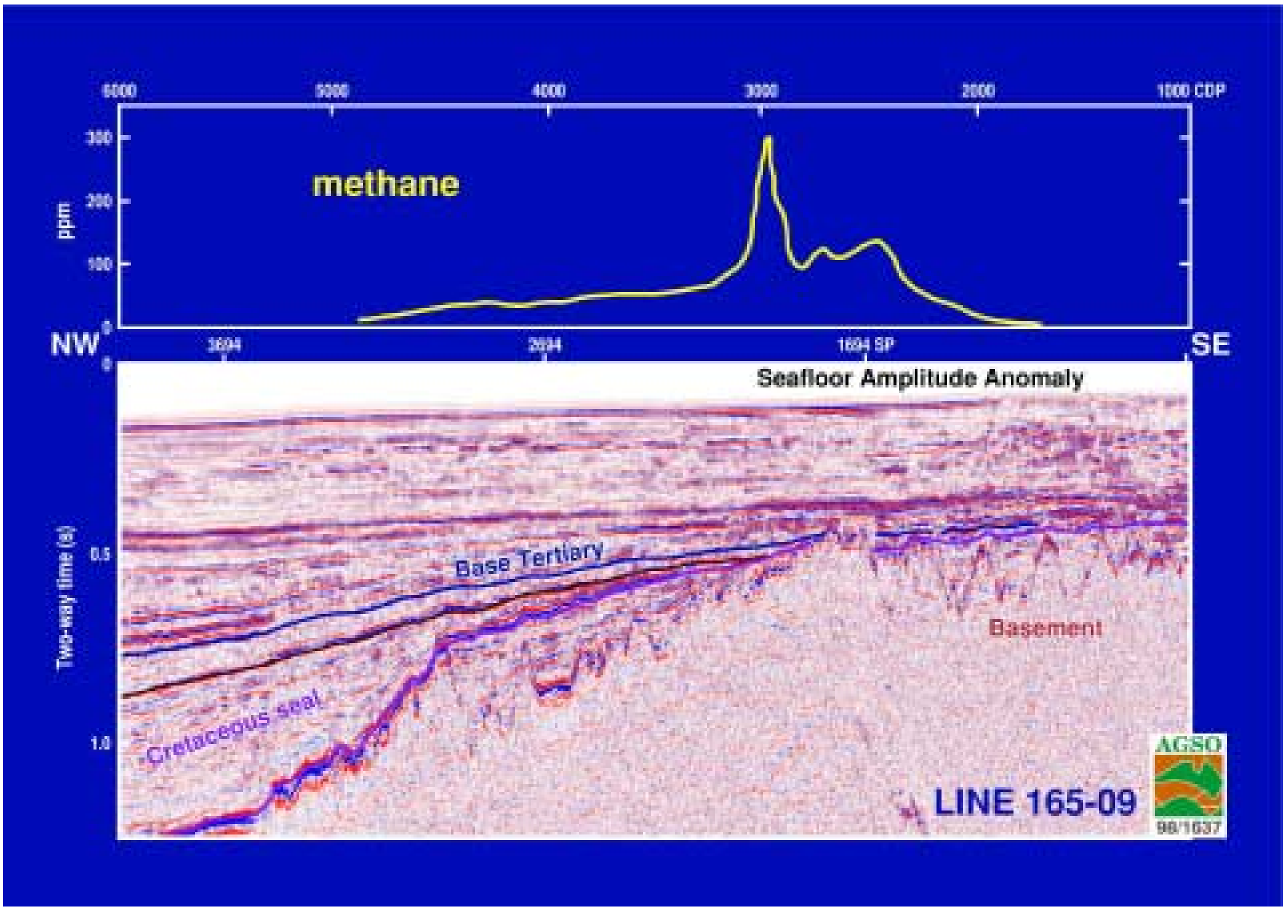

Figure 28d. Water column geochemical sniffer profiles (methane) overlain on regional seismic line YST 165-09 from the Yampi Shelf.

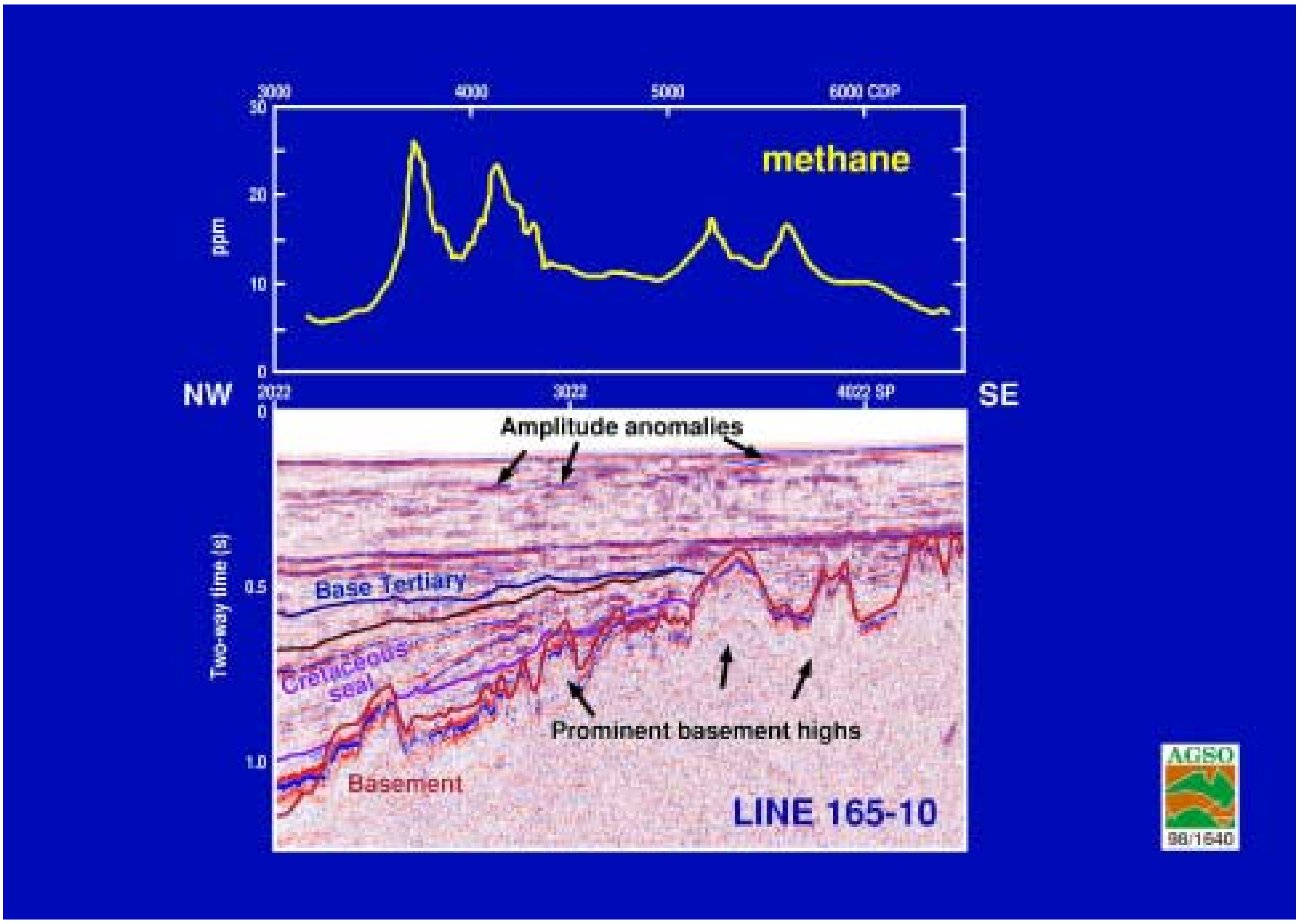

Figure 28e. Water column geochemical sniffer profiles (methane) overlain on regional seismic line YST 165-10 from the Yampi Shelf.

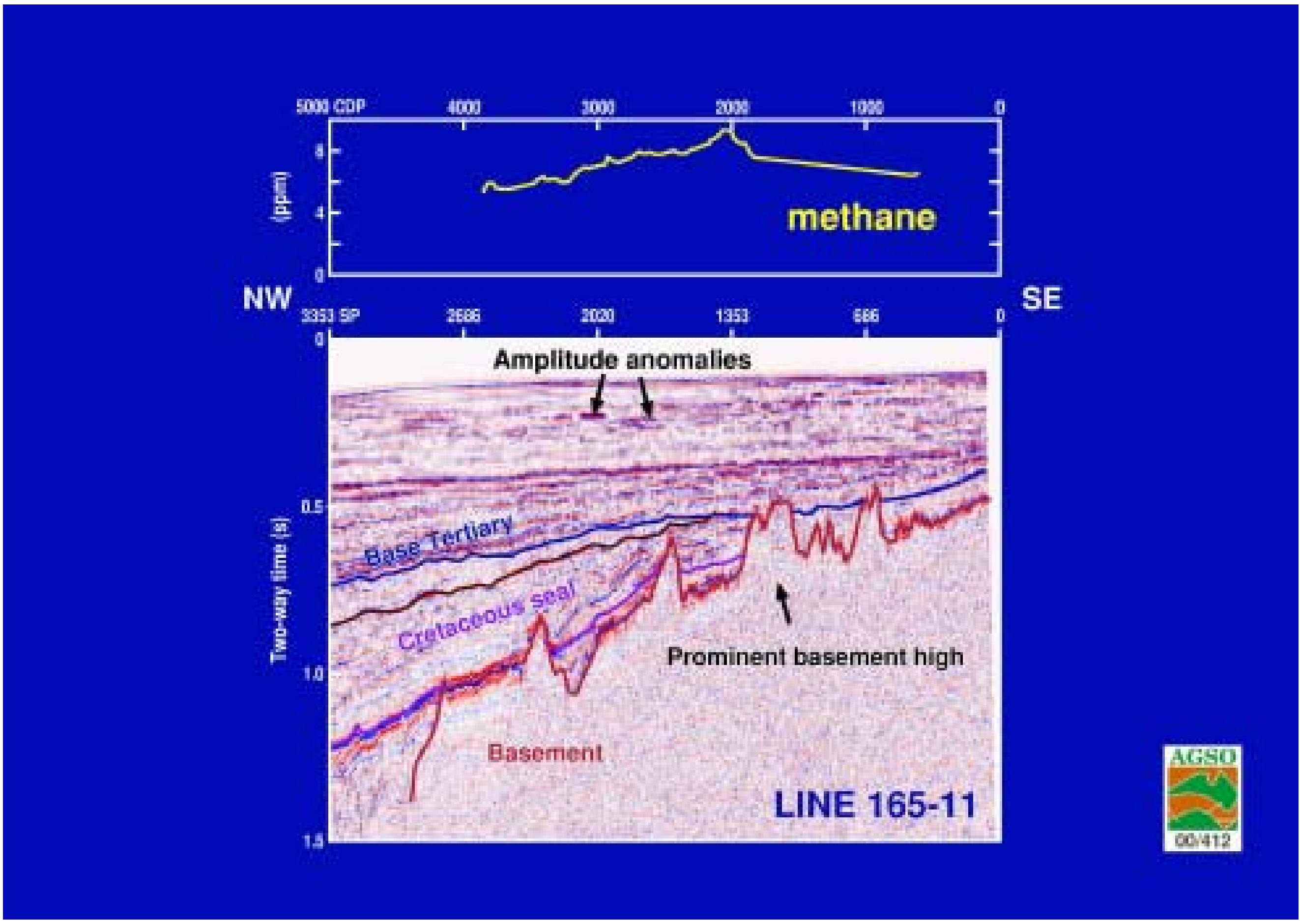

Figure 28f. Water column geochemical sniffer profiles (methane) overlain on regional seismic line YST 165-10 from the Yampi Shelf.

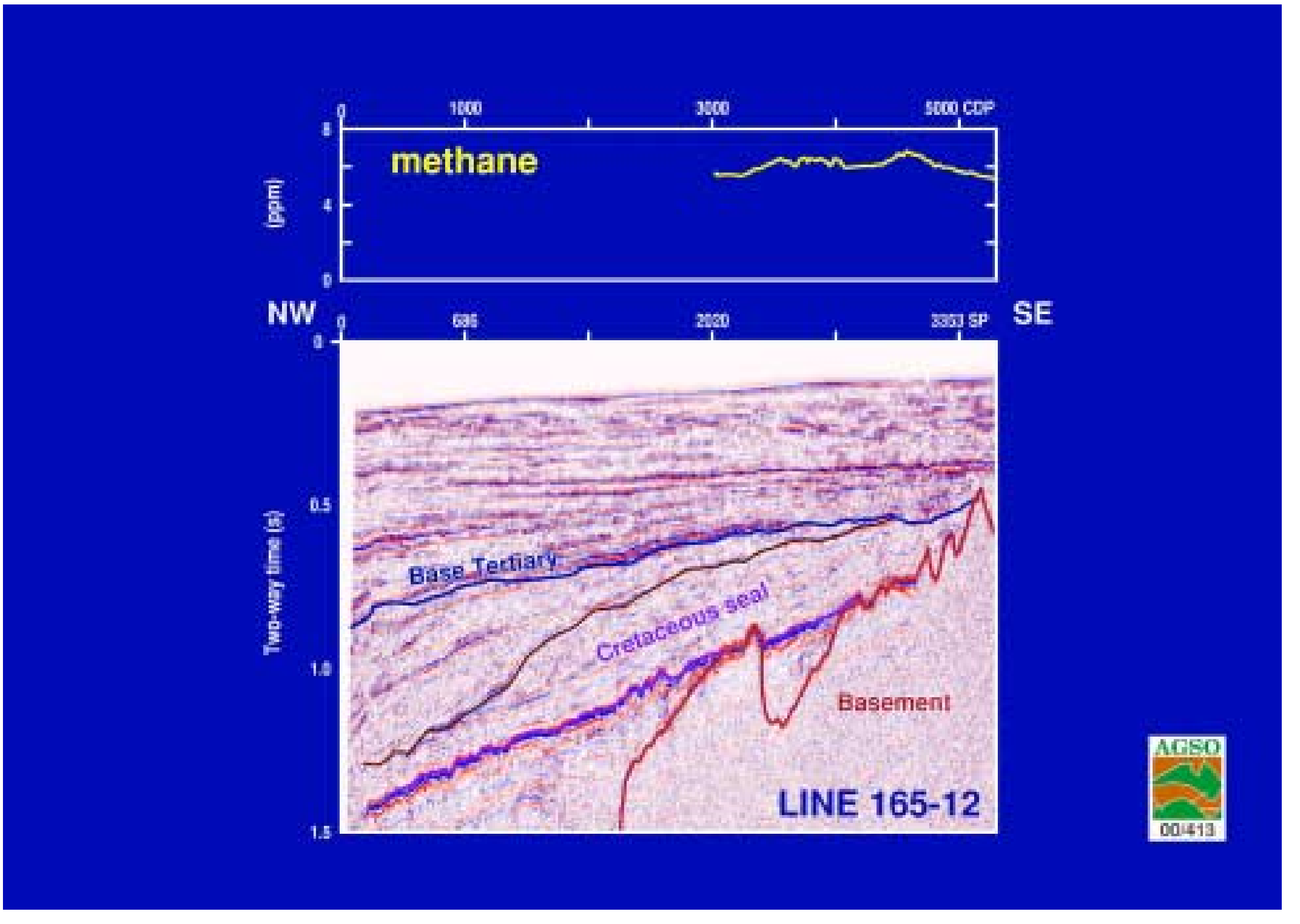

Figure 28g. Water column geochemical sniffer profiles (methane) overlain on regional seismic line YST 165-10 from the Yampi Shelf.

