GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

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Theme 5: Petroleum Geochemistry of the Great Australian Bight

THEME REPORT

Andrew Ross and Richard Kempton

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GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

The Great Australian Bight Research Program is a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI), the University of Adelaide, and Flinders University. The Program aims to provide a whole-of-system understanding of the environmental, economic and social values of the region; providing an information source for all to use.

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ACKNOWLEDGEMENTS

The Great Australian Bight Research Program (GABRP) is a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI), the University of Adelaide, and Flinders University. The Program aims to provide a whole-of-system understanding of the environmental, economic and social values of the region; providing an information source for all to use.

The research projects of Theme 5 were conducted by a large group of researchers without whose valuable contributions this research would not have been possible. These co-authors are listed in Kempton et al. (2017), Ross et al. (2017a,b).

The voyage data and samples used in the delivery of these projects would not be possible if not for the dedication of the participants on the SS2013_C02 and IN2015_C02 Marine National Facility (MNF) voyages. In particular, the voyage chief scientists are thanked (Alan Williams, SS2013_C02 and Rudy Kloser, IN2015_C02) as well as the scientific staff, MNF teams and crews of the vessels.

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CSIRO is thanked for the permission to use internal research outcomes from sedimentary forward models to enhance the outcomes of Project 5.1. Staff at CSIRO, the University of Adelaide and BP are thanked for their support in the development and execution of this project, as is the project team at SARDI (Jane Ham, Ben Baghurst and Steven Lapidge).

1. EXECUTIVE SUMMARY

The Great Australian Bight is one of the most prospective deep-water basins in Australia. However, its vast geographic extent and deep sedimentary sequence remain poorly characterised. The challenge for GABRP Theme 5 – Petroleum Geology & Geochemistry – was to enhance the prospectivity of the Bight Basin by developing a more detailed understanding of its petroleum systems prior to exploration drilling; and to characterise the baseline hydrocarbon loading of its sediments, water column and adjacent beaches.

Theme 5 objectives were to; (1) Project 5.1; identify potential seepage areas (Ross et al., 2017a), (2) Project 5.2; characterise the coastal bitumen that naturally strands along the shorelines of South Australia (Ross et al., 2017b) and (3) Project 5.3; detect traces of hydrocarbons in the sedimentary sequence and understand how and when they formed over geological time (Kempton et al., 2017). This report summarises the aims, objectives, results and conclusions from these projects and their linkage with other GABRP themes.

Theme 5 results together demonstrate unequivocal evidence for the presence of hydrocarbons and petroleum systems not only on the flanks of the Ceduna and Duntroon sub-basins but also in the central deep-water Ceduna Sub-basin.

Fluid inclusion studies did identify traces of oil, and in some cases gas, in most of the previous wells drilled in the Ceduna and Duntroon sub-basins. This was evidence that hydrocarbons had indeed been generated at some time in the past and then moved along migration pathways around the basin. In the Gnarlyknots-1A well (4,390 to 4,425 mMD) oil and gas-condensate trapped in inclusions during the Late Cretaceous (from ~70-75 Ma onwards), with the bulk geochemical fingerprint of this oil indicating sources from both algae and terrestrial plant matter deposited in a suboxic to oxic marine environment. Fluid inclusion oils in the Greenly-1 well (4,808-4,812 mMD) were, however, trapped either from ~23 Ma onwards or between ~75 and 52 Ma (based on fluid inclusion trapping pressures) and were sourced from terrestrial plant matter only, with a minor contributions from bacteria deposited in an oxic, clay-rich fluvio/deltaic depositional environment.

Whilst the research voyages undertaken as part of the GABRP did not identify unequivocal evidence of present-day seeps, Project 5.1 has shown that faults may have acted as conduits for hydrocarbon migration and paleo-leakage. Interpreted biogenic mounds that formed during the Eocene overlie faults with these features possibly being related to paleo-hydrocarbon seepage.

Three annual surveys collected a total of 631 asphaltites and tarball specimens form 31 beaches along the South Australian coastline and have extended the known geographic extent of coastal bitumen stranding locations to now include the Eyre Peninsula. Geochemical characterisation identified 15 oil families, many of which can be explicitly linked to Indonesian basins. However, at least two waxy bitumen sub-families and the asphaltites lack Indonesian signatures and have potential origins from seeps in offshore basins along Australia's western and southern continental margin. Independent oceanographic modelling more clearly defined the offshore transport mechanisms for both varieties of coastal bitumen. Contrary to previous suggestion, the Morum Sub-basin is now considered to be an unlikely source for the asphaltites with the highest number of particle tracks crossing the Duntroon Sub-basin.

Analysis of sediments and water samples collected during longitudinal depth stratified transects of the GAB showed that petroleum hydrocarbons were either absent or below the limits of detection in the majority of samples. Where trace petroleum hydrocarbons were detected these were ascribed to contamination. Comparison of the current bitumen loadings in this study with previous studies

shows that the natural hydrocarbon loading of the South Australian coastlines appear to be diminishing, the reasons for which are unclear. These datasets represent important pre-exploration baseline data on hydrocarbons in the GAB.

2. INTRODUCTION

2.1 Overview

The Great Australian Bight, and particularly the Ceduna Sub-basin, is considered one of the most prospective deepwater frontier basins in offshore Australia (Totterdell et al., 2008). It contains up to 15 km of mid- to late Cretaceous deltaic and marine sediments within the Tiger and Hammerhead Supersequences that provide potential reservoirs, seals and oil-prone source rocks at several stratigraphic levels (Blevin et al., 2000; Totterdell et al., 2000; Struckmeyer et al., 2001). Despite 44 years of petroleum-related activity in the Bight Basin only 13 exploration wells have been drilled, with no significant liquid hydrocarbons recovered. A petroleum system capable of producing commercial quantities of hydrocarbons has yet to be identified.

On commencement of the GABRP evidence for palaeo-hydrocarbons trapped in fluid inclusions had been identified only within some vintage exploration wells on the margins of the basin (Lisk et al., 2001) and not in the deep-water Ceduna Sub-basin. Previous geochemical studies of coastal bitumen (McKirdy et al., 1986, 1994; Currie et al., 1992; Padley et al., 1993; Padley, 1995, Edwards et al., 1998; Hall et al., 2014) had identified in the asphaltites biomarker and isotopic signatures consistent with their origin from an offshore mid-Cretaceous marine shale. There had only been two attempts to determine areas of natural seepage using marine surveys, and these surveys were performed without the availability of detailed 3D seismic data sets and other ancillary data. As such, they failed to unequivocally identify natural seepage from the seafloor, and the point of origin of the asphaltites, although they did confirm the presence of deep-water outcrops of Cretaceous shales with significant oil-source potential (SS01/2007; Totterdell & Mitchell, 2009).

Given the current renewal of interest in the Bight Basin, there was an opportunity to both understand in greater detail its petroleum systems, and to establish the baseline hydrocarbon loading of its sediments, water column and adjacent beaches prior to the commencement of exploration.

With a view to addressing these aims, the specific research objectives of Theme 5 were to:

- Detect and characterise hydrocarbon-filled fluid inclusions within core and cuttings from wells previously drilled in the Bight Basin. The purpose of this work was to gain a detailed understanding of the source and timing of hydrocarbon generation and the subsequent movement of these hydrocarbons in the subsurface of the GAB.
- Determine the distribution and provenance of stranded asphaltites and tar balls by undertaking three successive annual beach surveys. These surveys were tasked with gaining a more accurate measure of the contemporary natural hydrocarbon loading of South Australia's ocean beaches, and identifying other possible hydrocarbon leakage points by extrapolation from preferred asphaltite stranding sites.
- Identify and characterise the mechanisms for, and occurrence of, natural seepage in and around the BP permits in the GAB and, in addition, to characterise the natural hydrocarbon baseline within sediments and biota prior to further exploration.

The work of this theme is linked strongly to that of the oceanographic and benthic ecology investigations (Themes 1 and 3, respectively). Oceanographic models were a key component of the Project 5.2 deliverables in helping to determine the likely offshore transport mechanisms for the tar balls and asphaltites that strand along the South Australian coastline. When combined with geological data, the geochemical analysis of sediment and water samples recovered from the depth-stratified transect locations of Theme 3, permitted hydrocarbon concentration to be contemplated when interpretations of structure and abundance of fauna were considered in the context of habitat types. This was especially relevant for the characterisation of hydrocarbon-degrading microbial populations. Ultimately, a more detailed understanding of the geology and presence of hydrocarbons in the GAB will help define its prospectivity for oil and gas exploration and development.

3. PROJECTS

3.1 Project (5.1): Delineation and characterisation of cold hydrocarbon seeps and their associated benthic communities

3.1.1 Objectives

The overall intent of Project 5.1 was to enhance the petroleum prospectivity of the Bight Basin by looking for evidence of active hydrocarbon seeps and to provide baseline hydrocarbon concentrations at preselected reference sites (in conjunction with the Project 3.1 of the Benthic Biodiversity theme).

This multidisciplinary study aimed to develop an understanding of the potential mechanisms for hydrocarbon migration and seepage in the GAB, through a reconnaissance survey undertaken to acoustically characterise areas of potential seepage. Secondly, as part of the reconnaissance survey water and sediment samples were to be collected for geochemical analysis to check for the presence of petroleum hydrocarbons at preselected reference sites (away from areas of potential natural seepage) in order to establish pre-drill baseline conditions.

