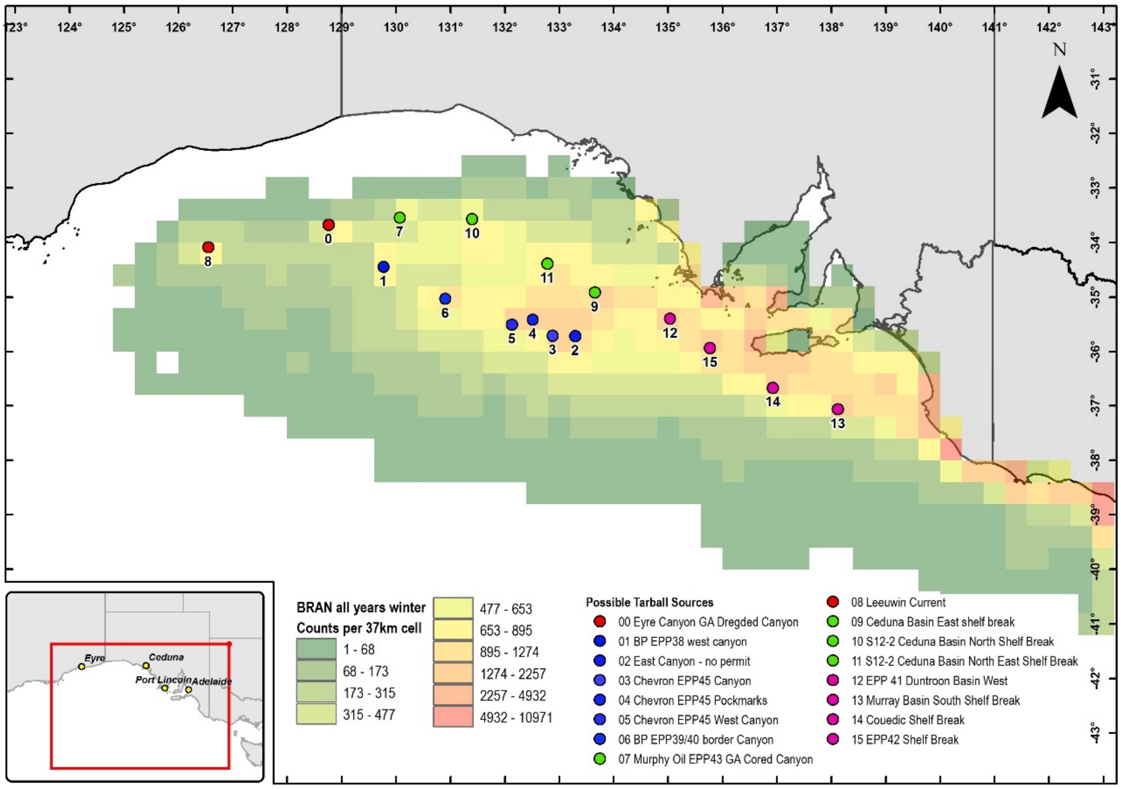

Figure 176: Heat map showing cumulative offshore seeded particles location for 2011–2016 April-September using BRAN2015.