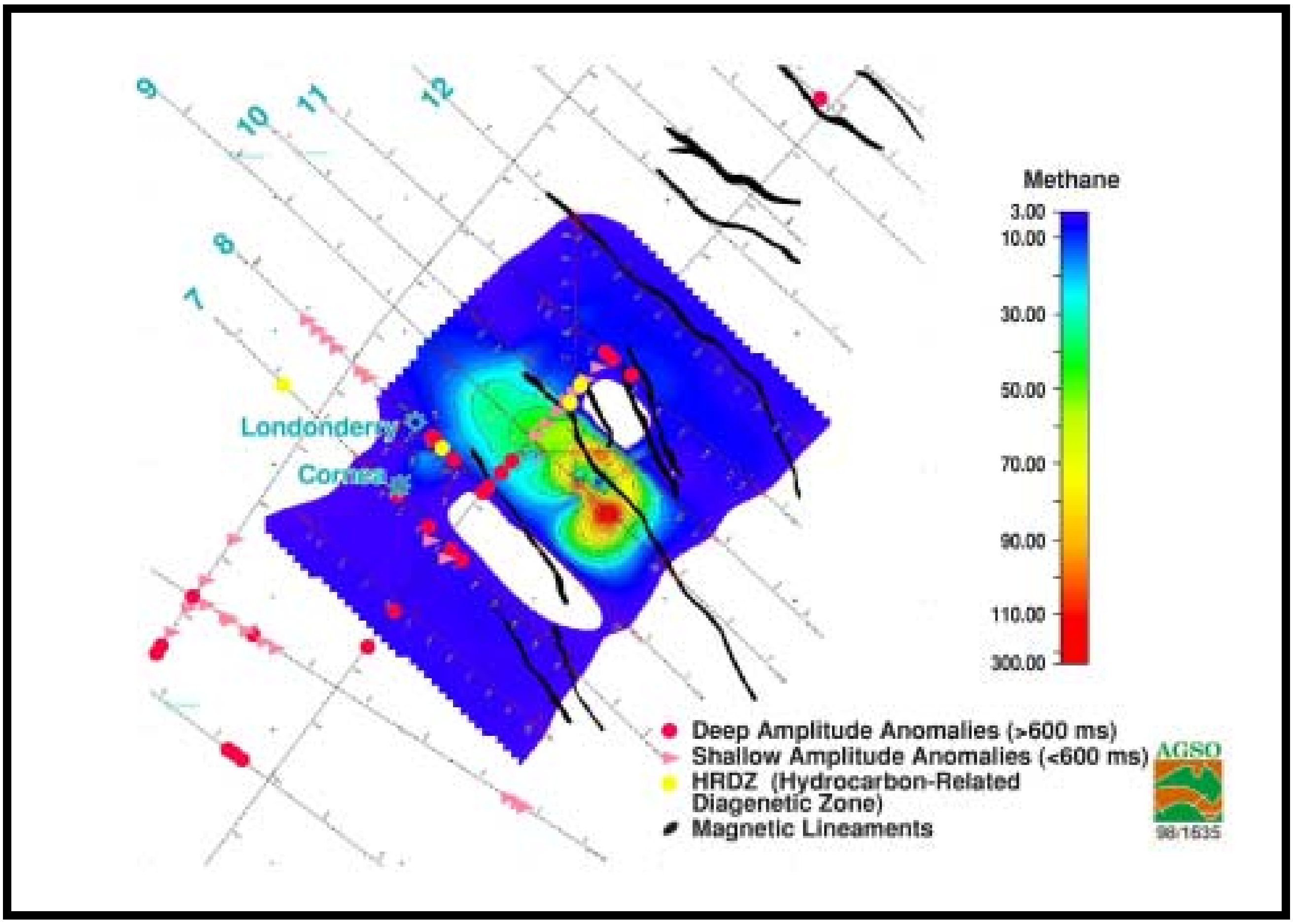

Figure 29. Contour map of methane in bottom waters in the Londonderry-Cornea area. Massive gas seepage was present through, and inboard from, the region containing numerous shallow amplitude anomalies and HRDZs.

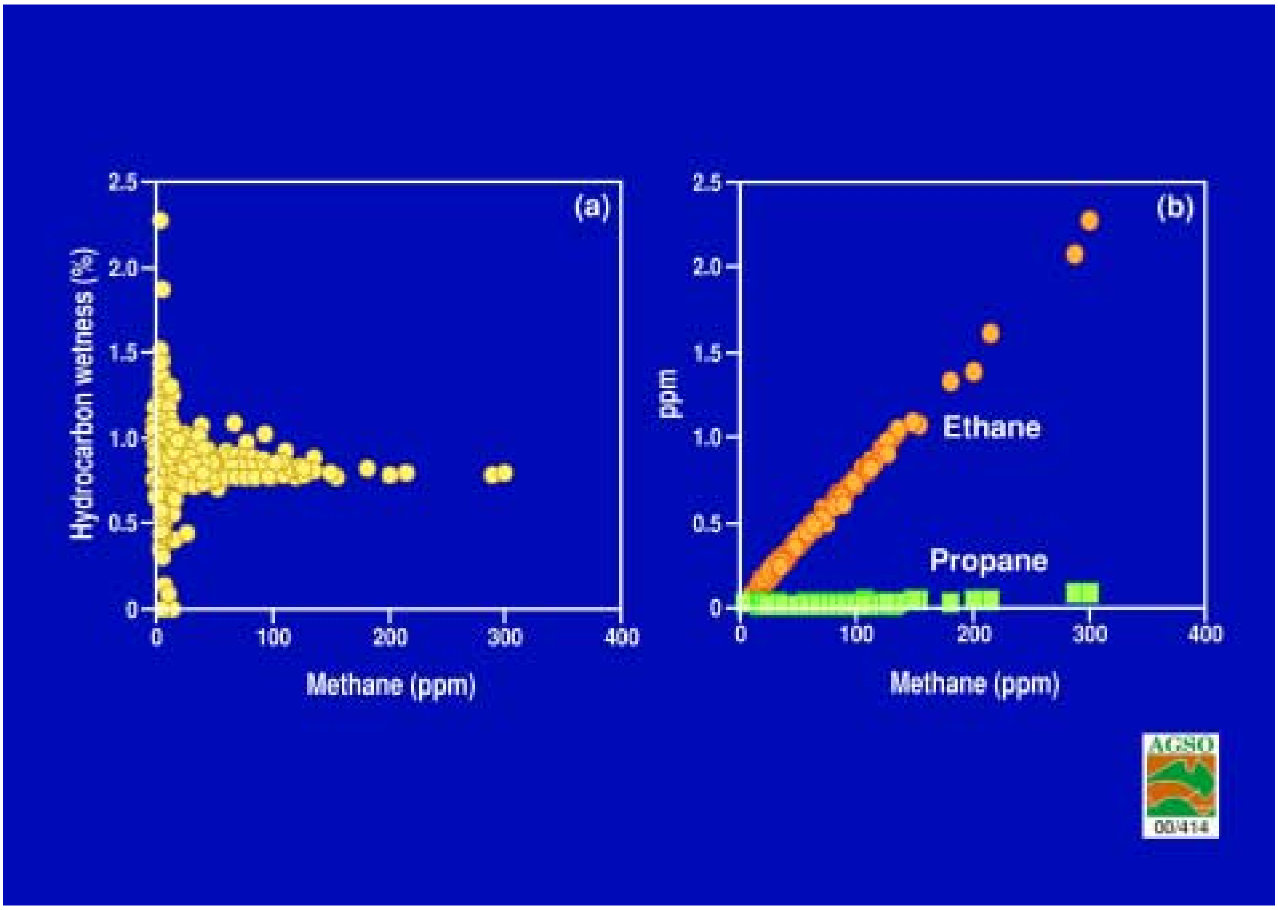

Figure 30. Geochemical cross-plots from seeps near the Londonderry and Cornea wells on the Yampi Shelf. a. Methane concentration versus hydrocarbon wetness. b. Methane concentration versus ethane and propane concentrations.

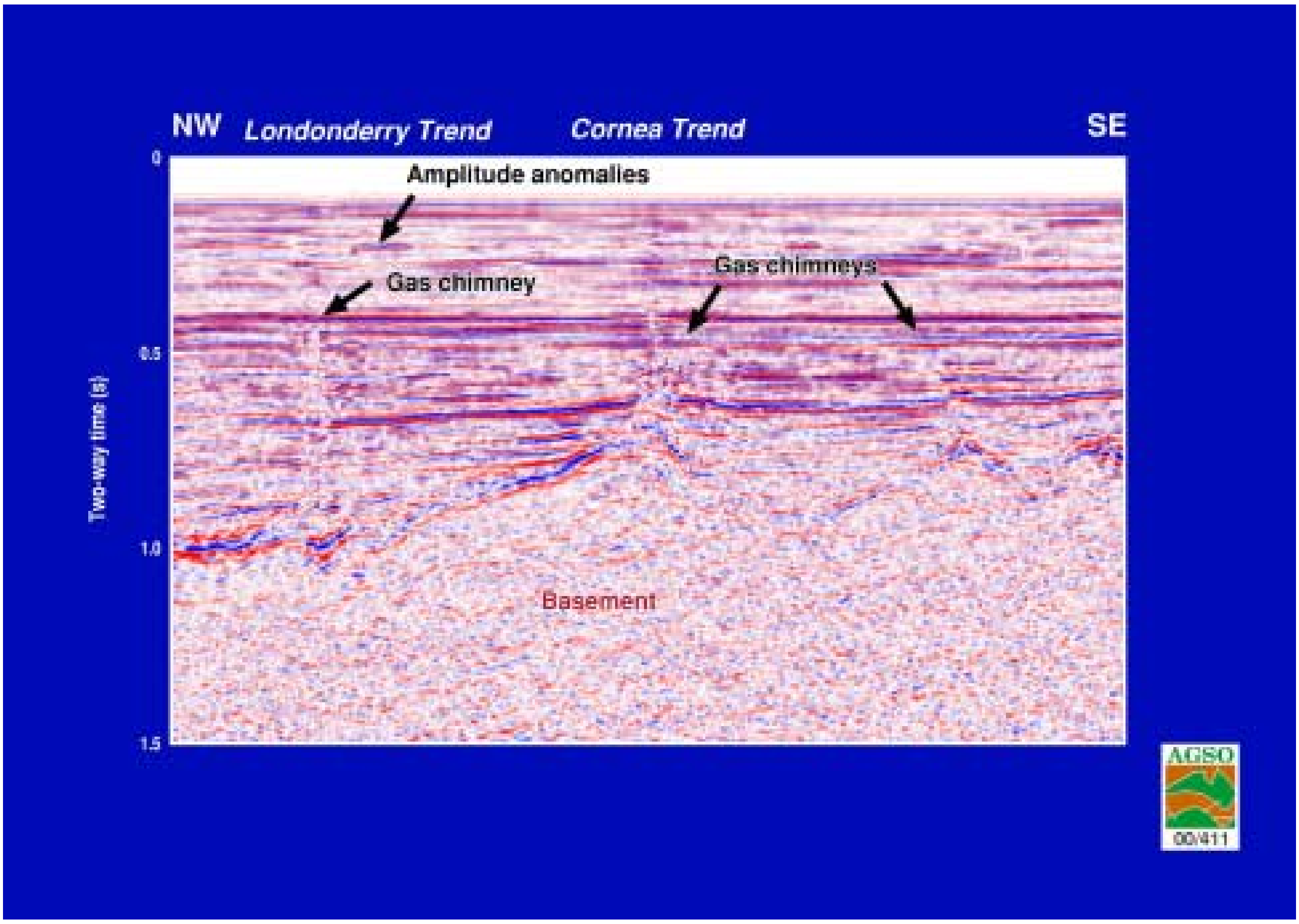

Figure 31. Gas chimneys developed over landward-dipping tilt blocks near the Londonderry-1 well and the Cornea trend, Yampi Shelf.

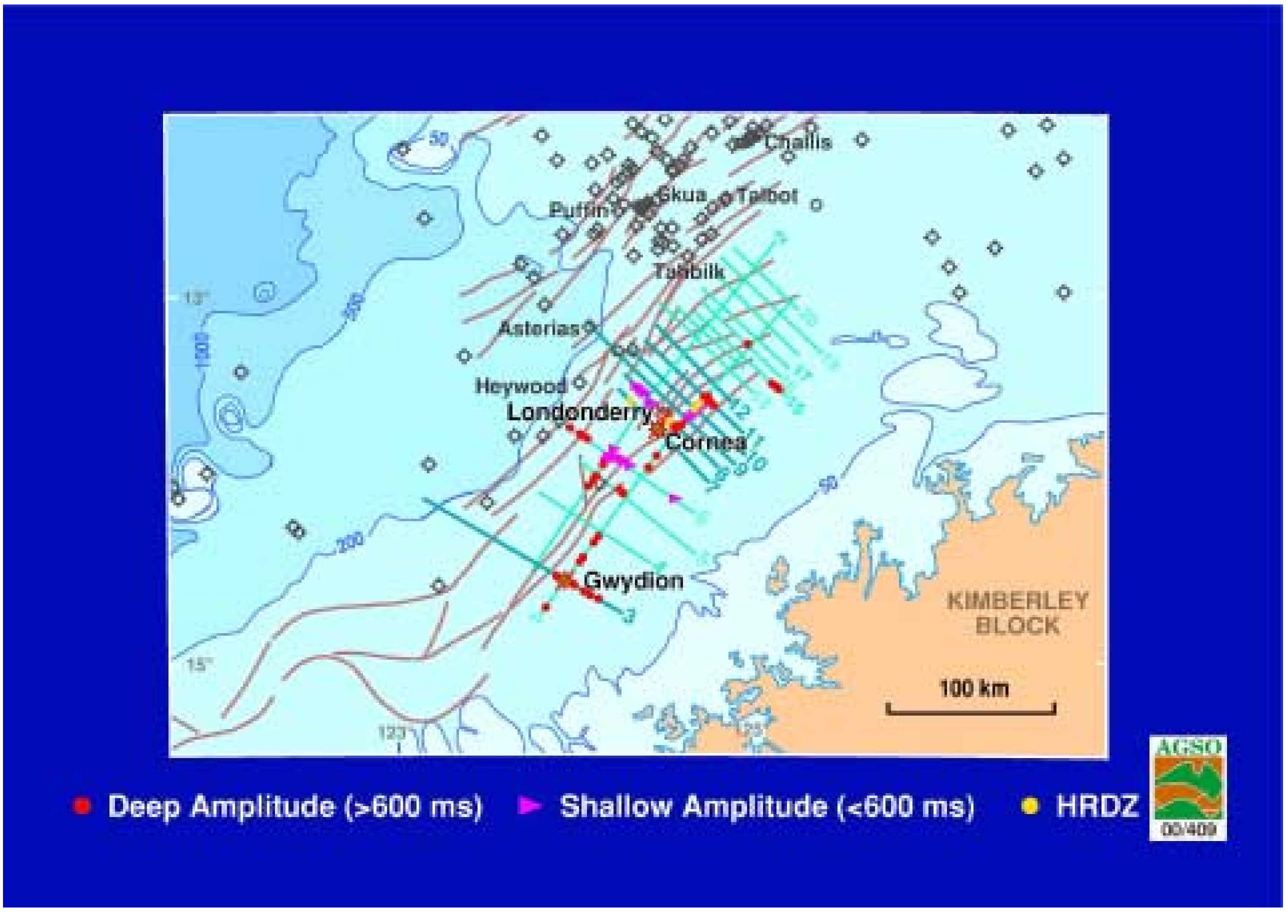

Figure 32. Location map showing YST 165 seismic lines. Lines highlighted have sniffer data acquired directly over them and are used in the present study. Positions of mapped HRDZs, and shallow and deep seismic amplitude anomalies are indicated.