The main subsurface structural elements (i.e. faults), that potentially act as pathways for hydrocarbon movement to the seabed, were defined and assessed. This was to be undertaken in combination with natural seepage reconnaissance mapping, with a view to developing potential targets (both seeps and habitats) for further study.

Complementary satellite-based remote sensing data were to be collected to help identify potential seep locations. Newly acquired or archival synthetic aperture radar (SAR) data over the GAB were to be integrated with synthetic aperture radar (SAR) observations, oceanographic data and the underlying geology to delineate possible seepage zones. These zones, if detected, were likely to be areas of key deep-water benthic biodiversity. Hence, work was undertaken in close collaboration with participants from Project 3.1.

Samples collected from the baseline-reconnaissance survey were subjected to various geochemical analyses, with subsequent data interpretation helping to inform the hydrocarbon baseline conditions that exist in the GAB.

3.1.2 Key results and discussion

Evidence for seepage

A total of 81 areas of potential hydrocarbon seepage were identified from 2D seismic data. No one area displayed unequivocal evidence of potential fluid leakage up to the seafloor, although this does not preclude seepage being present elsewhere in the GAB. Ranking of the features determined, however that those with the highest potential for leakage were strongly biased towards the outboard deep-water slope of the Ceduna Sub-basin. Review of the SAR data did not find explicit evidence of consistent surface slick anomalies over the areas of interest, although additional captures made just prior to the SS2013_C012 voyage did identify several potential slicks over areas with highly ranked seismic leakage indicators (Ross et al., 2017a).

The SS2013_C02 and IN2015_C02 voyages produced acoustic, water column and sediment chemistry data, which collectively indicated only weak evidence for seepage and requires further investigation and quantification. This was in part due to the fact that the sole purpose of the voyages was to acoustically identify and characterise sites of potential seepage, and there was insufficient time to sample any particular features of interest. This outcome is not definitive for the presence or absence of seepage in the basin, as there is a general paucity of data collected over the wider basin.

Understanding subsurface migration mechanisms and potential paleo-seepage

To gain an understanding of subsurface migration mechanisms, static geomodels, populated by Vshale (clay/shale volume), were derived for the Trim 3D seismic survey volume. Input data included seismic interpretation, basic well petrophysics and stratigraphic forward modelling scenarios. The model outputs enabled the faults to be tested with a range of possible shale gauge ratio related sealing scenarios (i.e. the amount of clay/shale in a fault determines its ability to form a seal against fluid movement). The most likely Vshale scenarios indicate that the Late Cretaceous Hammerhead Supersequence is at its most sensitive with respect to across fault seal (i.e. 0.1 to 0.25 SGR) in the vicinity of the Trim survey. It is likely that faults cutting sandier sections of the Hammerhead Supersequence in more proximal locations to this survey area will be less able to trap or prevent the movement of generated hydrocarbons, whilst those more muddy sections in more distal paleo-depositional settings may have more ability to trap hydrocarbons (Strand et al., 2017).

In the central Ceduna Sub-basin several mound complexes are interpreted from 2D seismic surveys and the Trim 3D seismic survey (Figure 1). Some of these mounds were previously interpreted as extrusive volcanics (Schofield & Totterdell, 2008). They are mainly located in the central Ceduna Sub-basin in an elongate zone, oriented north-south and approximately 80 km wide, to the east of the Trim 3D (Figure 1). Further east, biogenic mound complexes are absent and the Base Tertiary transition between siliciclastic and carbonate deposition is mainly characterised by extrusive volcanics (Schofield & Totterdell, 2008). As reported in Sharples et al. (2014), the mound complexes interpreted in the central Ceduna Sub-basin postdate the top Hammerhead unconformity. Their bases are usually found within or near the top of the thin Paleocene-Eocene Wobbegong Supersequence. The mound complexes are between 40 ms TWT and 180 ms TWT or 50 m and 200 m in height (Figure 2). The tops of the mounds and their internal seismic response are average to high amplitude suggesting a moderate to high impedance contrast with the surrounding sediments. The seismic amplitude can vary laterally within the mounds and the reflectors can become locally discontinuous. The mound complexes are distinct from deposits attributable to mass transport (e.g. debris flows, slides, and slumps) in having a generally higher amplitude, lower amplitude variation and more internal continuity (e.g. Moscardelli et al., 2006; Wu et al., 2011). They may be

differentiated from turbidites by the absence of a canyon or submarine feeder conduit and nearby stacked lobes and channels above lobes (e.g. Shanmugam & Moiola, 1988; Gervais et al, 2006); by the morphology of the bodies with turbidite lobes classically forming sheet-like deposits (e.g. Shanmugam & Moiola, 1991) and being elongate (e.g. Deptuck et al, 2008); and by the seismic facies within turbidites commonly exhibiting chaotic and discontinuous reflectors (sand) or flat parallel reflectors (mud) (Shanmugam & Moiola, 1988) that differ from the internal architecture observed in the central Ceduna Sub-basin.

Eocene to Pleistocene cold water biogenic mounds in the Eyre Sub-basin and on the Madura Shelf were constructed primarily by bryozoans (Feary & James, 1995, 1998; Feary et al., 2000; James et al., 2004). In the Potoroo-1 exploration well (Taylor, 1975) location in the northern Ceduna Sub-basin, Sharples et al. (2014) reported large Early Tertiary bryozoan mound complexes that they interpreted to exist along the paleobathymetric threshold provided by the paleo-shelf edge of the Paleocene to mid-Eocene post-rift Wobbegong delta. Bryozoan biogenic mounds are a recurring worldwide phenomenon throughout the Phanerozoic, and their origin is one of the most controversial topics in carbonate sedimentology (James et al, 2004). Their growth usually requires a low energy environment and an increased nutrient supply (e.g. Hageman et al, 2003; Sharples et al, 2014). There are numerous indications of links between benthic chemosynthetic communities, authigenic carbonates and petroleum seeps in the Gulf of Mexico, (Roberts & Aharon, 1994; Roberts et al., 2006; Cordes et al., 2008; Becker et al., 2009) and the Atlantic Ocean (Hovland et al., 1998; Henriet et al., 2001; Hovland & Risk, 2003; Pierre & Fouquet, 2007). Similar observations have been made on the Australian North West Shelf (e.g. O'Brien & Woods, 1995; Lavering & Jones, 2001; O'Brien et al., 2002; Langhi et al., 2010; Logan et al., 2010) where Hovland et al. (1994) suggested a link between the formation of Late Tertiary carbonate buildups and focussed hydrocarbon seepage up fault conduits and localised venting of gas at the seafloor in the Vulcan Sub-basin.

Although the development and growth of the Early Cenozoic mound complexes in the central Ceduna Sub-basin could be controlled by oceanographic processes, their distributions do not support a purely bathymetric control. As they overlie deep rooted faults, they may represent biogenic mounds associated with hydrocarbon leakage. However, further research and data collection is required to determine if this is the case.

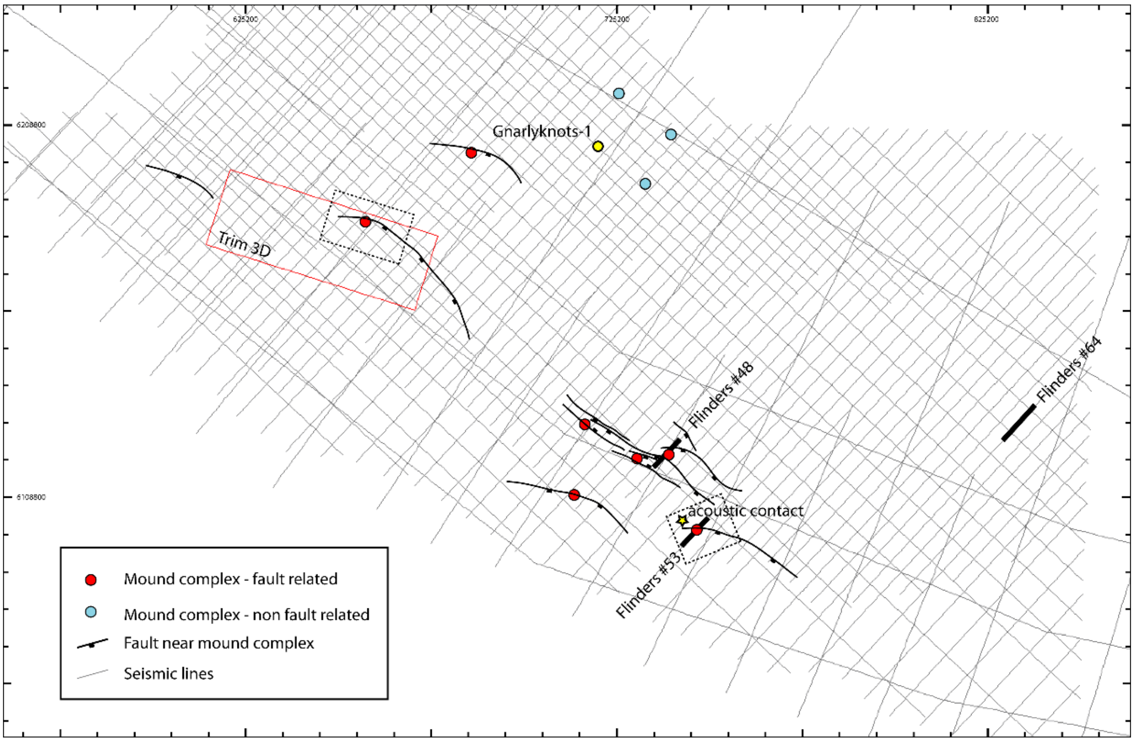

Figure 1 Mound complexes in the central Ceduna Sub-basin. Locations of Figure 36 and Figure 37 are shown near the acoustic contact and the Trim 3D survey, respectively.

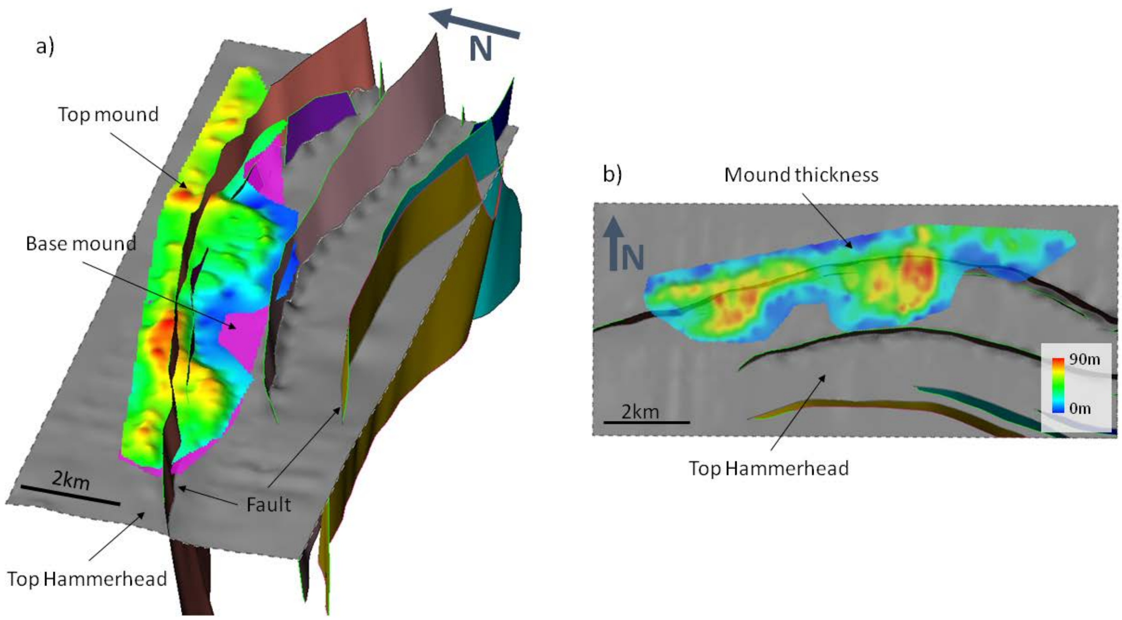

Figure 2 Interpreted mound complex on the Trim 3D seismic survey. A) 3D geometry of the mound complex. B) Thickness data showing the main parts of the mound complex developed on the hanging-wall compartment. Location shown in Figure 1.

Hydrocarbon baselines

There is a paucity of previous geochemical data on the water column and sediments of the GAB, especially for hydrocarbon species, with fewer than 200 surface sediment samples having been previously analysed from the shelf slope and deep waters (Hughes et al., 2009; Totterdell et al., 2009). These studies, which included organic geochemical analyses, failed to identify thermogenic hydrocarbons (Freary et al., 2004; Hughes et al., 2009; Totterdell et al., 2009). As part of the present study, an expansion of this dataset was identified as an important objective for understanding geochemical baseline conditions in the GAB. During the SS2013_C02 voyage, and associated M/V Southern Supporter voyage (Ahmed et al., 2014), samples were collected from the water column and seafloor at reference sites along the same five longitudinal transects constructed for biodiversity assessment in Themes 2 and 3 (Figure 3).

A suite of geochemical analyses were performed on these samples (Ahmed et al., 2014), the principal findings of which are summarised below:

- Quantitative analysis of solvent extracts isolated from seawater samples indicate that polycyclic aromatic hydrocarbons (PAHs) are largely absent in and around the BP permits in the GAB. Small amounts of naphthalene, a highly volatile bicyclic aromatic hydrocarbon, detected in the majority of the samples, was probably a contaminant cumulatively inherited from solvents, glassware and/or unknown source(s).
- Qualitative analyses of extractable organic matter isolated from seawater, seabed sediment, and GO net samples, and headspace gases extracted from multicore/piston core samples reveal that petroleum hydrocarbons are either absent or below the limits of detection, in and around the sampling sites.
- Two push core water samples contained low to moderate amounts of petroleum hydrocarbons. Preliminary geochemical data provide a tentative indication of their generation within the peak oil window from a source rock originally deposited in an anoxic to suboxic environment. Due to the absence of any known oil seepage around the surveyed sampling sites, it is very likely that these trace amount of hydrocarbons are inherited from a contaminant oil of an unknown source.
- The seabed sediment samples contain variable amounts of extractable organic matter, (ranging from ≈ 2 to 3200 mg EOM/kg of sediment, with one sample yielding no extractable organic matter), but did not include any detectable quantities of petroleum hydrocarbons. It is likely that this EOM is composed almost entirely of lipids and/or functionalised organic compounds from recent organic matter.
- The aliphatic and aromatic hydrocarbon distributions of EOM isolated from the GO net sample and GO net blank are very similar and resemble those of a typical crude oil. It is very likely that hydrocarbons from these two samples represent some contaminant oil, and not natural seepage.
- The headspace gas samples analysed do not contain any detectable amounts of petroleum hydrocarbons (i.e., methane, ethane, etc.). CO_2 gas detected in samples ranged from low to very high amounts (≈1 to 50 %), and had highly variable $\delta^{13}C_{CO2}$ values. The isotopic data indicate an origin of the Southern Surveyor CO_2 gas from magmatic sources and the Southern Supporter CO_2 gas from mixed magmatic and recent organic matter sources.

These samples from key reference stations developed for the GABRP illustrate the natural hydrocarbon loadings in the water column and seabed of the GAB and can be augmented with additional studies in the future.

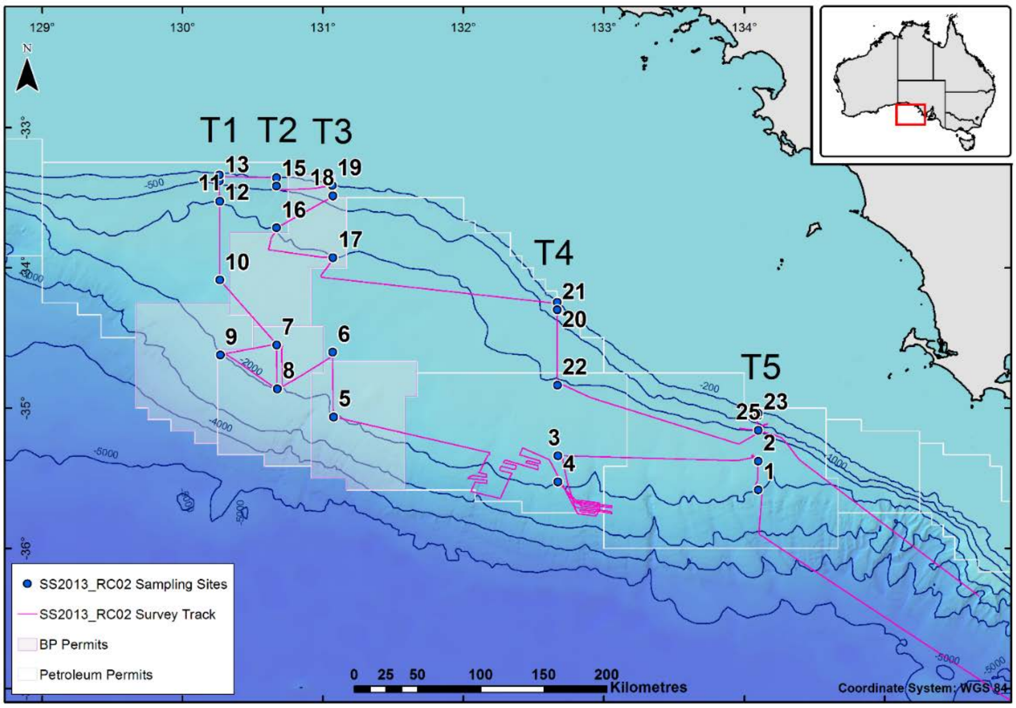

Figure 3 Map of the central and eastern GAB regions showing the 25 sampling stations (blue circles) on five transects (T1-5).