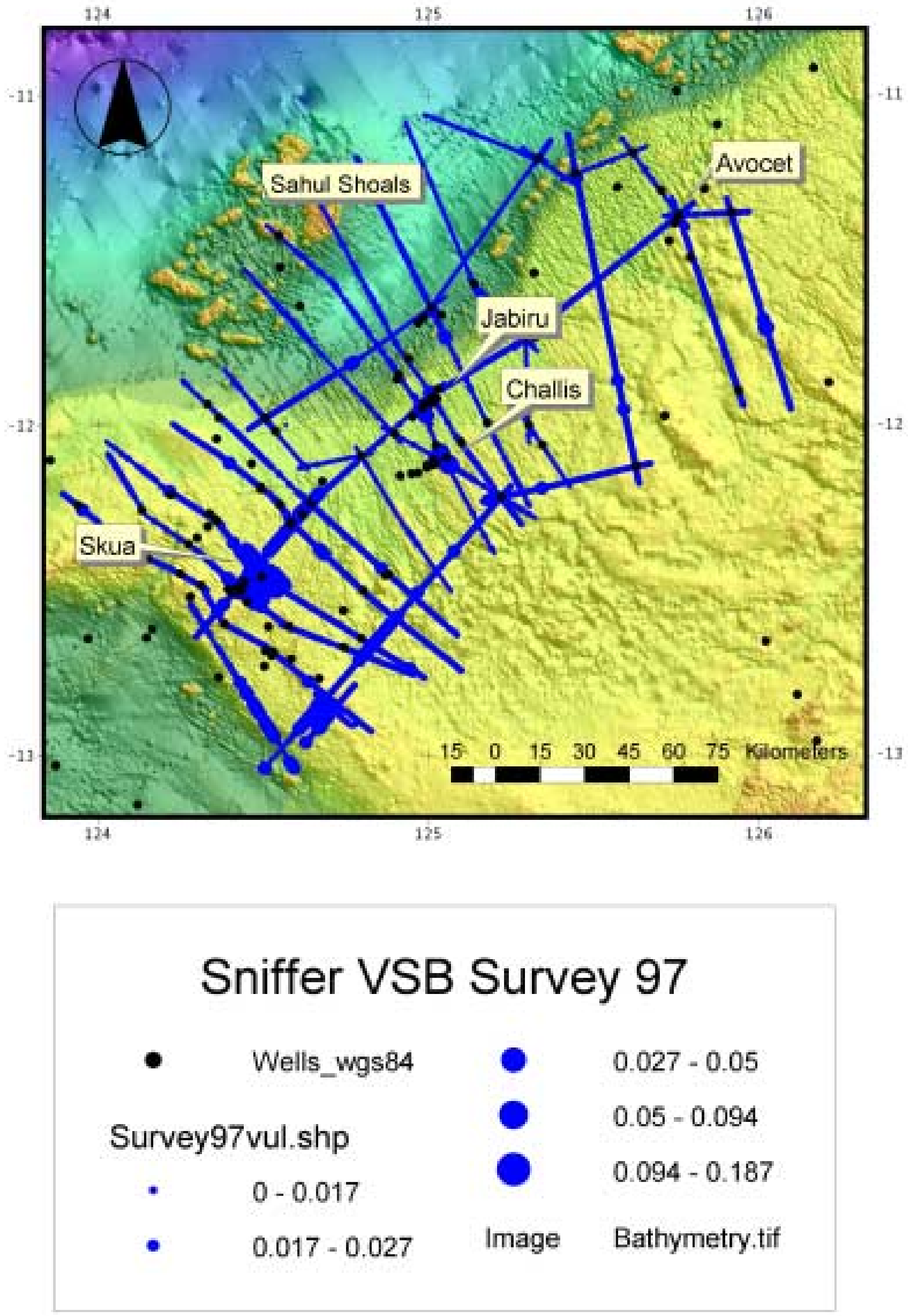

Figure 33. Water column geochemical sniffer profiles from Survey 97, Vulcan Sub-basin, overlain on bathymetry. Symbol size is proportional to bottom water ethane content.

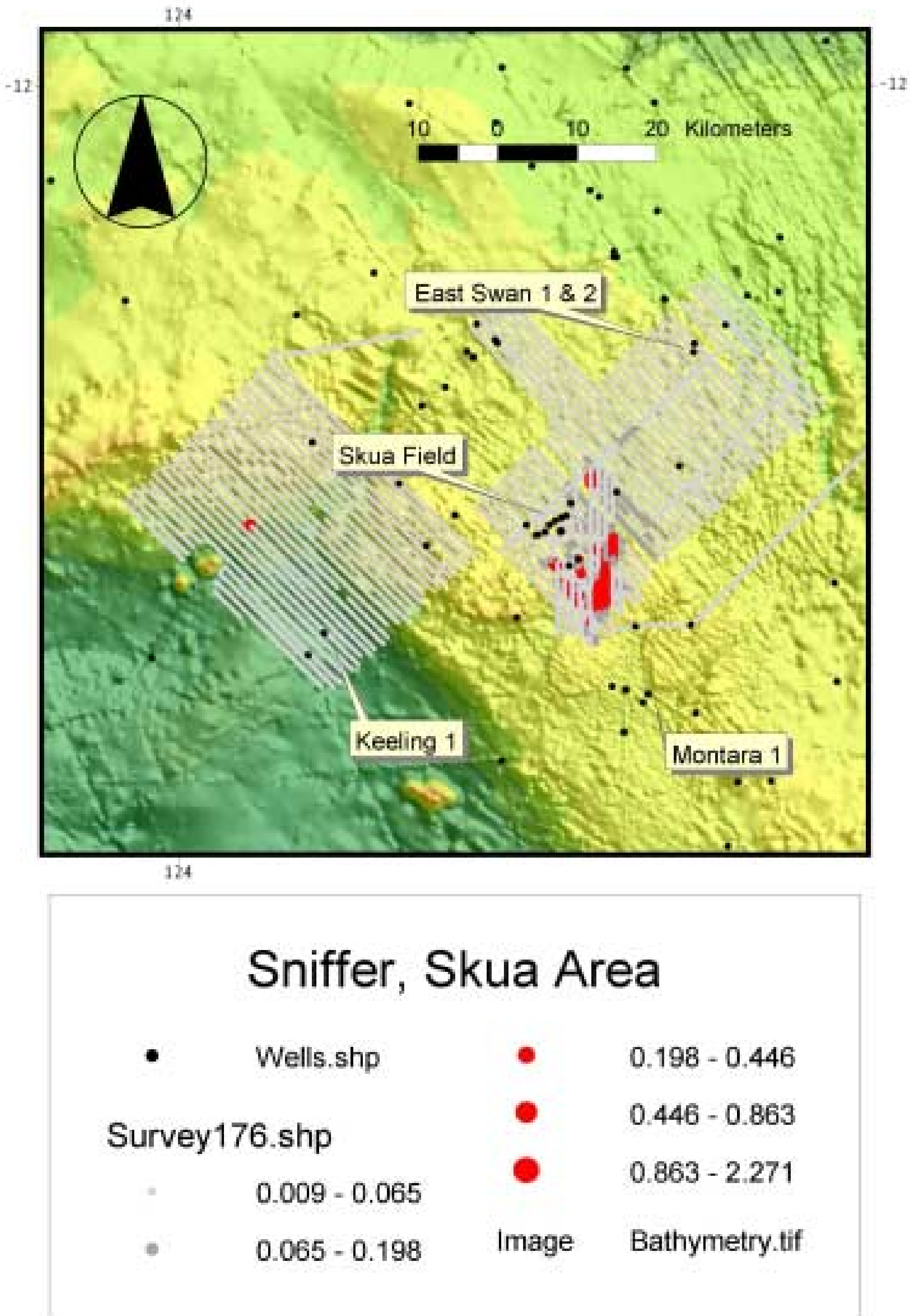

Figure 34. Water column geochemical sniffer profiles from Survey 176, Vulcan Sub-basin, overlain on bathymetry. Symbol size and colour is proportional to bottom water ethane content. Strong water column hydrocarbon anomalies are evident over and around the Skua Field.

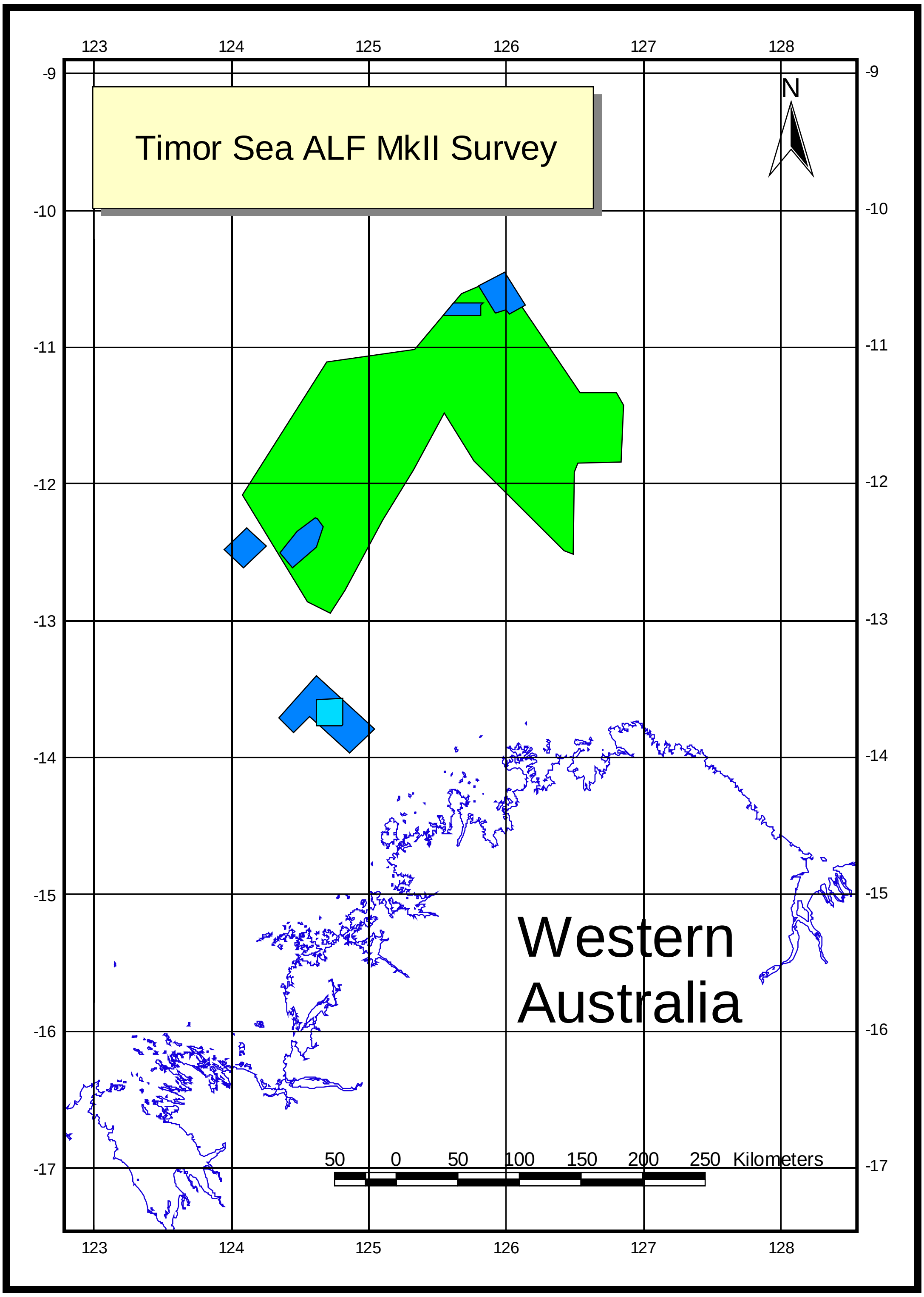

Figure 35. . Timor Sea ALF BP Mk II survey location map.

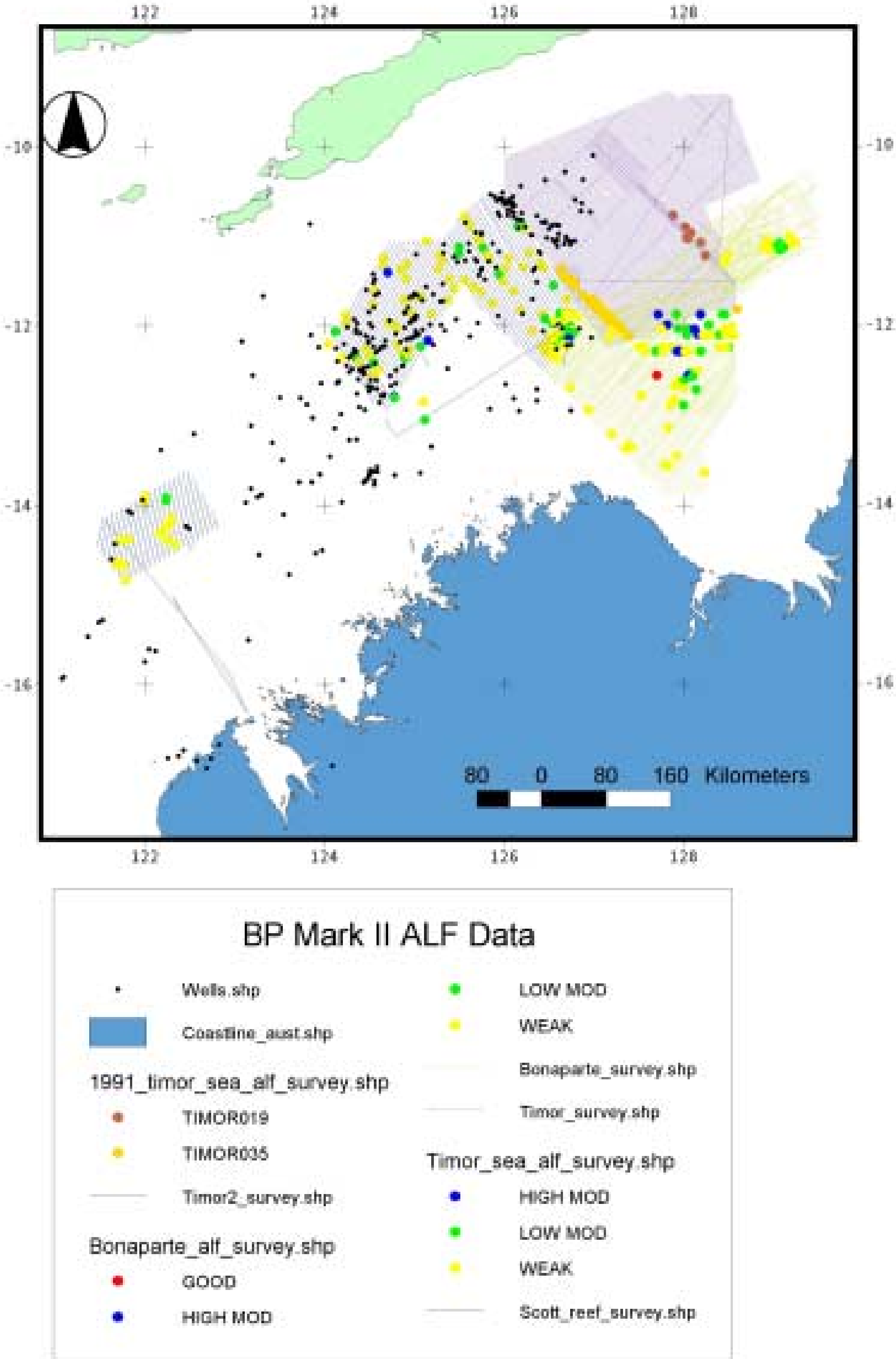

Figure 36. Location of BP Mark II ALF anomalies interpreted by BP.