3.2 Project (5.2): Asphaltite and tar ball surveys

3.2.1 Objectives

To better constrain the provenance of natural coastal bitumen in the GAB region, Project 5.2 aimed to address the following key knowledge gaps identified within the literature:

1. The contemporary natural hydrocarbon loading of the South Australian coastline.

2. The sites of most frequent present-day (as opposed to historical) stranding of asphaltite and tarballs, and their geographic relationship to offshore sea-surface currents.

3. The molecular and isotopic characteristics of a statistically significant population of freshly stranded asphaltites, necessary to determine their degree of weathering and hence their proximity to the parent seep(s).

In order to address these knowledge gaps, the objectives of Project 5.2 were to:

1. Map and quantify the contemporary natural hydrocarbon loading of selected ocean beaches on Eyre Peninsula, Kangaroo Island and the Limestone Coast. The latter two areas are known sites for the regular stranding of asphaltites, waxy bitumens (tarballs) and/or oil slicks. The collection of tarballs and asphaltites on the beaches of South Australia would allow their geochemistry to be

documented, and their probable origins to be ascertained using oceanographic and geological models.

Establishing the present-day hydrocarbon loading of the South Australian coastline (its geographic distribution, concentration in kg/km, compositional heterogeneity and principal sources) would act as a baseline against which the environmental impact of any potential spill arising from future activity in the GAB can be measured, and also serve as a predictive template for the likely destination(s) of such spill.

2. Identify the provenance and weathering of the asphaltites and any non-Indonesian tarballs and oil slicks using their elemental, isotopic and molecular fingerprints. In particular, their source and maturity-specific parameters will provide essential clues to their origin. These data, in combination with stranding distributions (GABRP Project 5.2 objective 1); oceanographic modelling based on detailed knowledge of the sea-surface currents traversing the continental margin of South Australia, including zones of upwelling (Oceanography Theme); geological interpretations of leakage indicators and offshore seepage studies (Seeps and leakage GABRP Project 5.1); and other petroleum migration, timing and accumulation indicators (Fluid Inclusions, GABRP Project 5.3), would help delineate possible seafloor hydrocarbon leakage points within GAB.

3.2.2 Key results and discussion

Establishing distribution and abundance

The study was the first multi-annual geospatial, geochemical and oceanographic study of the stranding of coastal bitumen (asphaltite and tar balls) on representative ocean beaches (n = 31) along the entire coastline of South Australia (Figure 4). Previous investigations of this phenomenon, dating back to the mid-1800s, were episodic and limited to beaches on the Limestone Coast, southern Kangaroo Island and the foot of Eyre Peninsula. The present study revisited the same 31 beaches after winter in 2014, 2015 and 2016, collecting a total of 631 specimens, and in so doing filled a major gap in our knowledge of bitumen stranding along the western side of Eyre Peninsula to the head of the Great Australian Bight (Ross et al., 2017b).

This investigation employed an updated version of the NOAA SCAT method for assessing shoreline oiling conditions in order to establish the natural baseline hydrocarbon loading of the South Australian coastline. Major findings from this part of the project are:

- Tar balls (waxy bitumen) preferentially strand in the upper intertidal to upper shore zones of southwest-facing ocean beaches, whereas the less common, denser asphaltites tend to accumulate on beaches with a northwest aspect.
- The number and size of individual strandings is considerably less than reported for the period 1960-1995.
- Waxy bitumens strand along the entire South Australian shoreline, with a particular focus on the Limestone Coast (Figure 5).
- Asphaltites are more commonly found along the west coast of Eyre Peninsula, suggesting different transport mechanisms and/or a different point of origin (Figure 6).
- The high abundance of waxy bitumens with geochemical similarities to Indonesian-sourced oils is consistent with the transport of these materials as flotsam, first in the southward Leeuwin Current which then feeds into the eastward-flowing Coastal and South Australian currents.

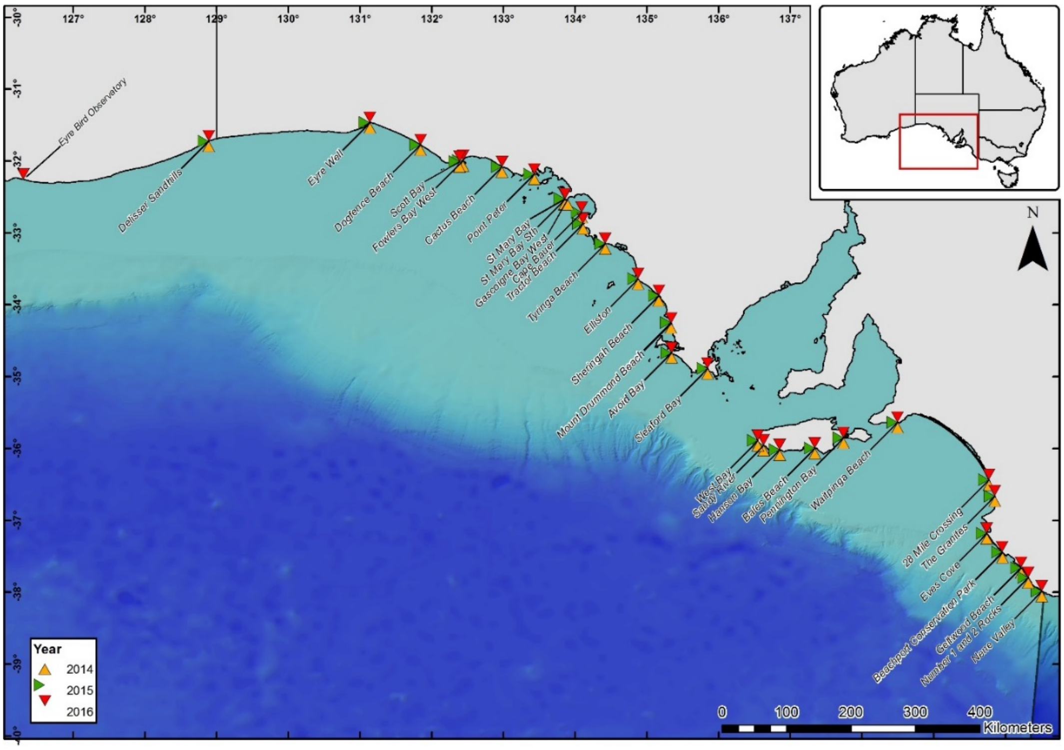

Figure 4: Beaches visited during the 2014 / 2015 / 2016 seasons.

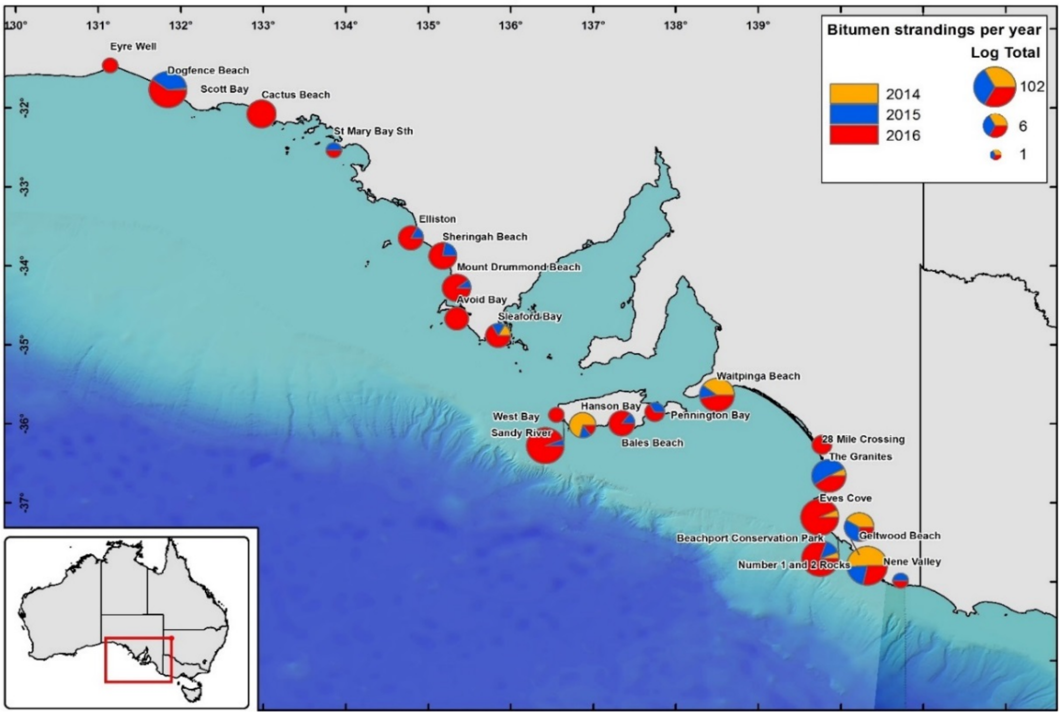

Figure 5: Total tarball strandings and distribution per year on a log scale.