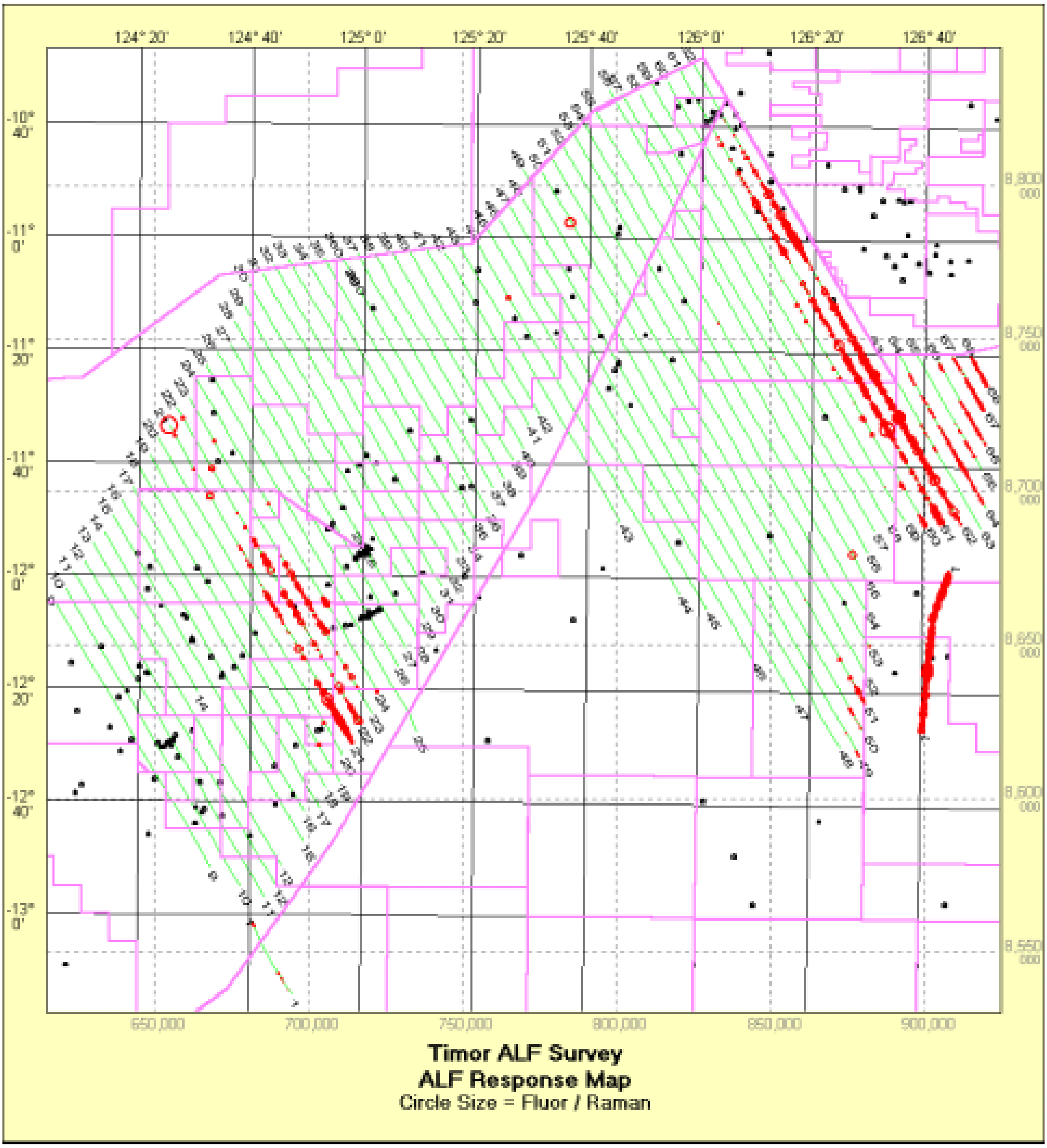

Figure 37. The Timor Sea ALF Mk II Survey Fluor Map (Jabiru region excluded.).

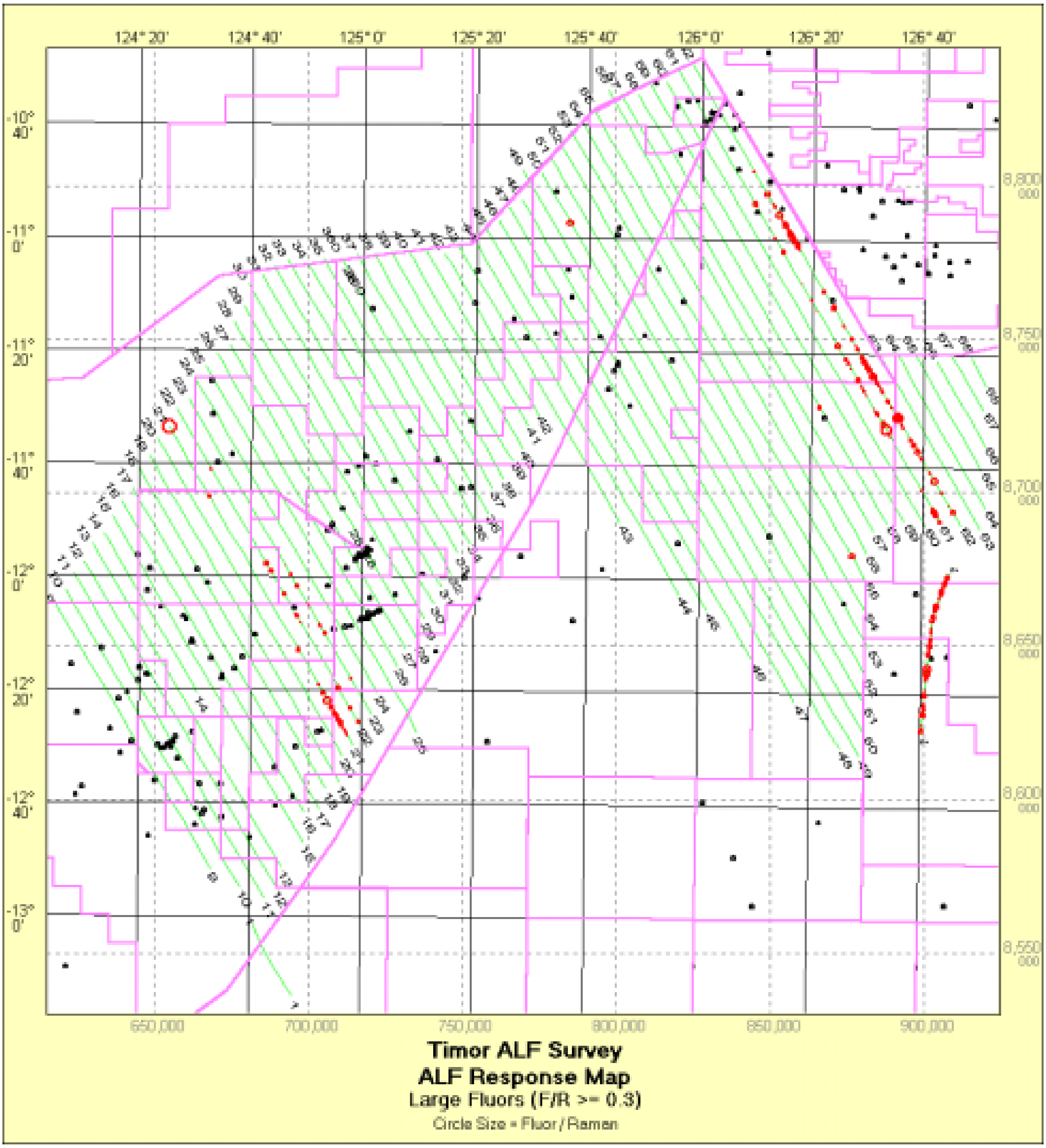

Figure 38. Timor Sea BP ALF Mk II Survey Large Fluor Map (Jabiru region excluded). This map shows a map of the large fluors detected on the Timor ALF Mk II survey. A F/R cutoff value of 0.3 was used. After editing of noisy spectra, 374 fluors were selected.

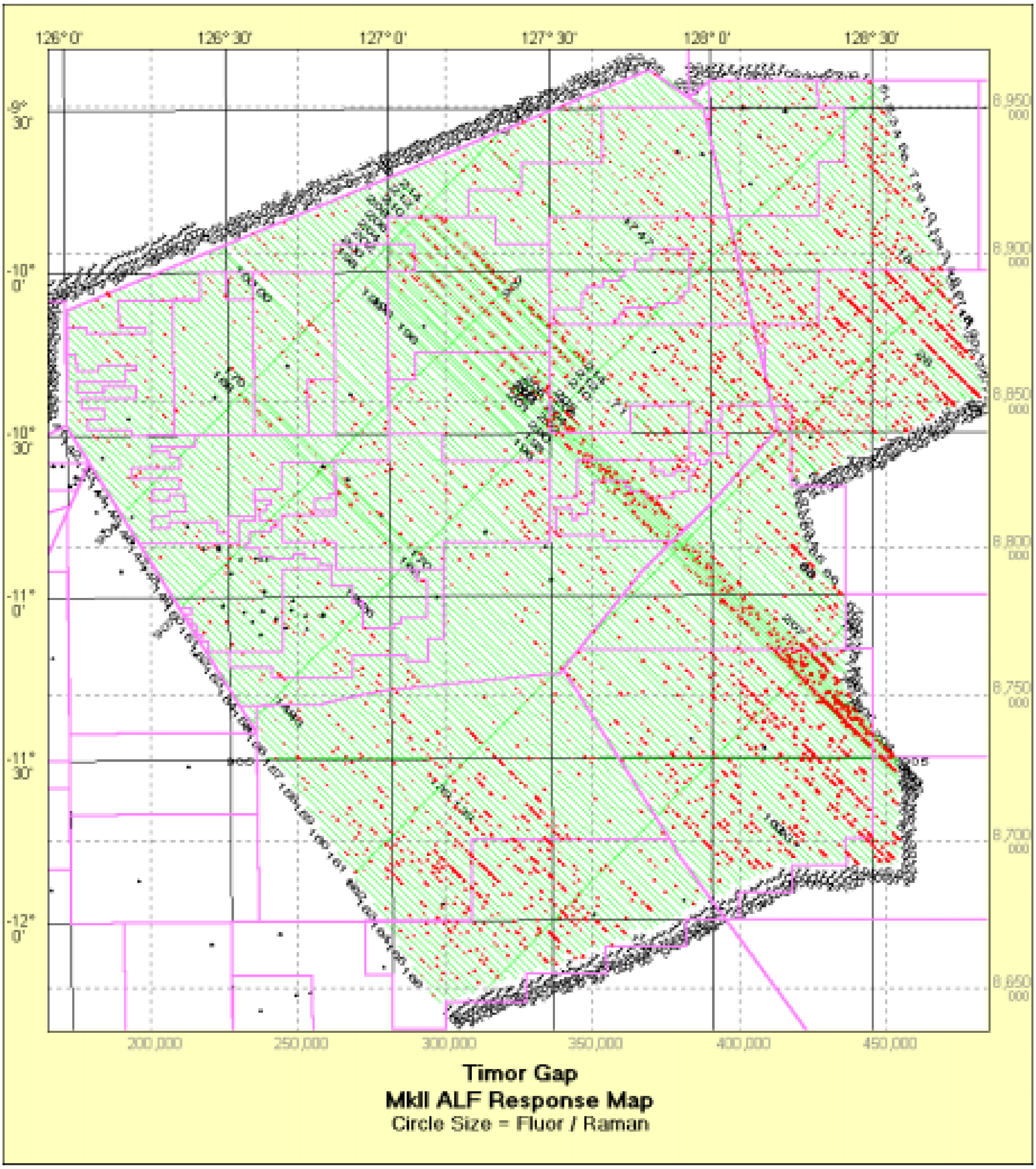

Figure 39. The Timor Gap ALF Mk II survey confident fluor map.

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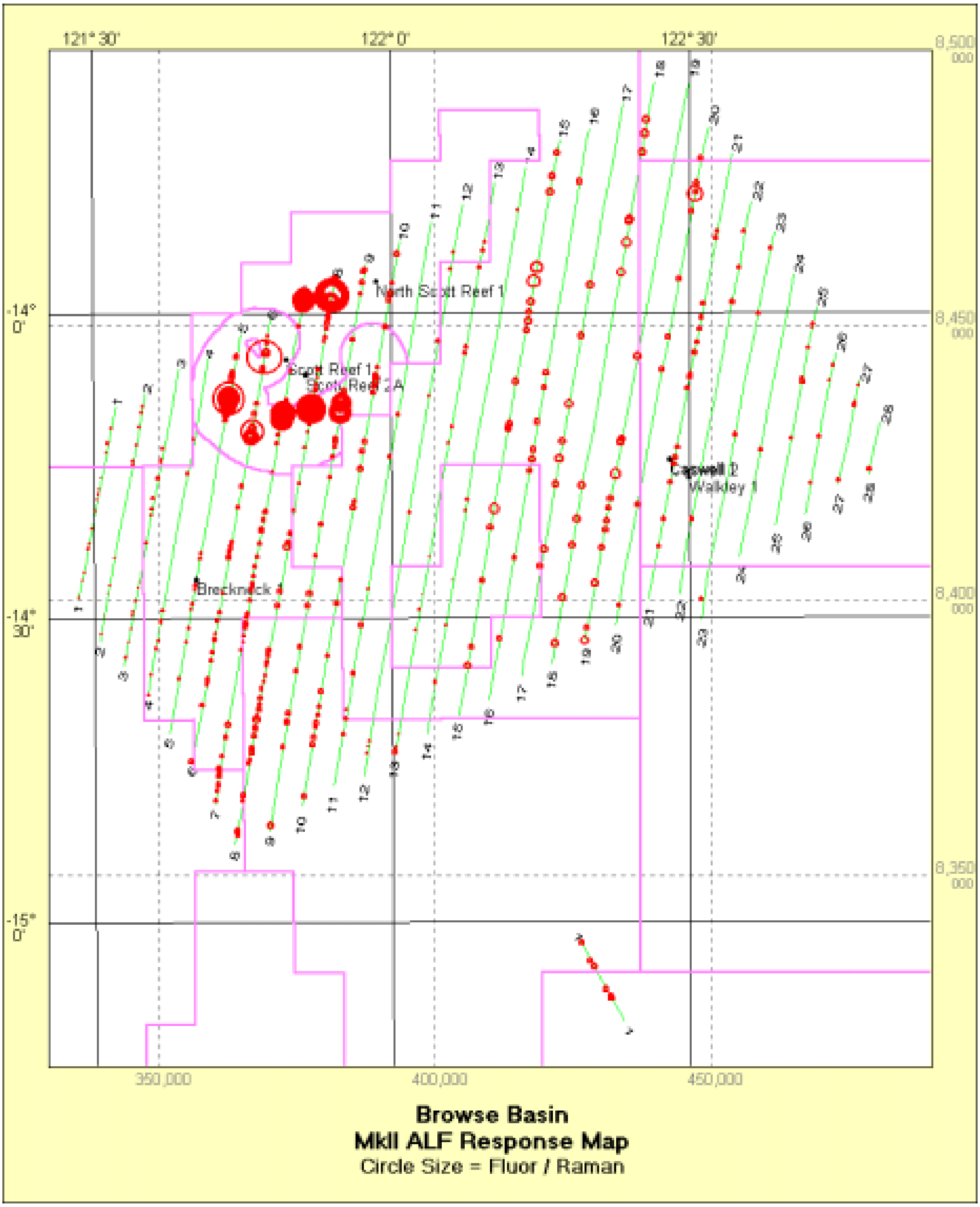

Figure 40. The Browse Basin ALF Mk II survey confident fluor map.

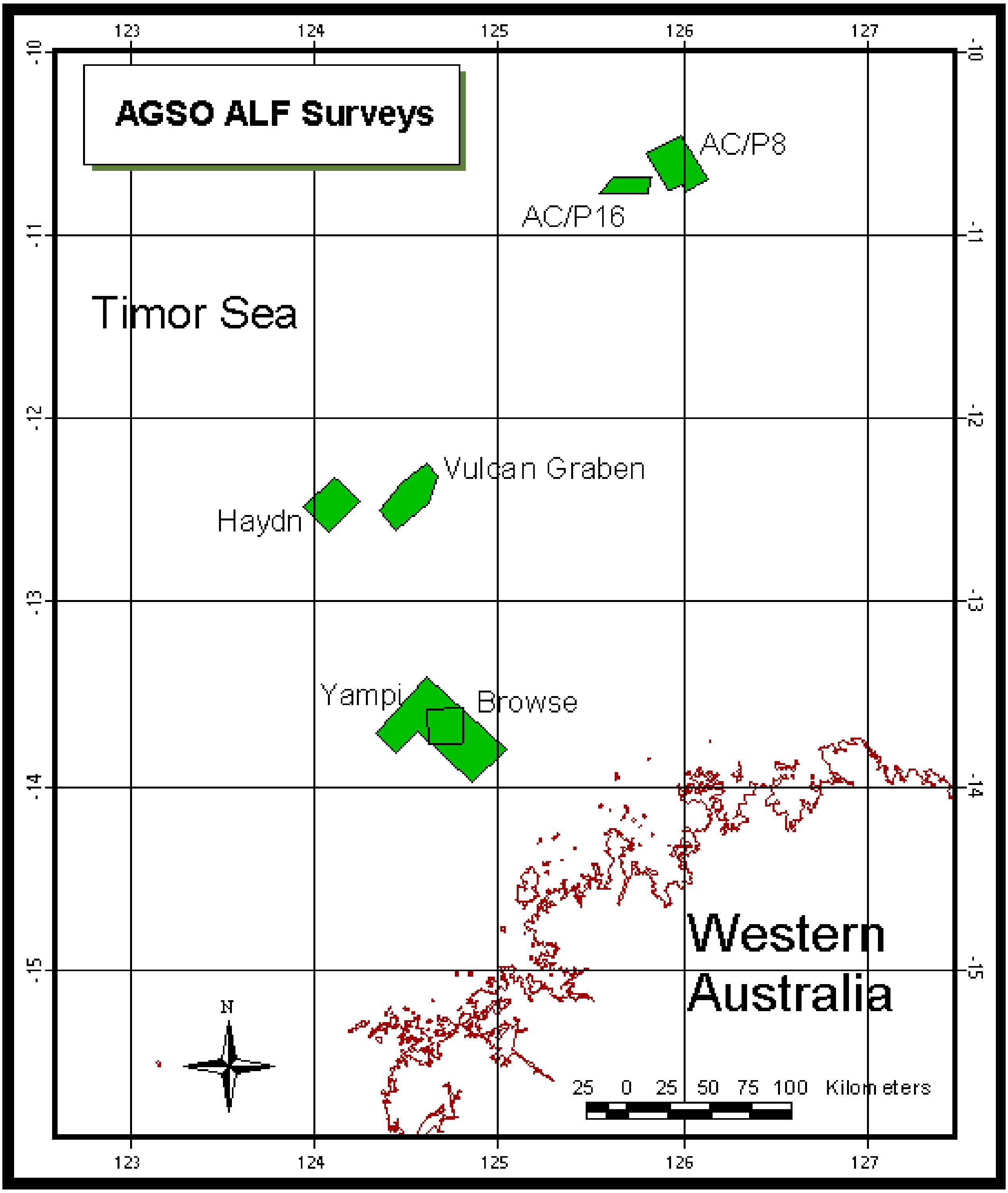

Figure 41. Location map of the reprocessed AGSO Mark III ALF surveys.

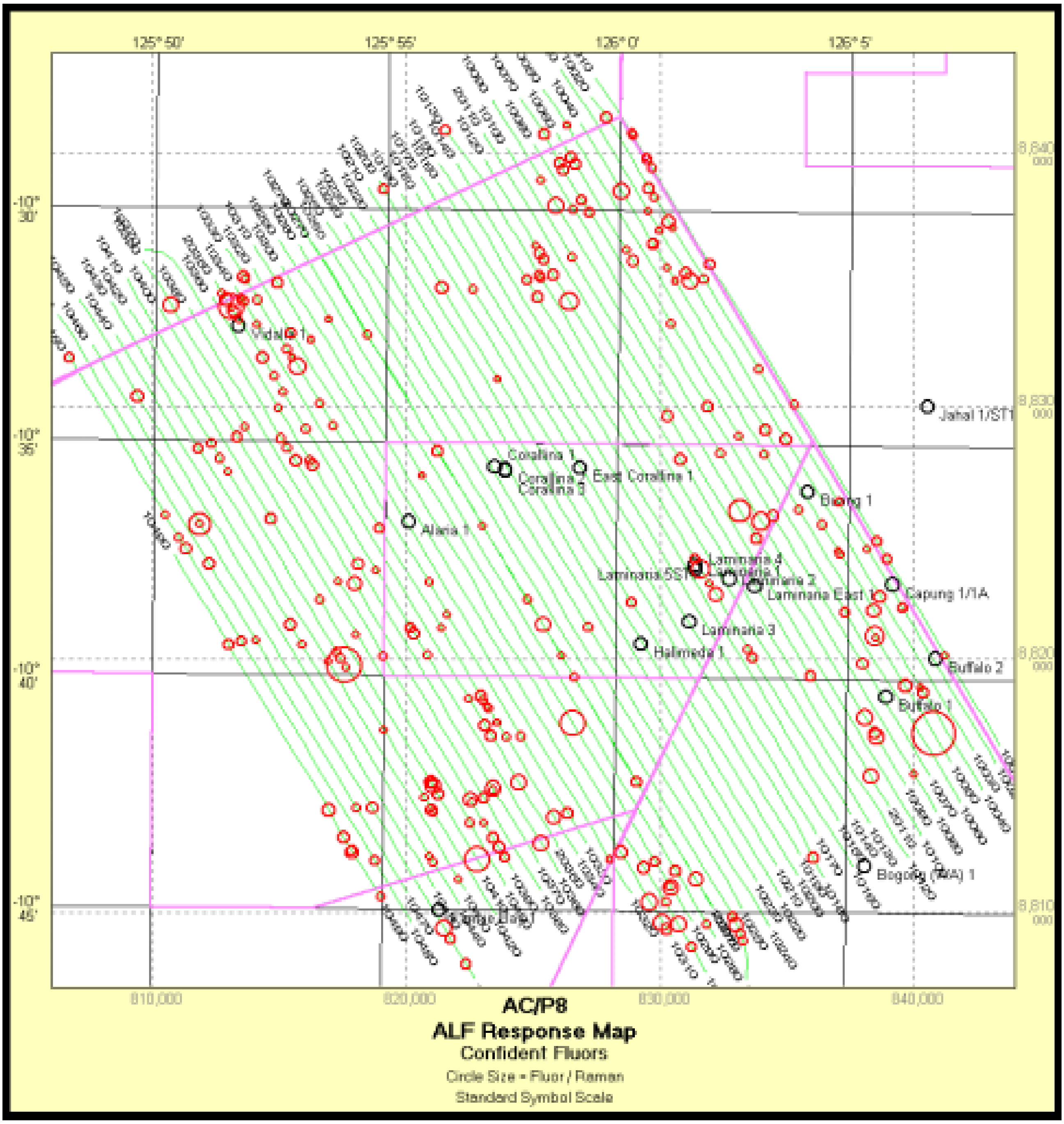

Figure 42. The AC/P8 ALF Survey Standard Fluor Map.

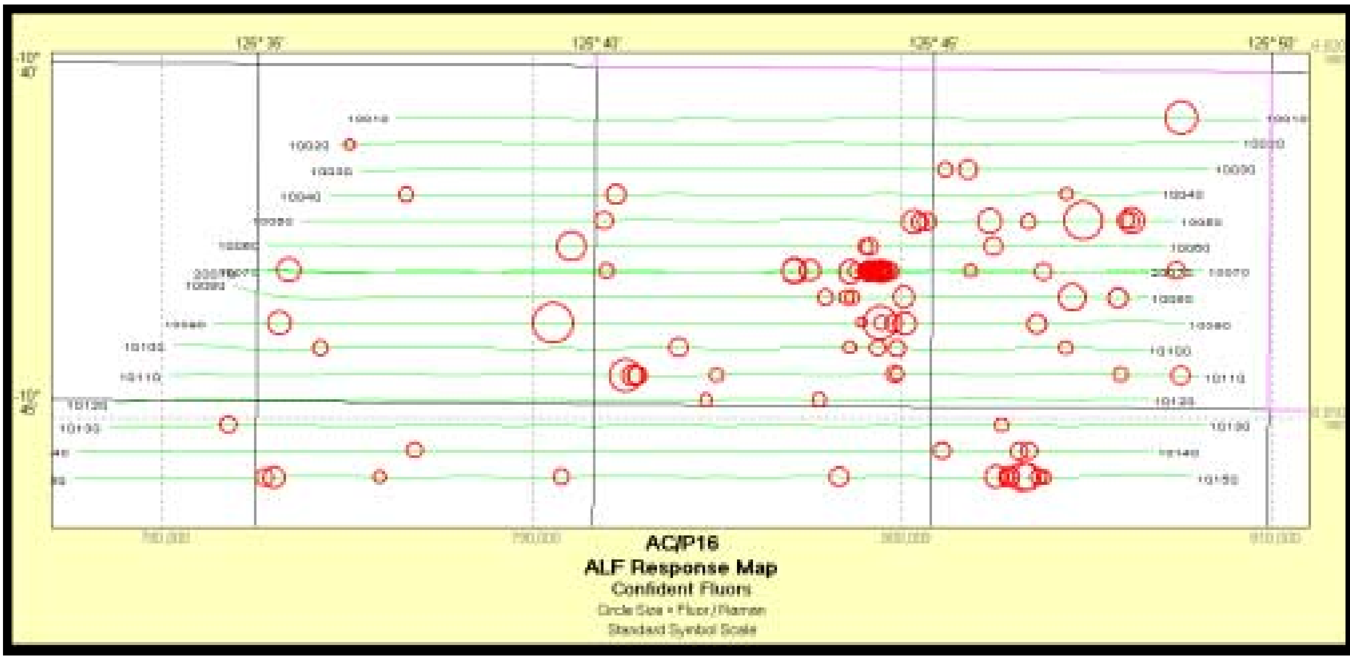

Figure 43. The AC/P16 ALF Survey Standard Fluor Map.

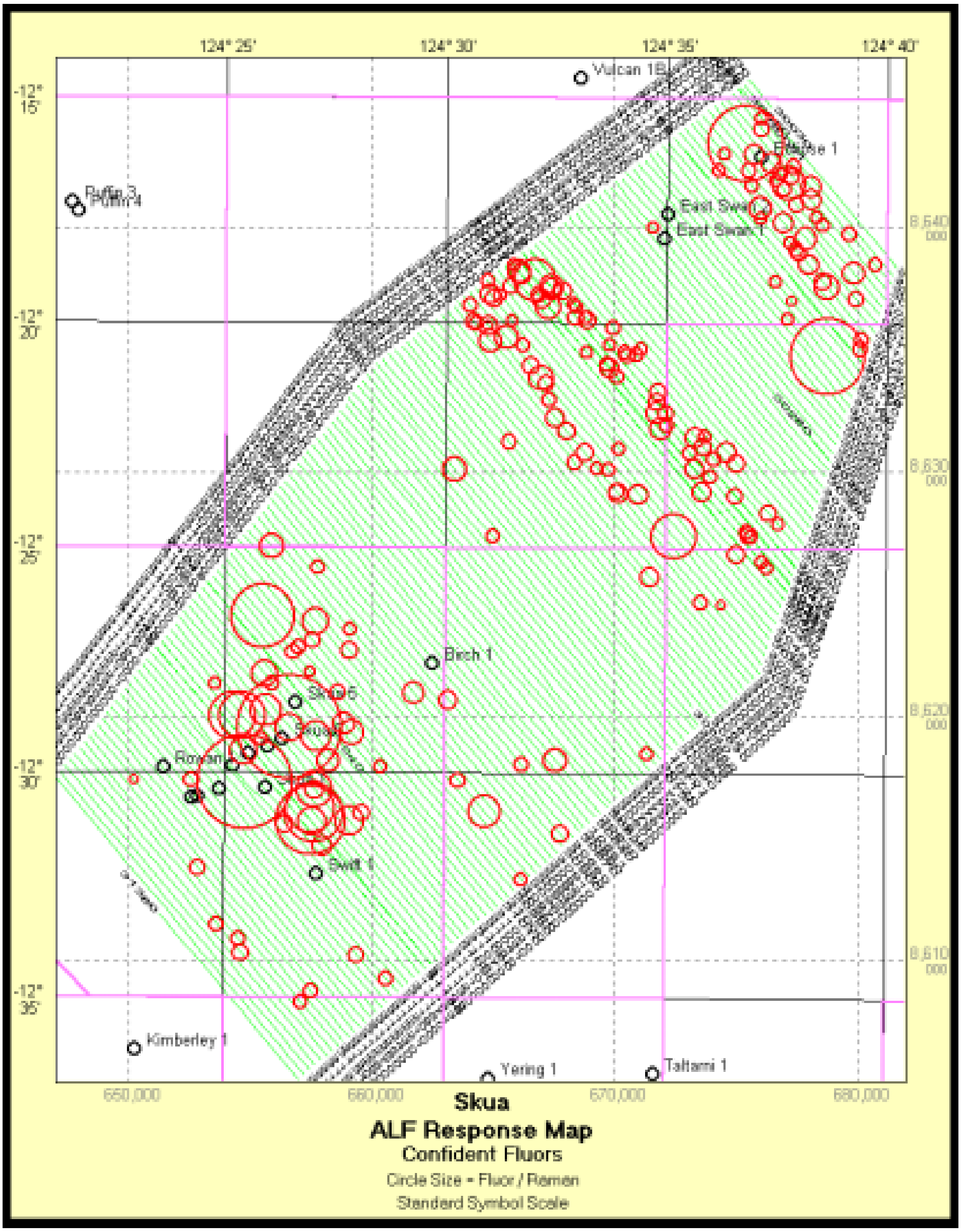

Figure 44. The Skua ALF Survey Standard Fluor Map.