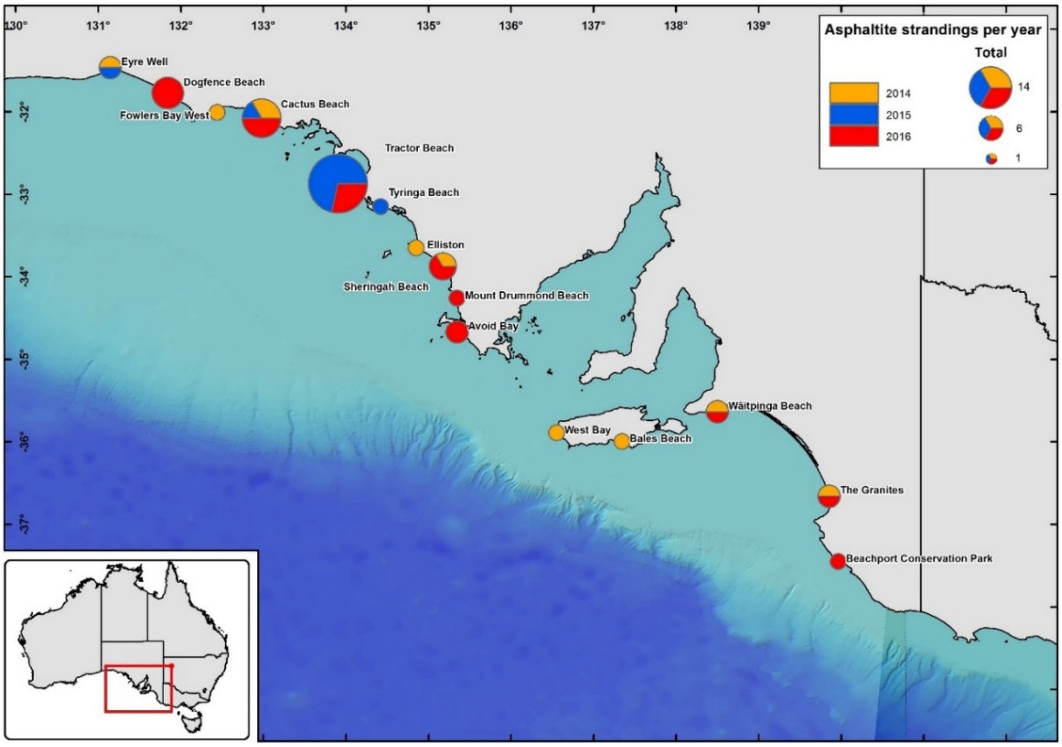

Figure 6: Total asphaltite strandings and distribution per year.

Understanding source affinity and alteration

The resulting catalogued collection of asphaltites and tar balls, the largest yet assembled for any geochemical investigation of this type in Australia, underwent detailed physical, elemental, isotopic and biomarker characterisation. The principal findings of this work are:

- Fifteen oil families and sub-families of South Australian coastal bitumen were identified, significantly more than the six families known from previous studies (Figure 7).
- The waxy bitumens differ from those found along the same coastline between 1960 and 1995 in being much more weathered and biodegraded, consistent with both their smaller size and lesser numbers (Figure 8).
- Soft asphaltic bitumen recovered from a site on the Limestone Coast is unique, and likely represents an early expulsion product from a Cretaceous marine source rock similar to that which gave rise to the asphaltites. Both point to the likely existence of an active petroleum system in the Bight Basin.
- The majority of the waxy bitumens have distinctive Cenozoic lacustrine biomarker signatures which mark their origin from distant offshore oil seeps in the Indonesian Archipelago.
- The abundance of both asphaltite and waxy bitumen stranding on South Australian beaches has declined dramatically over the past 20+ years, attesting to a diminution of seep activity and/or, in the case of the latter, improved environmental practices related to tanker washing and oil spillage within Indonesian waters.
- At least two waxy bitumen sub-families lack Indonesian signatures and could therefore originate from seeps in offshore basins along Australia's western and southern continental margin.

- The discovery of several new oil families of non-Indonesian provenance among the ocean wanderer bitumens that impact the South Australian coastline has potentially important implications for the prospectivity of its offshore sedimentary basins.

Oceanographic transport

For the first time, oceanographic modelling was employed to develop an understanding of the transport of coastal bitumens in the Great Australian Bight. The findings show that:

- Oceanographic models, which simulate currents alone, do not adequately account for the observed stranding locations of tarballs and asphaltite.
- Models which simulate both currents and Stokes drift (the effect of water movement by wind driven waves) can better describe their stranding locations across the region.
- Winter strandings are dominated by materials transported from west to east by the Leeuwin Current and storms.
- The winter modelled conditions can supply materials to all of the beaches in the GAB from areas along the shelf break at the western extent of the model, consistent with the discovery of Indonesian-sourced waxy bitumens on all the beaches surveyed.
- The winter modelling shows that there is a low probability of bitumens sourced in the Ceduna or Duntroon sub-basins reaching the coastline at the Head of the Bight and on the northern Eyre Peninsula.
- Summer strandings are dominated by materials transported from the southeast by Stokes drift caused by strong northerly to northwesterly winds.
- Throughout all seasons there is a low probability of any materials sourced in the Morum Sub-basin travelling to the west of Kangaroo Island and encountering the ocean beaches on Eyre Peninsula.
- The area with the highest frequency of particle tracks is located to the west of Kangaroo Island and overlies the Duntroon Sub-basin and the eastern part of the Ceduna Sub-basin.
- Any locally derived materials within this area can reach all beaches in the study area and there is seismic support for potential leakage indicators in this area.

These research findings have addressed and exceeded the original project objectives and offer an unprecedented insight into the transport mechanisms, stranding processes, alteration and source of bitumens which are found along the coastlines of South Australia. The data produced forms an important, and continuing, baseline for hydrocarbon loadings on the beaches of South Australia and, whilst a definitive origin of the new tarball oil families and asphaltites has not been established, they provide evidence of active hitherto unknown regional petroleum systems.

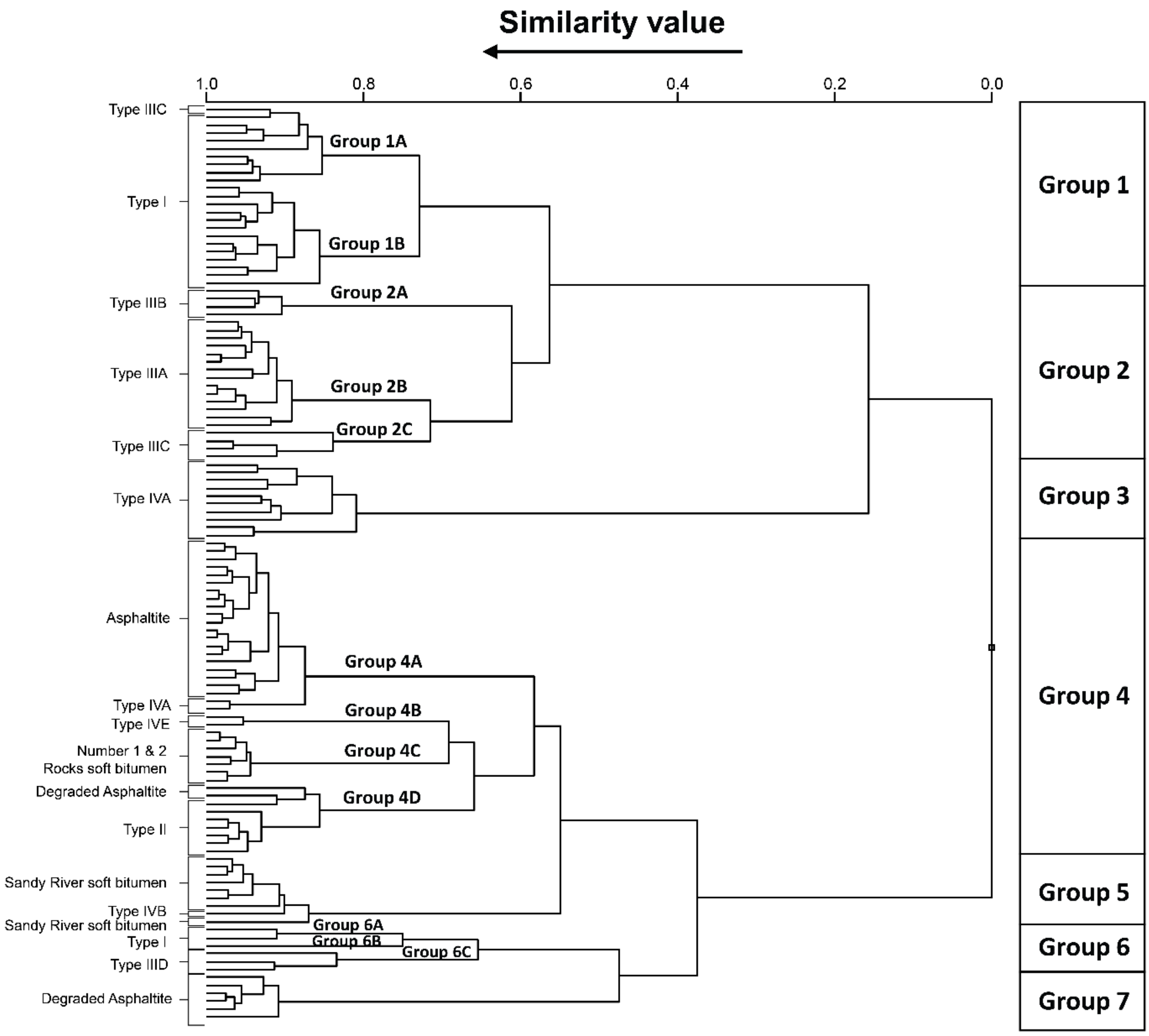

Figure 7: Hierarchical cluster analysis (HCA) of coastal bitumen samples. Left hand labels correspond to the individual oil families identified.

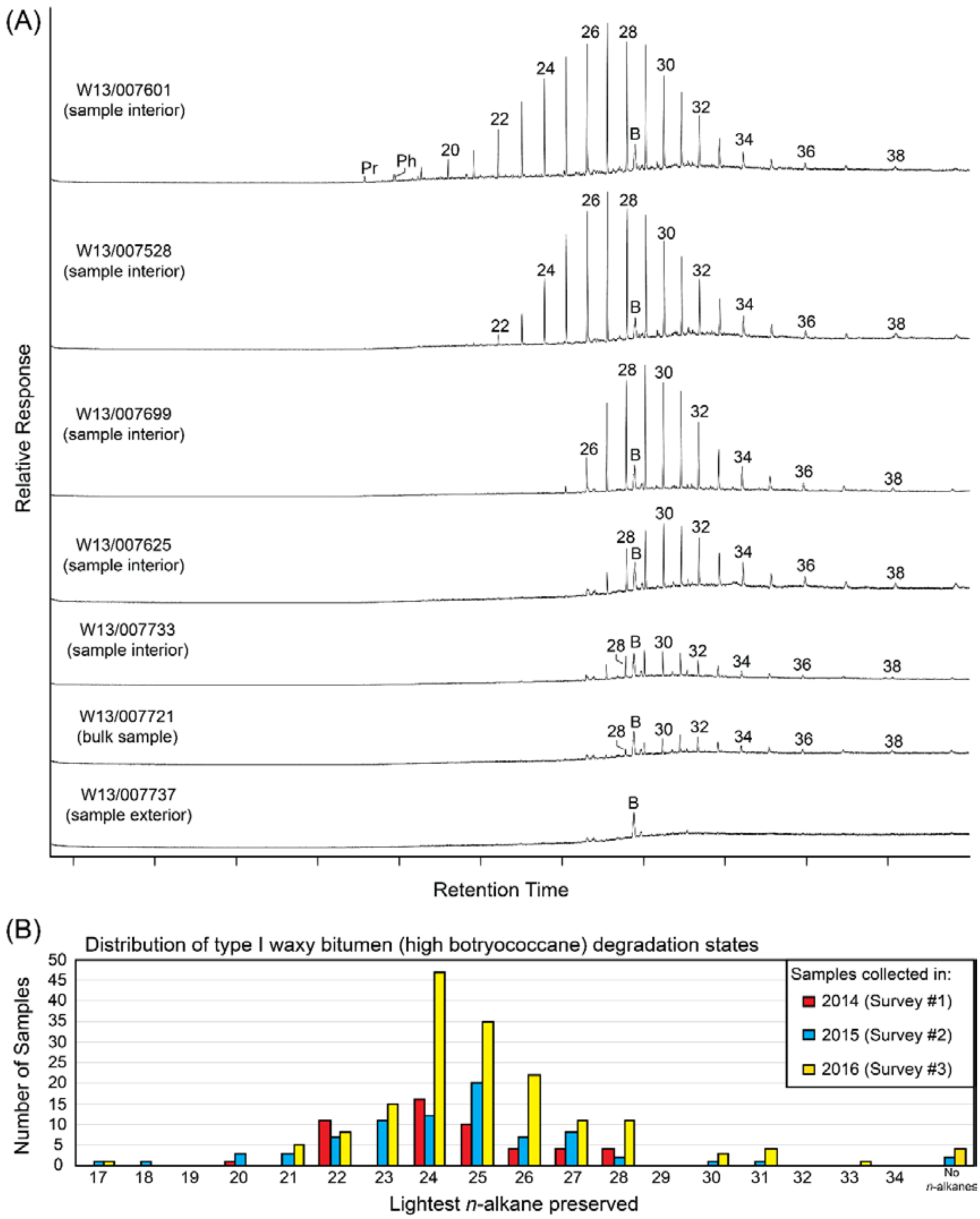

Figure 8: Degradation overview for Type I waxy bitumen (high botryococcane). Each chromatogram is scaled such that no compound which is not a product of biodegradation may have a higher response than the freshest sample. (A) Representative examples of degradation states revealed by whole-oil GC-MS analysis. (B) Histogram plot of the lightest preserved *n*-alkane from each beach survey.

3.3 Project (5.3): Fluid inclusion study

3.3.1 Objectives

The perceived risk of hydrocarbon charge in the Bight Basin was a significant driver for undertaking detailed fluid inclusion-based studies of oil/gas migration. The outputs of this project were ultimately intended to provide source-analogues of locally derived liquid hydrocarbons for comparison with the coastal bitumen strandings in the GAB (Project 5.2).

The petroleum system is a core concept of petroleum geology that consists of a mature source rock, migration pathway, reservoir rock, trap and seal. Appropriate relative timing of formation of these elements and the processes of generation, migration and accumulation are necessary for hydrocarbons to accumulate and be preserved.

In this context, the main objectives of Project 5.3 were to constrain several key elements of the petroleum system(s) in the GAB. Unlike conventional basin modelling approaches, an important factor for this project was to acquire baseline data directly from the rocks.

1. MIGRATION: detect hidden hydrocarbon migration pathways in the GAB.
2. SOURCE: obtain source-specific molecular fingerprint data from fluid inclusions (oil and gas) to identify probable source rock types.
3. TIMING: constrain the timing of hydrocarbon migration events from pressure-temperature reconstructions.

3.3.2 Key results and discussion

Hydrocarbon occurrence and migration

To screen the Bight Basin for hidden hydrocarbon indications, 36 samples were analysed from 7 historic exploration wells Potoroo-1, and the previously untested Gnarlyknots-1A in the central Ceduna Sub-Basin; and Borda-1, Duntroon-1, Greenly-1, Jerboa-1 and Platypus-1 in the eastern Ceduna and Duntroon sub-basins–using CSIRO's Grains with Oil Inclusions (GOI™) technique.

The identification of oil-bearing (and in some samples gas-rich) inclusions at low abundance (GOI <0.7%, up to a maximum of 1.1% in Greenly-1) is positive evidence for widespread oil and gas migration in the Bight Basin. These hidden oil indications (Figure 10) are more common in the Late Cretaceous White Pointer, Tiger and Hammerhead supersequences and are a significant improvement over conventional oil indications that are limited to Greenly-1 (Kempton et al., 2017). The presence of these hydrocarbon inclusions implies generation and expulsion from active petroleum systems, and therefore the presence of effective source rocks. Their discovery improves the GAB's exploration potential, particularly in the poorly understood deep-water part of the Ceduna Sub-basin. In attempting to integrate previous GOI results into this investigation, palaeo-oil zones in Jerboa-1 from the Eyre Sub-basin are no longer supported by repeat GOI measurements.

Hydrocarbon source

To geochemically fingerprint their hydrocarbons, CSIRO's Molecular Composition of oil Inclusions (MCI) and gas-isotope techniques were applied to the minute quantities of oil and gas extracted from the aforementioned fluid inclusions. Fluid inclusion (FI) oil from Gnarlyknots-1A (4,390 to 4,425 mMD; Tiger Supersequence, Figure 11) comprises a mixture of types, including oil and gas-condensate. Their n-alkane and biomarker characteristics show a mixed organic matter input from both algae and terrestrial plants to the source rock(s) that were deposited in suboxic-oxic marine

environment(s). The wide range of maturities, 0.65% to 1.3% equivalent vitrinite reflectance (VRE), in the Gnarlyknots-1A FI oil suggests either a mixture of oils generated from different source rocks– Blue Whale and Tiger having a potential marine algal input, and White Pointer a potential terrestrial plant input – or from the same source rock at different maturity stages–, perhaps an unrecognised paralic facies of the White Pointer, containing both algal and terrestrial organic matter. Either way, the recognition of some algal input is the first direct evidence for generation from rocks containing Type II kerogen and this significantly improves the prospectivity in the deepwater Ceduna Sub-basin. The light gasoline-range hydrocarbons are dominated by toluene and originated, in part, from coeval aqueous inclusions. The δ13C isotopic compositions of methane (-28.4 ‰ and -28.6 ‰ replicates) and ethane (-17.6 ‰ and 18.1 ‰ replicates) indicate a thermogenic origin for these gases, probably derived from Type III (humic/coaly) organic matter. The δ13C isotopic composition of carbon dioxide (-3.9 ‰ and -4.4 ‰ replicates) indicates a wholly inorganic origin from inherited inclusions of probable magmatic or metamorphic sources.