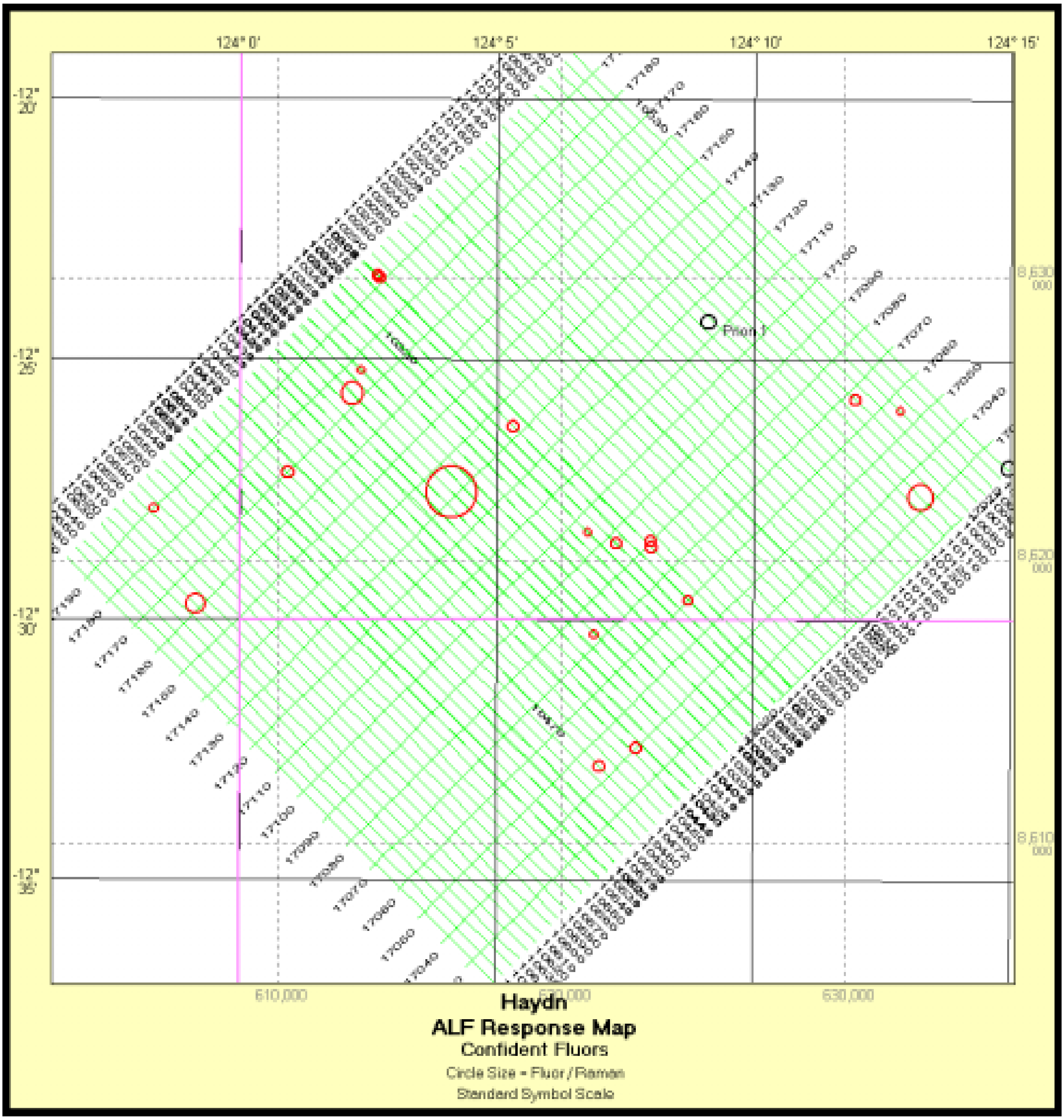

Figure 45. The Haydn ALF Survey Standard Fluor Map.

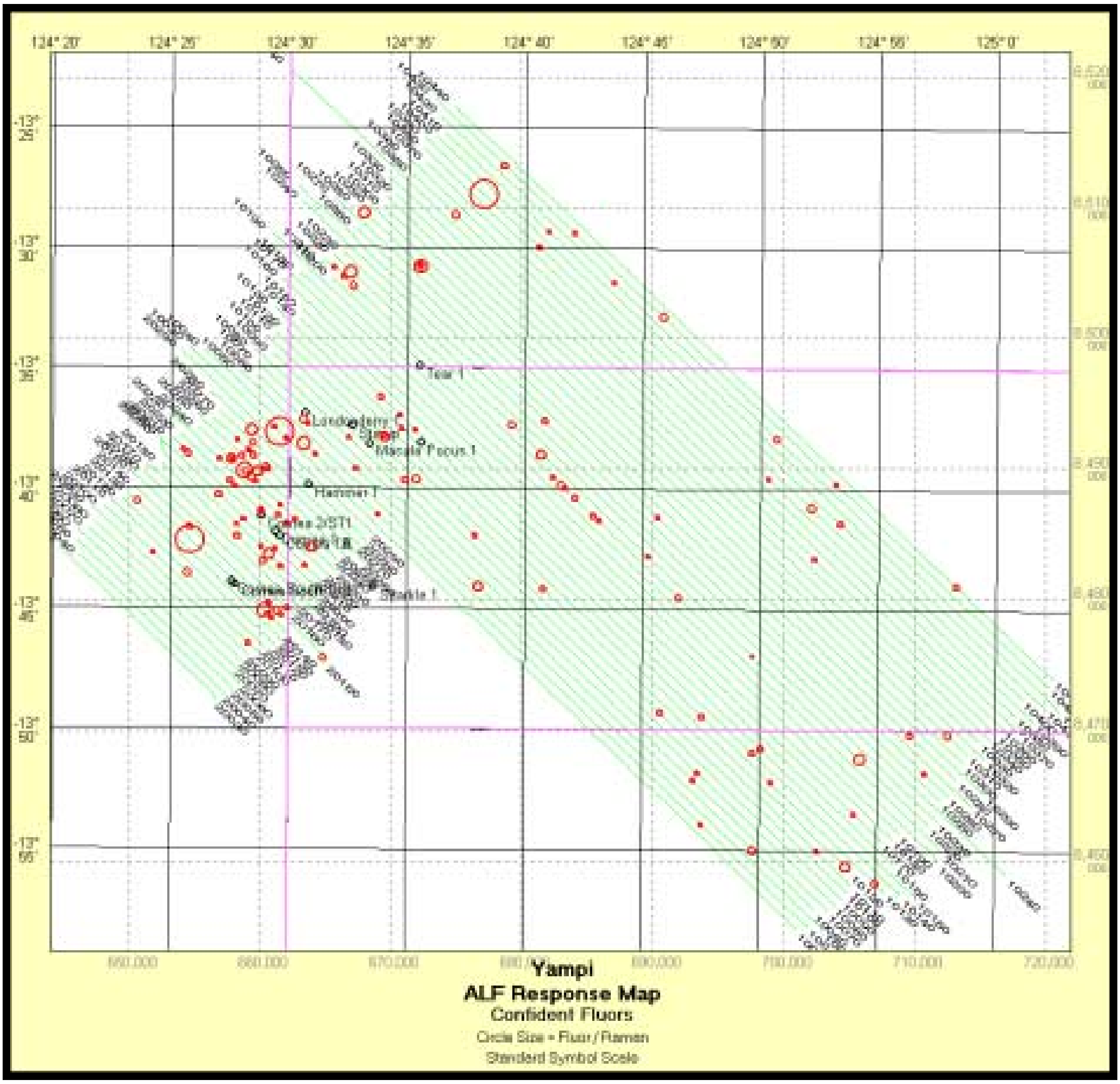

Figure 46. The Yampi ALF Survey Fluor Map.

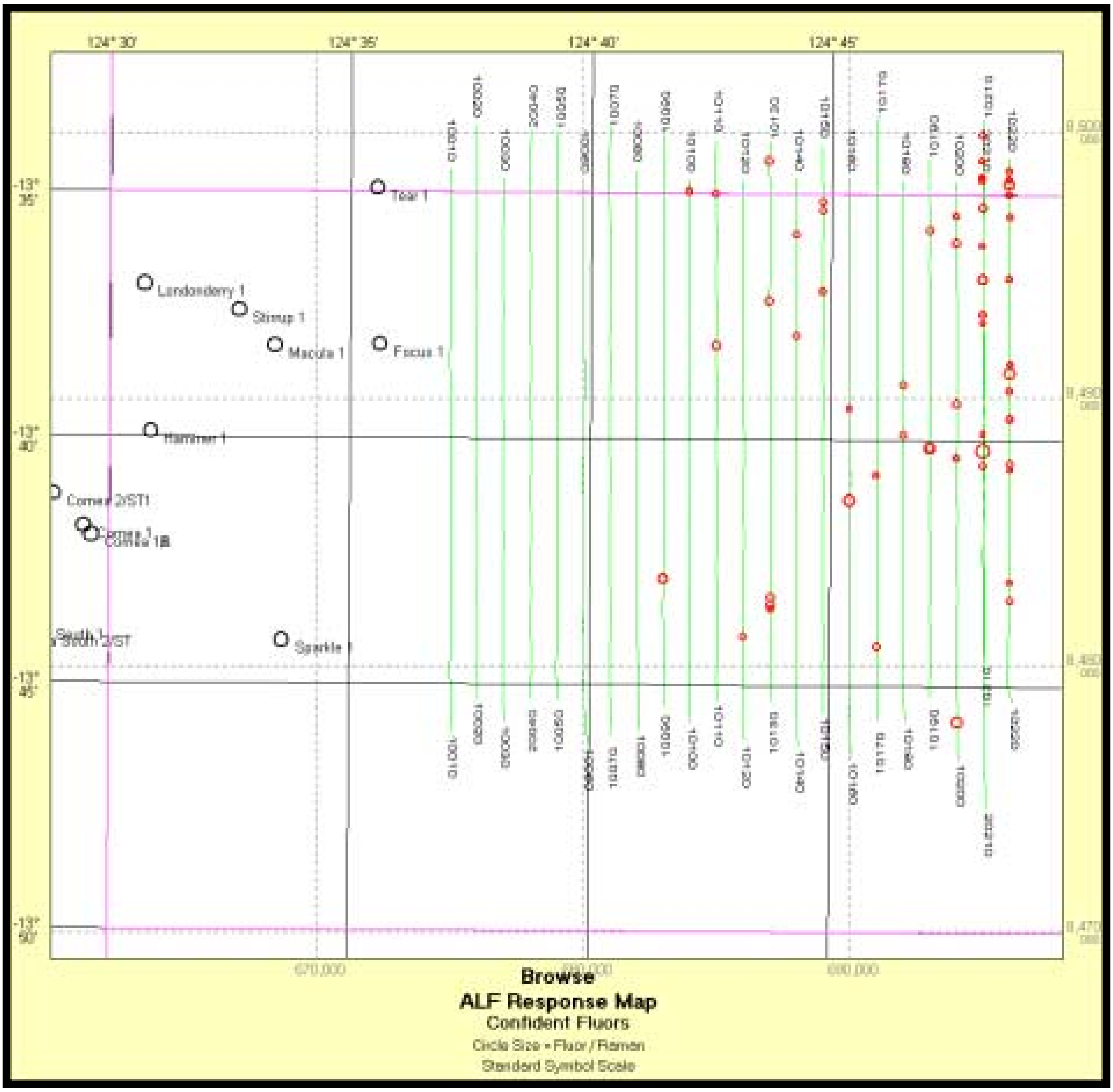

Figure 47. The Browse ALF Survey Standard Fluor Map.

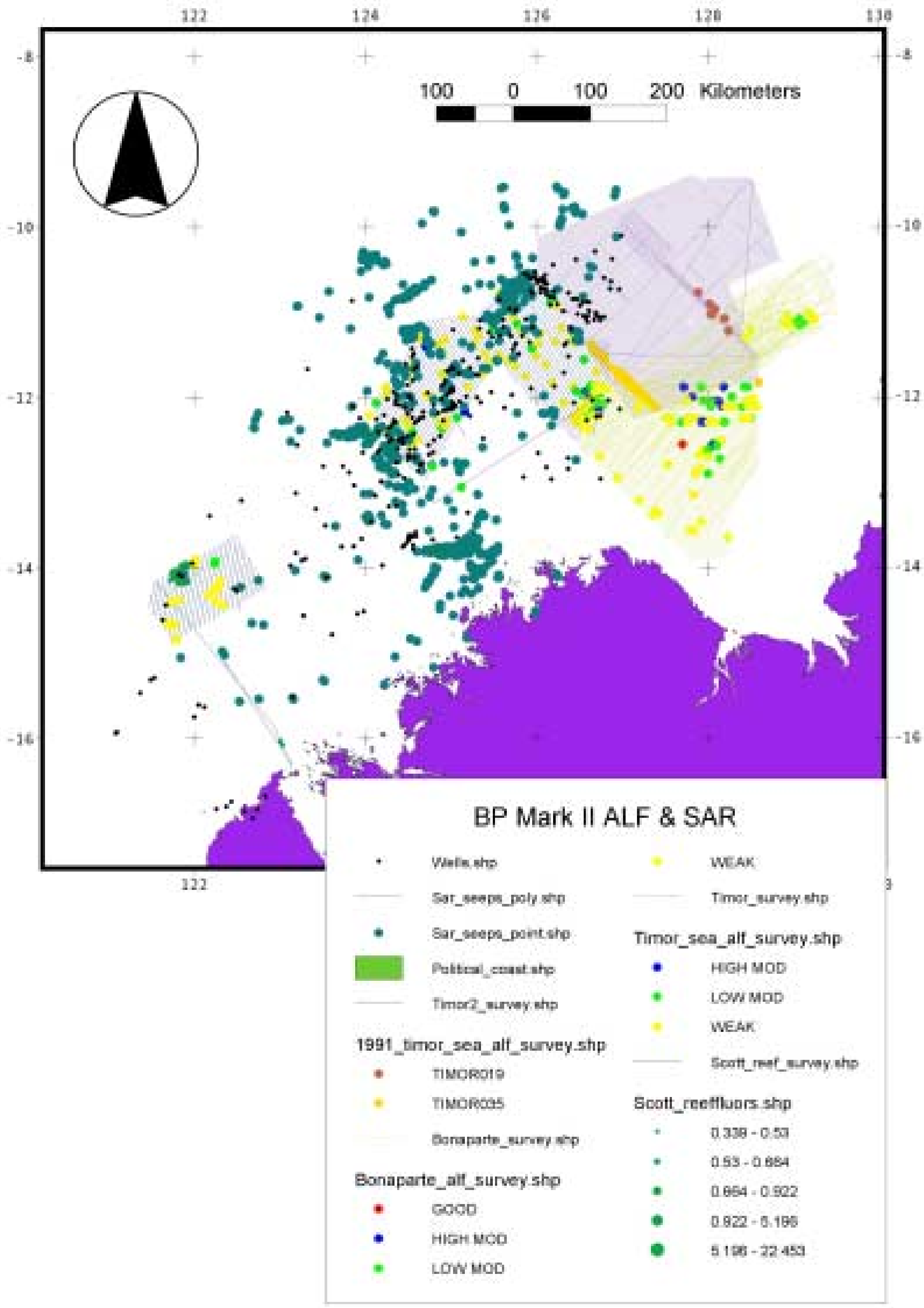

Figure 48. Comparison between the location of BP Mark II ALF fluors and Slicks. Slicks are grey-green; fluors range from red, through blue, green and yellow.