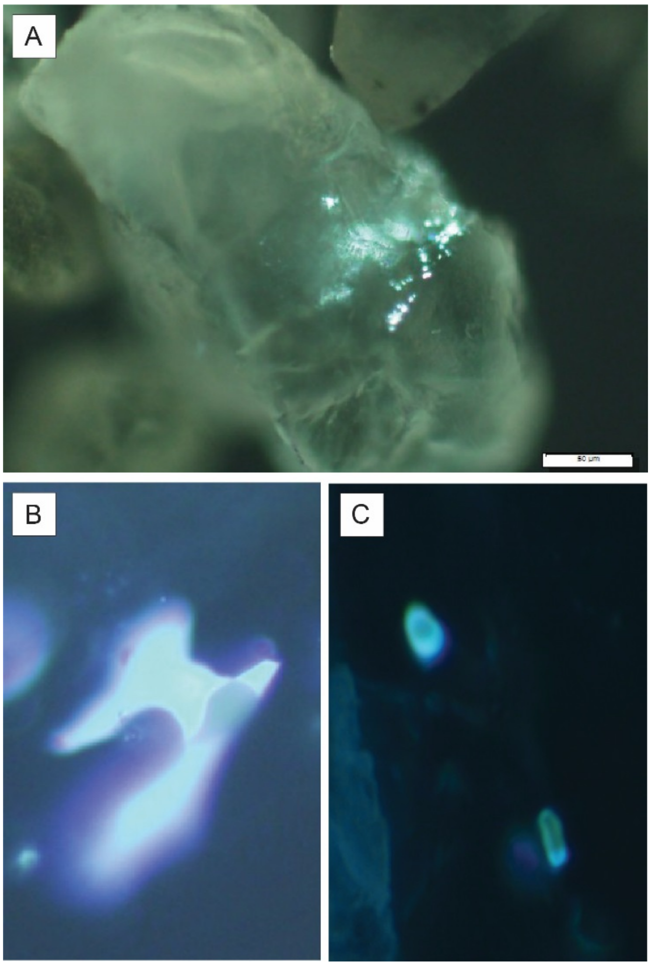

Figure 9. Hydrocarbon inclusions in Gnarlyknots-1A. (A) Detrital quartz grain with oil inclusions (4410-15 mMD). (B) Photomicrograph of an oil inclusion (2535-40 mMD). (C) Photomicrograph of oil-bearing gas-condensate inclusions (4410-15 mMD).

By comparison, FI oil from Greenly-1 (4,806-4,818 mMD; White Pointer Supersequence, Figure 11) comprises only oil, with no gas-condensate visually detected. The n-alkane and biomarker characteristics indicate significant organic matter input from terrestrial plants, and a minor bacterial

contribution, and generation from a source rock deposited in an oxic, clay-rich fluvio/deltaic environment. This FI oil represents a pristine oil sample that was generated over a narrow maturity range within the early to peak oil window (0.8 to 1.1% VRE), and lacks the mixed algal input of the current oil indications in the same well.

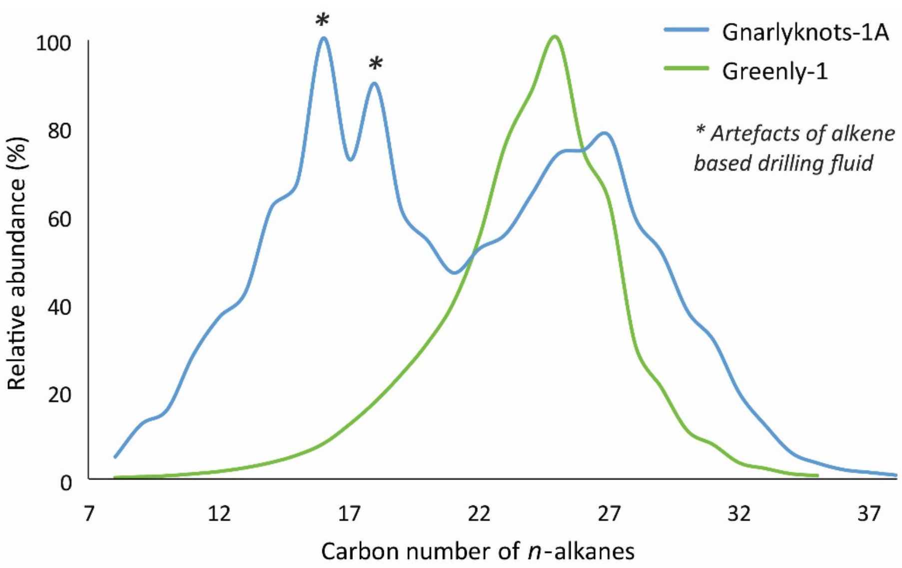

Figure 10. Comparison of normalized n-alkane distributions in the Gnarlyknots-1A (4390-4425 mMD) and Greenly-1 (4806-4818 mMD) FI oils.

Timing of hydrocarbon migration

To understand the timing of oil migration, the pressure-temperature (PT) trapping conditions of hydrocarbon inclusions were determined in Gnarlyknots-1A, Greenly-1, Duntroon-1 and Potoroo-1. The intra-Coniacian primary target in Gnarlyknots-1A (4,410-4,415 mMD; Tiger Supersequence, Figure 12) was a migration pathway, over an extended period of time, for a variety of hydrocarbon fluid compositions modelled by Petroleum Inclusion Thermodynamic (PIT) as black oil, light oil, gas-condensate and gas+CO2. There is good concordance of the measured PT data with independent PT curves from basin models. The earliest oil entrapment took place at a minimum of 58°C, with constrained PT conditions of light oil (240-270 bar; 69.2°C) in the Late Cretaceous at ~70-75 Ma (Campanian). Phase separation of light oil, and entrapment of both gas-rich phases and gas-depleted black oil, occurred at PT conditions (285-308 bar; 80-85°C) consistent with the Late Cretaceous at ~70 Ma (Maastrichtian). Subsequent entrapment of gas-condensate took place at pressure conditions (350-410 bar; 80°C) reached later at ~35-15 Ma (Oligocene to Early Miocene), followed by gas+CO2 at PT conditions (370-408 bar; 78-88°C) reached at ~27-15 Ma (Late Oligocene to Early Miocene, Figure 12). This apparent sequence of hydrocarbon entrapment from oil to gas over time might simply be explained by generation from a single mixed organic source unit over a range of thermal maturity stages–perhaps an unrecognised paralic facies of the White Pointer The earlier oil-rich assemblages are easily explained by sediment loading of the Upper Cretaceous succession by the Hammerhead Supersequence, but a mechanism for generation of later stage gas-rich inclusions, plus late stage oil, in the Miocene is less clear.

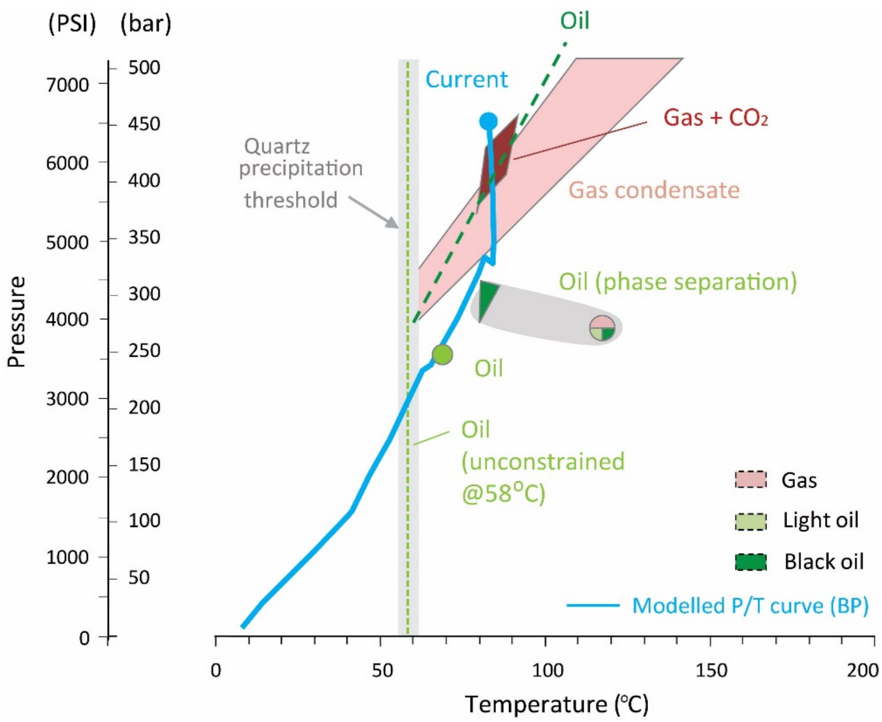

Figure 11. Fluid inclusion *PT* data on oil and gas-bearing inclusions assemblages from Gnarlyknots-1A (4410-15 mMD). The modelled *PT* curve is a 1D extract from a 3D model at closest depth point.

The Cenomanian interval in Greenly-1 (4,808-4,812 mMD; Tiger Supersquence) trapped remarkably consistent hydrocarbon assemblages modelled by PIT as black oil. While this consistency is also reflected in the measured PT entrapment conditions (270-340 bar; 127-135°C), they are not concordant with an independently modelled PT curve. If the temperatures reflect the entrapment conditions, then this constrains oil charge from the Early Miocene (~23 Ma onwards) and at a depth equivalent to about 2 km less than modelled. Tertiary carbonate progrades over the Late Cretaceous deltas, and rapid burial peaking around 15 Ma, might help to explain this. If, however, the pressures reflect the entrapment conditions, then this possibly constrains oil charge in Greenly-1 to the Campanian–early Eocene (~75-52 Ma) and temperatures about 30°C higher than modelled. One explanation might be a transient period of hotter fluids that were in thermal disequilibrium with the rock.

The Turonian-Santonian interval in Duntroon-1 (2,505-10 mMD; Tiger Supersequence) and the Cenomanian-Santonian interval in Potoroo-1 (1,778-86 mMD; Tiger Supersquence) were migration pathways for a variety of hydrocarbon fluid compositions modelled by PIT as black oil, light oil and, in the case of Duntroon-1, gas (+N2 and CO2). In both these wells, on the shallower margins of the basin, hydrocarbon charge appears to be late. Because pressure evolution over much of the Cenozoic in Duntroon-1 was static, temperature constraints (81-95°C) suggest entrapment of oil from the mid Miocene (~17 Ma). CO2 and N2 rich hydrocarbon gases entrapped in the Holocene potentially have volcanic origins similar to those in the Otway Basin (McKirdy & Chivas, 1992). In Potoroo-1, hydrocarbon entrapment occurred either from the Oligocene (~32 Ma), or from the Early Miocene (~25 Ma), to the present.

Multivariate statistical analysis of source-related biomarker data on the Gnarlyknots-1A and Greenly-1 FI oils, reveals that neither is closely related to the asphaltites that naturally strand along the South Australian coast and are postulated to have a local southern margin origin. Nor are the FI oil is also

not closely related to any waxy bitumen type. While the majority of waxy bitumens have distinctive biomarker signatures indicative of an origin within the Indonesian Archipelago and therefore transport into southern Australian waters by a complex system of surface ocean currents, there are other waxy bitumen types which lack these diagnostic biomarkers.

This study has, for the first time, proven the existence of migrated hydrocarbons in the central deepwater region of the Ceduna Sub-basin, the primary focus of the renewed exploration activities in the Bight Basin. In addition, through geochemical analysis of the composition of both liquids and gases there is now a clearer understanding of possible hydrocarbon kitchens that may have generated these hydrocarbons, including the eastern Ceduna and Duntroon sub-basins. Detailed new information on the timing of entrapment and oil type has placed constraints on when hydrocarbon charge took place which, in turn, helps to validate petroleum systems models. The outcomes of this project have significantly enhanced prospectivity and reduced exploration risks within the Bight Basin.

4. CONTRIBUTION TO THE GABRP

Theme 5 received significant research contributions from Theme 1 - Physical Oceanography of the Great Australian Bight: the science that underpins - in developing and understanding of the offshore transport mechanisms for the bitumens that naturally strand along the coastline of South Australia.

Close collaboration of the Theme 1 and Theme 5 teams led to the development of a conceptual model of tar ball and asphaltite behaviour and the selection of both representative offshore seeding locations and representative seeding beaches.

Several sets of particle tracking studies were undertaken for the specific purpose of providing information to Theme 5. These were:

1) General connectivity studies conducted using ROMS (as detailed above). These were forward tracking studies using neutrally buoyant particles: as a proxy for asphaltites.
2) A second set of forward tracking ROMS/BRAN2015 studies with the origins of the particles assumed to be known or using suspected sites of deep-water hydrocarbon seepage.
3) Backward tracking studies of tar balls conducted using the global BRAN model and Wavewatch III estimates of surface Stokes drift from Theme 1 (Project 1.2).

Results of these studies allowed the determination of possible origins for the asphaltites and tar balls and the processes responsible for the wide distribution of coastal bitumen observed along the South Australian shoreline. The studies permitted the Theme 1 researchers to trial a number of particle tracking simulations and develop an understanding of the relative impacts on these surface drifters of the various physical and circulation processes operating in the GAB. The multidisciplinary approach and combination of skill sets employed in this work have been instrumental in advancing our understanding of coastal bitumen distributions.

During planning of the GRBRP's marine research voyages the Theme 5 team provided advice and support to other researchers in Themes 2 and 3 on the identification of geological features of possible interest on the seafloor. Theme 5 team members participated in the SS2013_C02 voyage, conducting hydrocarbon sensor and sampling operations. They also interpreted bathymetry data collected during the 2013 and 2015 research voyages providing these interpretations to Theme 3 to in the characterisation of the seafloor habitats. Geochemical data on water and sediment samples

has been used by Theme 3 microbiologists to understand the influence of hydrocarbon concentration on benthic microbial assemblages.

5. CONCLUSION

The Bight Basin encompasses an offshore area of 804,000 km^2 and contains a 15 km sedimentary sequence. This vast under-explored region represents one of Australia’s most prospective frontier hydrocarbon exploration provinces.

The objectives of Theme 5 were to compile evidence for the presence of hydrocarbons in the subsurface; understand the mechanisms responsible for fluid movement; identify sites of potential seepage, and characterise the natural coastal bitumen that strand along the shorelines of South Australia. The ultimate aims of this research were to define potential petroleum systems in the basin and to provide qualitative and quantitative baseline hydrocarbon data of use in de-risking exploration activities in the region.

Petroleum systems

The research outcomes of Theme 5 have demonstrated the existence of active hydrocarbon systems, not only on the flanks of the Ceduna and Duntroon sub-basins but also in the deep-water central Ceduna Sub-basin.

The determination of trapping pressures and temperatures, and the geochemical characterisation of fluid inclusion assemblages have provided detailed insights into the source of the trapped hydrocarbons and the timing of their movement in the subsurface. Together these data provide robust proof of several key elements of one or more petroleum systems (viz. source and migration) in the Late Cretaceous of the Bight Basin.

Coupled fault-seal and sedimentary forward modelling of this sequence in the central deep-water Ceduna Sub-basin has shown the sensitivity of the sealing ability of subsurface faults to the net-to-gross (sand-shale) relationships. This helps with an understanding of faults as either barriers or conduits to cross-fault fluid migration. Some of these faults may have also acted as up-fault paleo-leakage conduits, where they are capped by interpreted biogenic mounds that are constrained as having formed during the Eocene. These features may be related to paleo-hydrocarbon seepage. Whilst the research voyages undertaken as part of the GABRP did not identify unequivocal evidence of present-day seepage, they did reveal a complex seabed geomorphology which warrants further investigation.

Oceanographic modelling of coastal bitumen transport revealed the importance of not only currents, but also Stokes drift, in controlling the distribution of these materials across the GAB. The modelling has also shown that there is a low likelihood that asphaltites are being sourced from the Morum Sub-basin. The beach surveys have for the first time rigorously investigated the Eyre Peninsula, significantly extending the known geographic extent of coastal bitumen stranding. These lines of enquiry, combined with detailed geochemical characterisation, have led to a much more explicit linkage of many of the waxy bitumen to oil families in Indonesian basins, as well as to the identification of at least two sub-families that lack Indonesian signatures. Together with asphaltites of as yet the unknown origin the latter may be products of seafloor seeps in offshore basins along Australia's western and southern continental margin.

Hydrocarbon baseline characterisation

Sediments and water samples collected from the longitudinal depth stratified transects across the GAB represent a significant addition to the knowledge of baseline hydrocarbon concentrations and compositions in the region. This information comprises an important reference dataset which can be augmented into the future.

The quantification, and geochemical characterisation, of the coastal bitumen currently stranding on the ocean beaches of South Australia serves as an important benchmark. Its comparison with historical data reveals that the natural hydrocarbon loadings of the coastline appears to be diminishing.

Knowledge gaps and future work

Whilst this research has significantly advanced our knowledge of the geology, petroleum systems and baseline hydrocarbon abundance in the sediments and waters of the GAB and on the beaches of South Australia, many knowledge gaps remain.

These include:

- Fluid inclusion data are suggestive of late-stage migration of hydrocarbons to the margins of the Ceduna and Duntroon sub-basins. In addition, the oceanographic modelling has shown that the highest number of particle tracks cross the Duntoon Sub-basin. This suggests that if seepage is occurring in the basin it may be associated with faults along the inboard proximal section of the basin. These areas have not previously been surveyed for the presence of active seeps.
- On the completion of the next phase of exploration drilling, additional fluid inclusion studies, in combination with petroleum systems modelling, would further constrain the petroleum systems in the region.
- Whilst the GABRP has collected valuable baseline hydrocarbon data, sampling is sparse and no hydrocarbon seeps were identified or sampled. The range and variability of hydrocarbon concentrations in the sediments and waters of the GAB is therefore unlikely to have been adequately documented.
- Three successive annual surveys of representative ocean beaches along the entire coastline of South Australia have identified a much wider geographic spread of bitumen strandings than previously shown, as well as identifying probable stranding mechanisms. Expanding the surveys and oceanographic modelling to encompass the Western Australian side of the GAB, would allow better definition of potential origins as well an ability to predictively determine where stranding may occur and where materials accumulate on these beaches. This would be important in the unlikely event of an offshore incident where an understanding of probable shoreline impact would be required.

The research undertaken in Theme 5 of the GABRP has been successful in addressing the objectives of the theme. The research outcomes have not only identified and characterised hitherto unidentified petroleum systems but have also collected important baseline datasets. These findings will help reduce the risks pertaining to further exploration within the GAB and also provide valuable information on the hydrocarbons already known to exist in the Bight Basin.

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