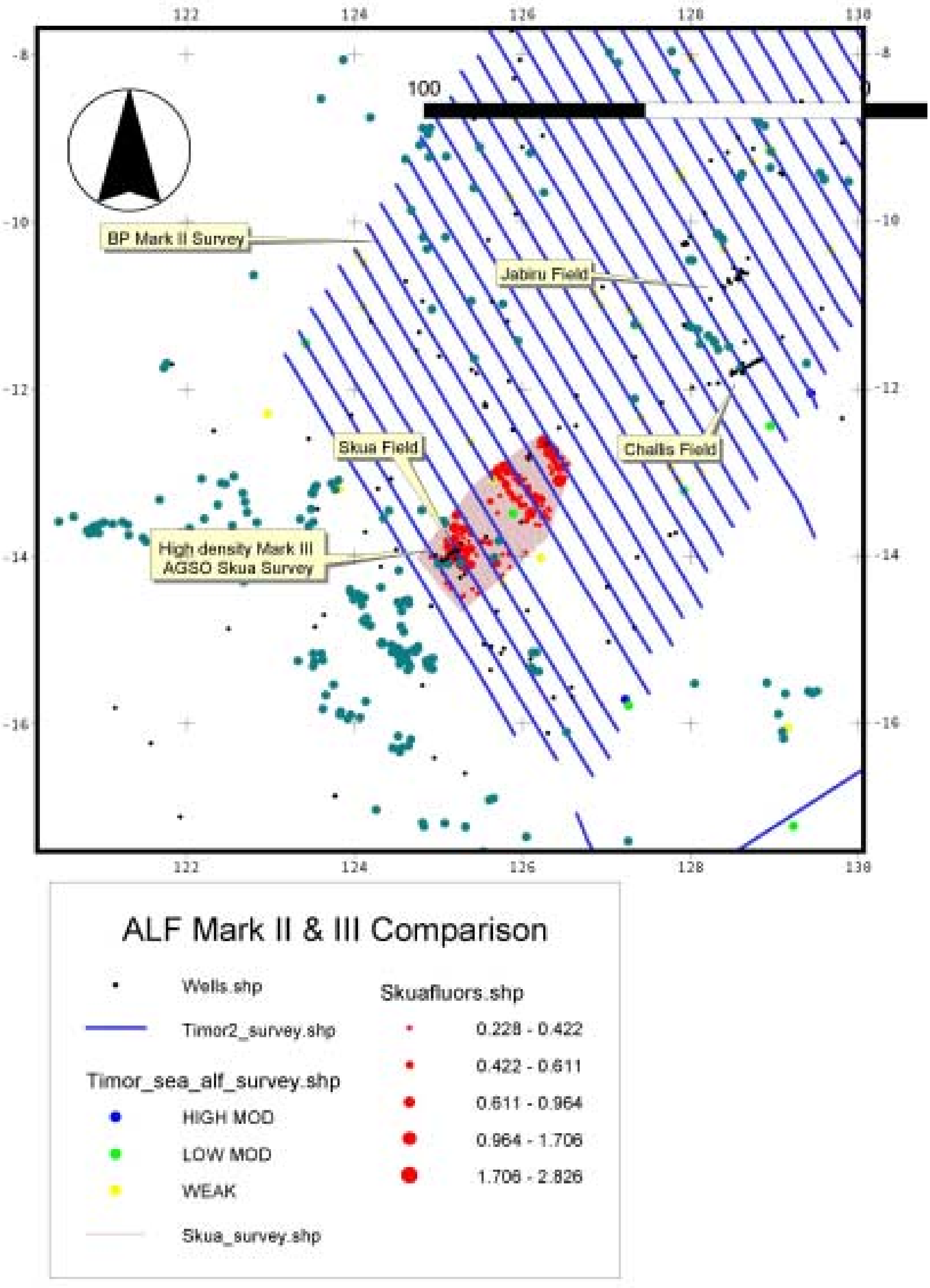

Figure 49. Comparison between the density of Mark II and Mark III ALF anomalies in the southern Vulcan Sub-basin. Mark III ALF fluors are ion blue, graded by size according to intensity. Mark II fluors are in yellow or green. Survey lines shown.

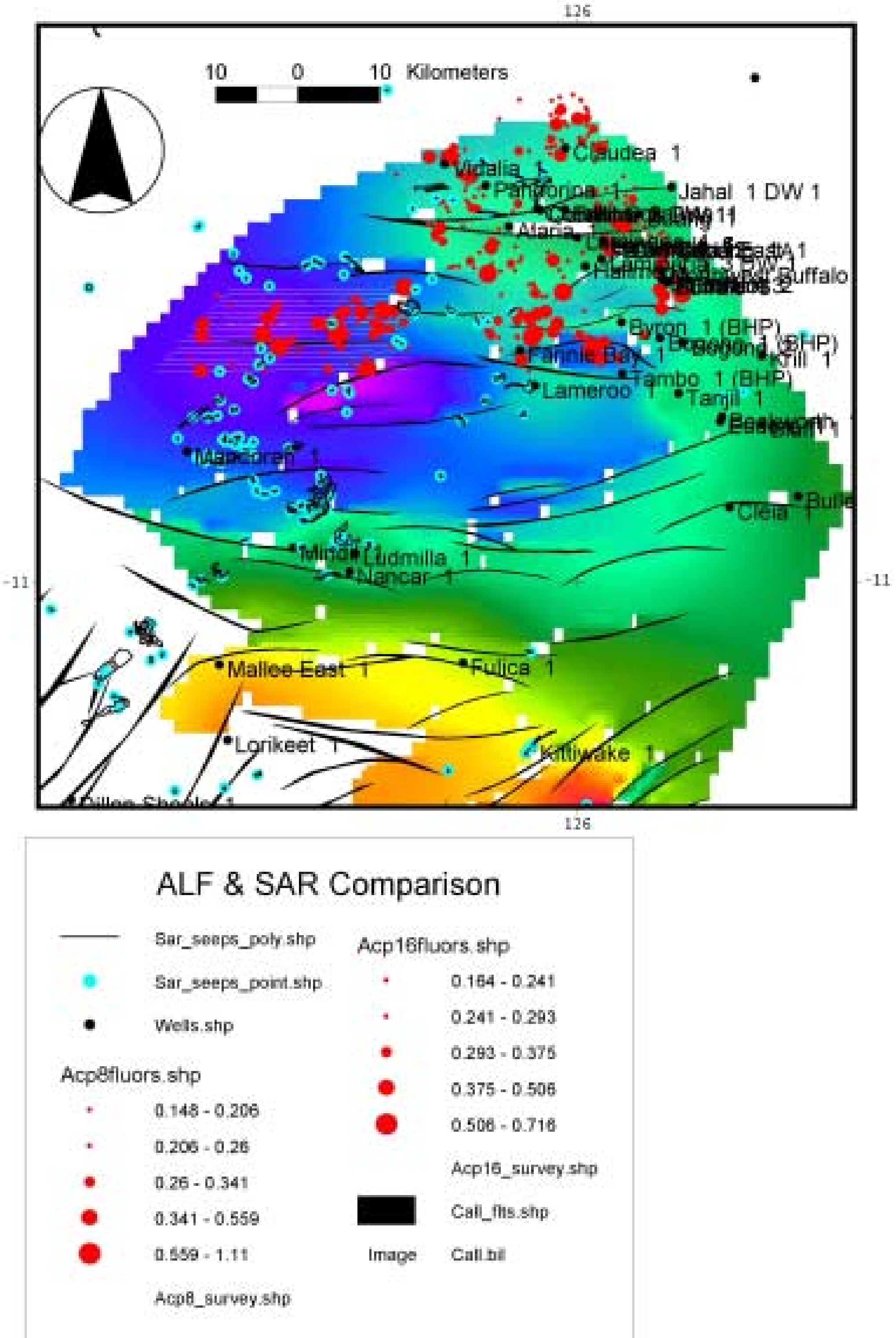

Figure 50. Relationship between Slicks (light blue) and ALF anomalies in the AC/P8 and 16 areas.

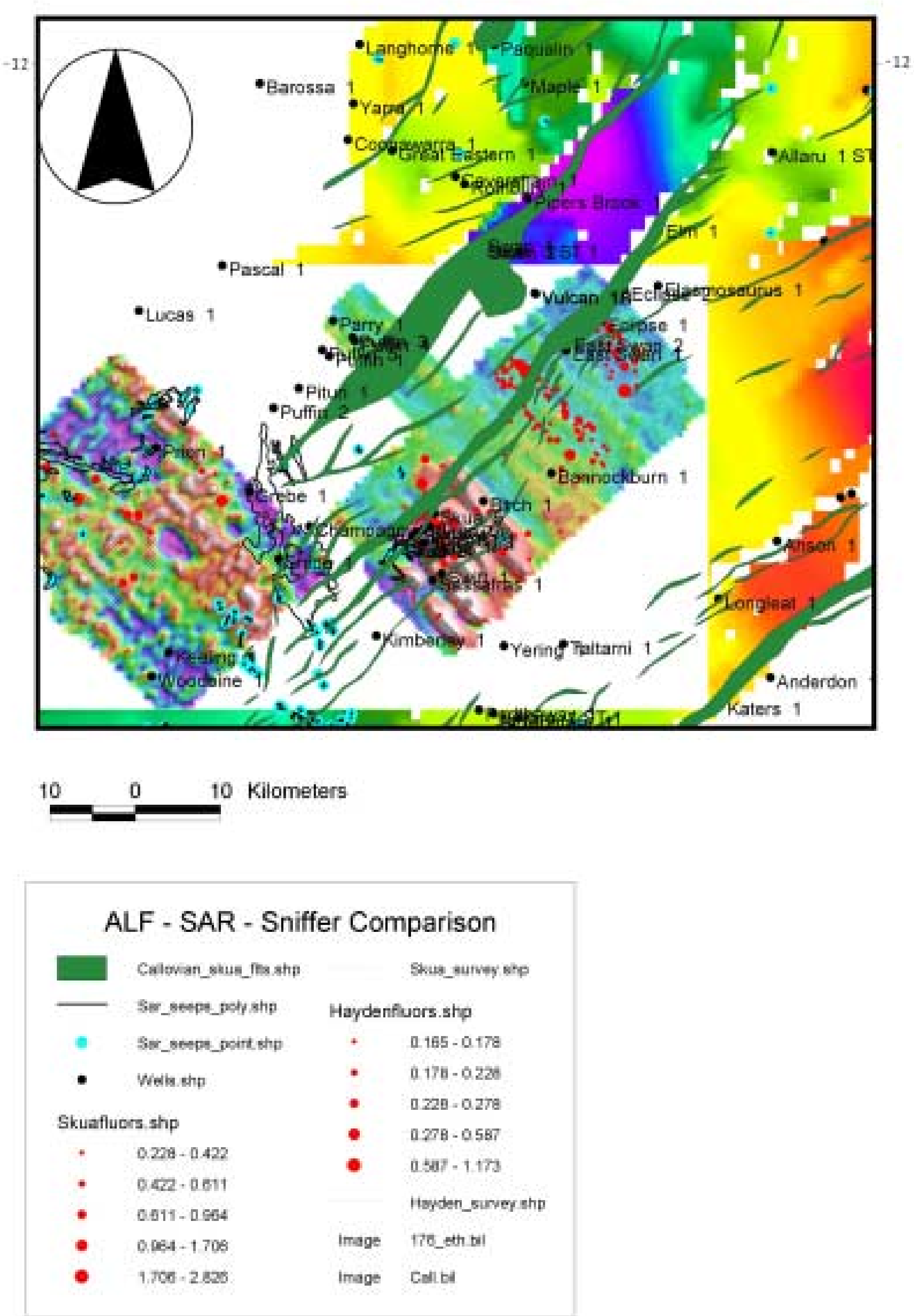

Figure 51. Relationships between Slicks (light blue), Mark III ALF anomalies (red) and water bottom ethane concentrations in the southern Vulcan Sub-basin. Callovian fault traces shown.

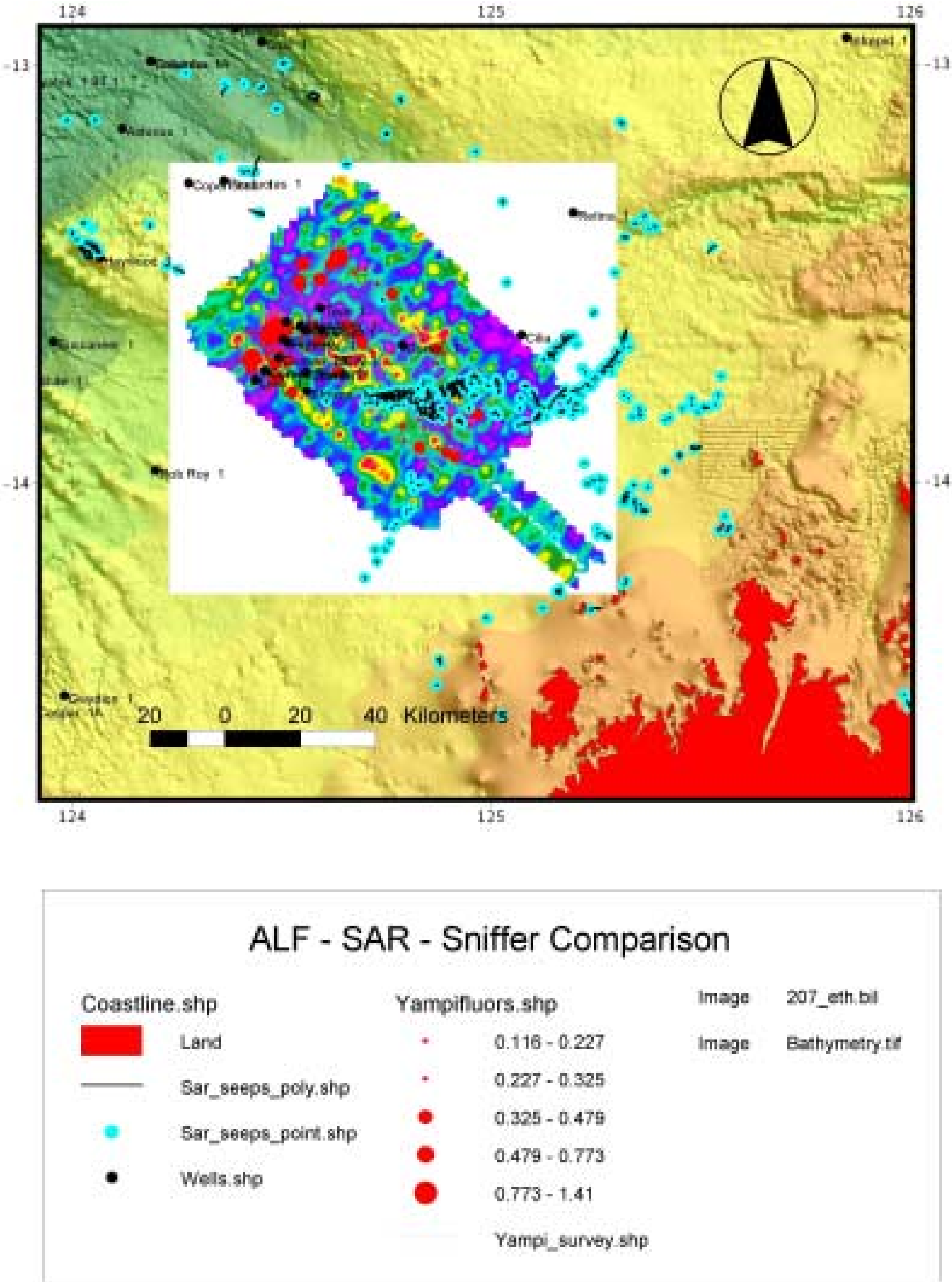

Figure 52. Relationships between Slicks (light blue), Mark III ALF anomalies (red) and water bottom methane concentrations in the Yampi Shelf.

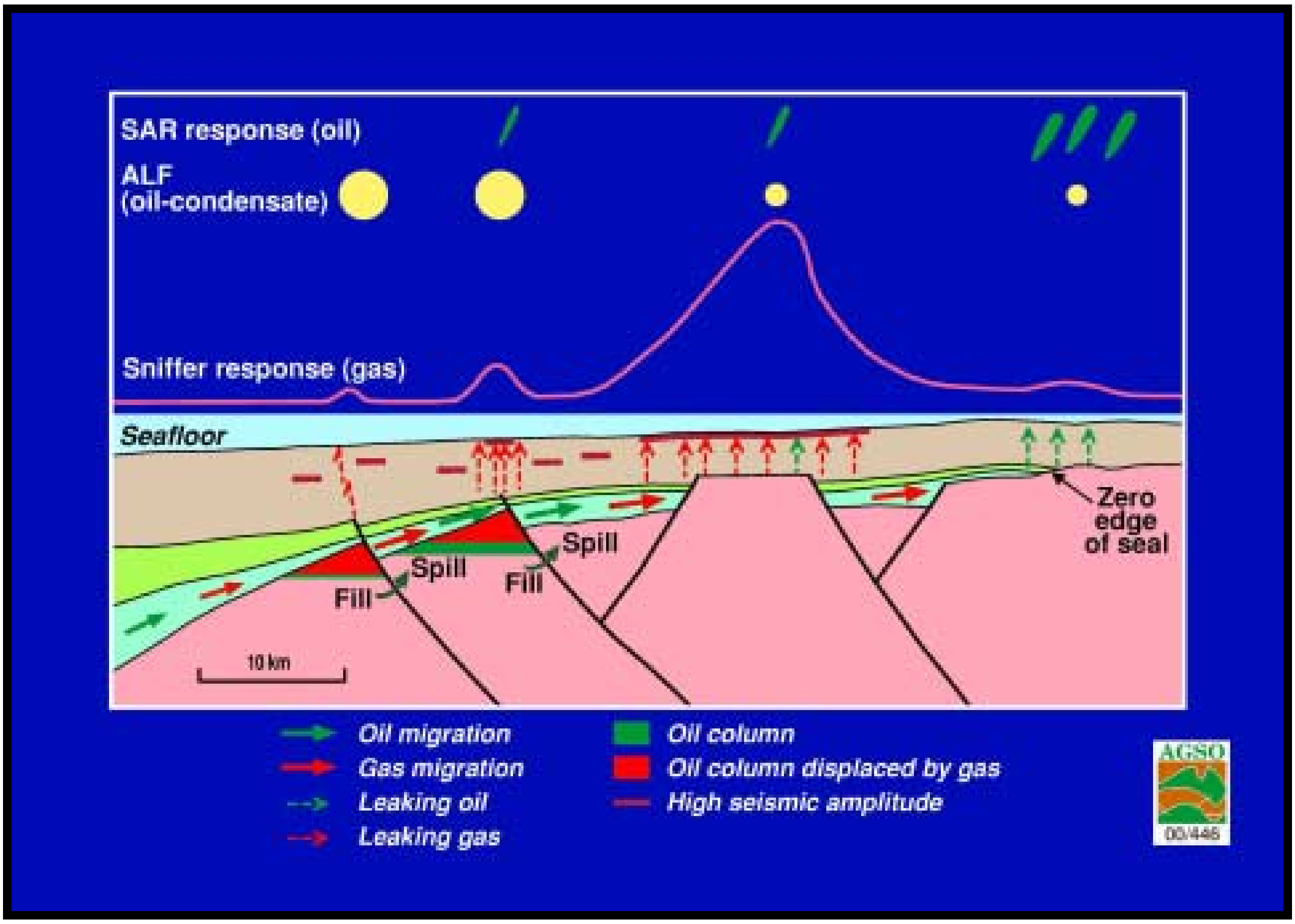

Figure 53. Schematic model of hydrocarbon migration and seepage across the Yampi Shelf.

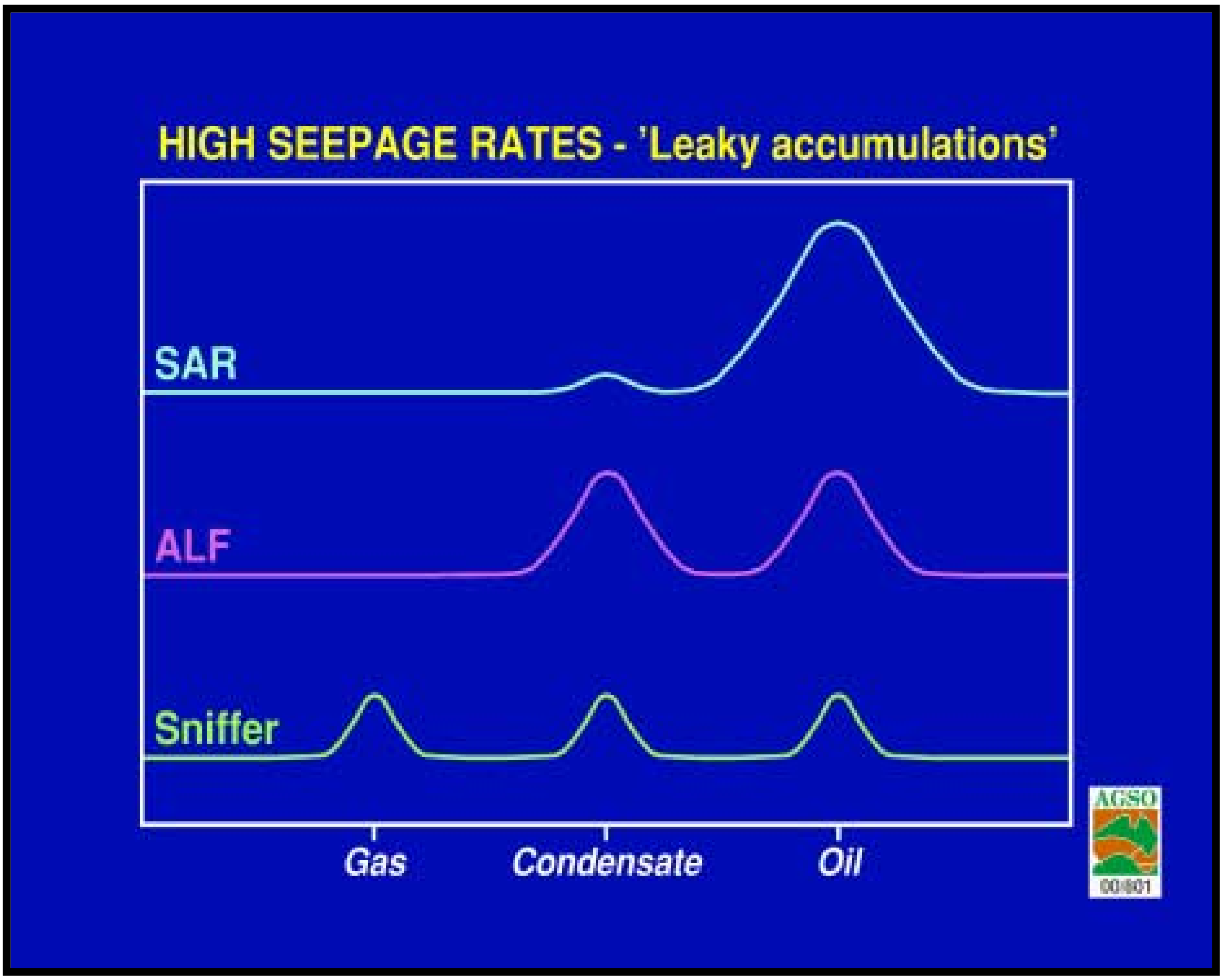

Figure 54. Proposed relationships between seepage rates, hydrocarbon phase and remote sensing response.

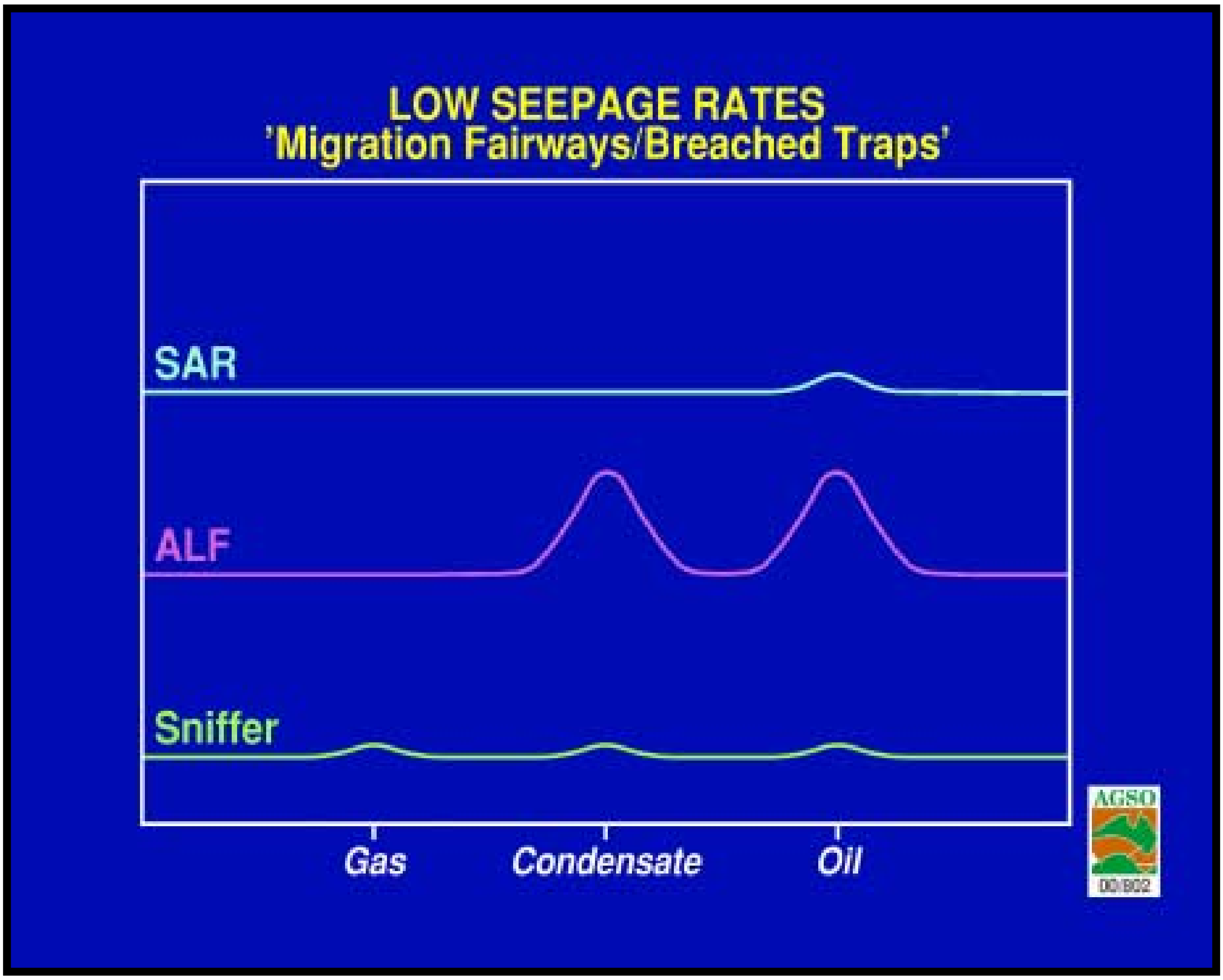

Figure 55. Proposed relationships between seepage rates, hydrocarbon phase and remote sensing response.

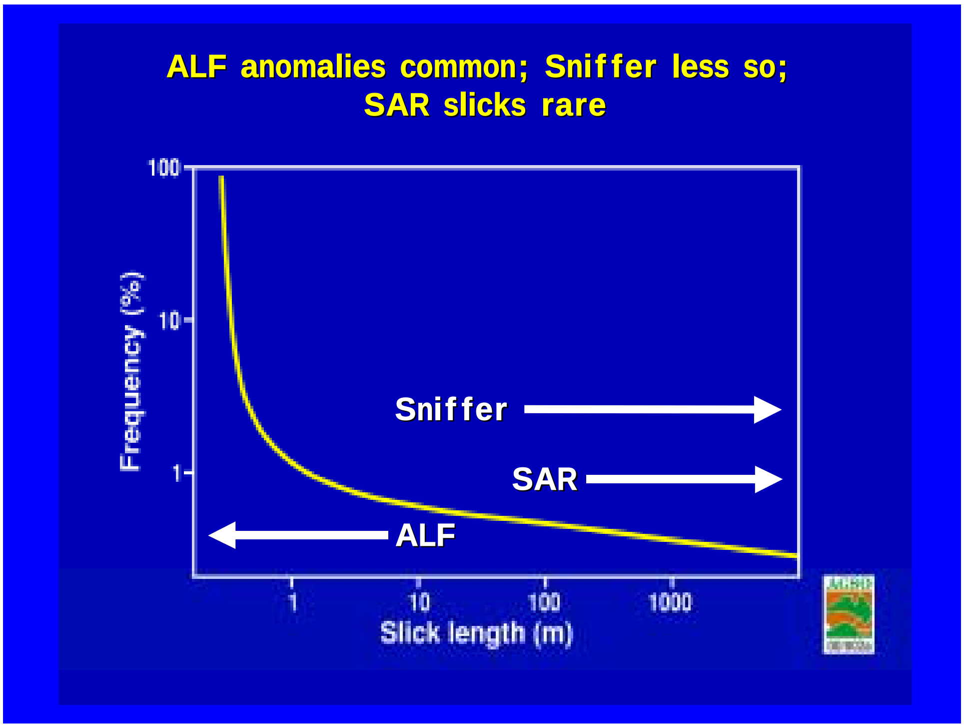

Figure 56. Proposed relationships between size of seepage slicks and sampling “foot-print” of various detection tools.