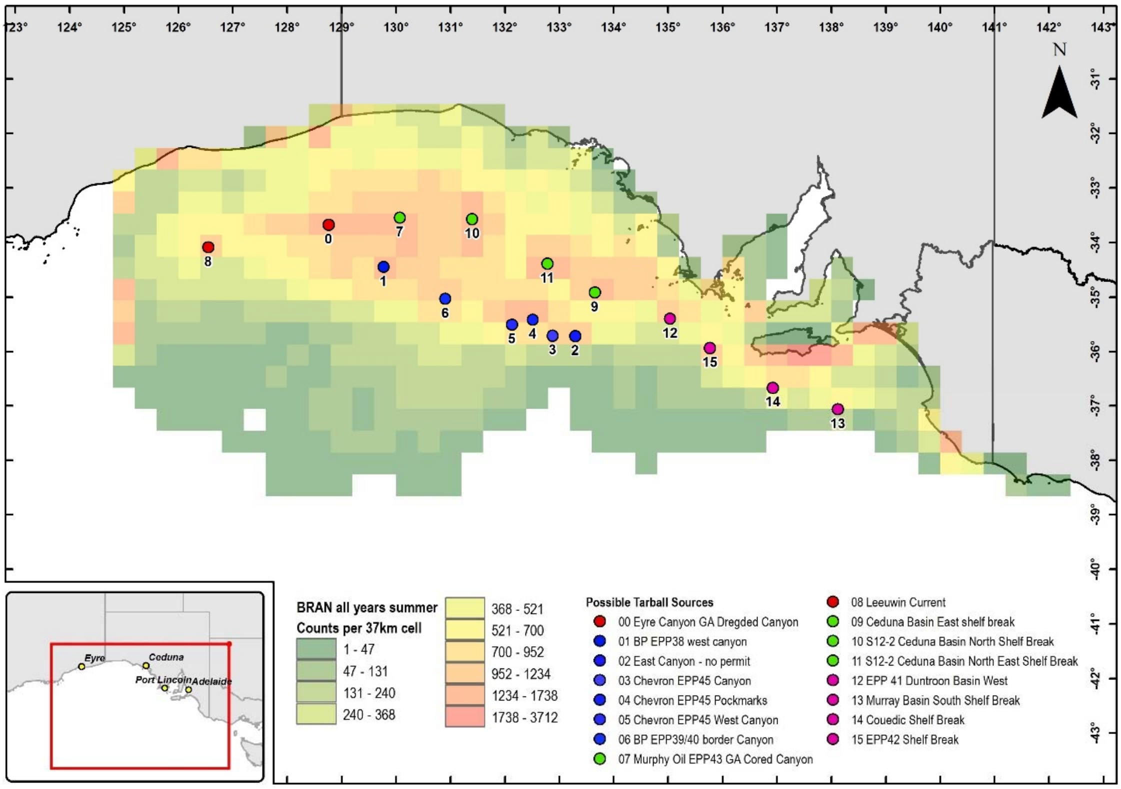

Figure 177: Heat map showing cumulative offshore seeded particles locations for 2011–2011 October-March using BRAN2015.

Finally, particles released over the Duntroon sub-basin and Morum sub-basin (pink points) typically encounter the Limestone Coast and Kangaroo Island during winter conditions. During summer conditions particle trajectories take two main routes. Particles seeded to the southeast of Kangaroo Island (Morum sub-basin) typically encounter the beaches of the Fleurieu Peninsula and Kangaroo Island, but do not travel further west. Those particles seeded to the west of Kangaroo Island during summer conditions have trajectories can permit the particles to encounter all of the beaches along the Eyre Peninsula, including those at the Head of the Bight.

If there is an offshore origin of coastal bitumens in the GAB, the results of these forward models suggest that those arriving on the coastlines of the Eyre Peninsula during the summer months are most likely to originate from the eastern Ceduna or Duntroon sub-basin. In addition, the models also suggest that the peak stranding time for any GAB-sourced coastal bitumens along the Northern Eyre Pennisula coastline may be the summer months, whilst along the southern Eyre Pennisula through to the Limestone Coast winter conditions would lead to the highest stranding frequency, which has been confirmed by prior studies (Edwards et al., 2016).

Scenario 3 – Back track models

The BRAN2015 backtrack modelling of beach-seeded particle trajectories over 3-month periods between January 2011 and December 2016 once again showed significant differences between winter and summer trajectories across all of the years modelled. The BRAN2015 modelled 3-month model results for 2014-2016 are shown in Figure 178-180. The modelling results for 2011–2013 are included in APPENDIX 8: BRAN MAPS FOR 2011, 2012 and 2013. These results are more difficult to interpret as beach origin of the seeded particles occurs on the last date of the model realisation.

As with the BRAN2015 forward model, the backtrack winter model (July, August and September) shows a number of general trends in the model iterations which are summarised below:

a) Onshore surface shelf transport to the east;
b) General eastward flow including the Leeuwin Current (LC) (maximum over shelf break); and
c) Offshore eddies with diameters of 100-200 km.

Particle trajectories from the backtrack beach seeding locations for 2014 (Figure 178), 2015 (Figure 179) and 2016 (Figure 180) all show that the combined surface currents and Stokes drift can lead, over the three-month period, to the majority of the particles encountering the western boundary of the modelled area. This is consistent with the tarballs of Indonesian origin being transported on the Leeuwin Current along the coast of Western Australia. In addition, other particle backtracks move from the beaches across the shelf break and into meso-scale eddies in the deepwater region of the GAB.

As with the prior BRAN2015 models, the autumn (April, May, June) particle backtracks also yield very similar results to those observed in the winter models. This is consistent with the strongest Leeuwin Current velocities occurring between autumn and winter.

To illustrate the average April–September trajectory patterns across years, a cumulative heat map, which sums all particle trajectories across a 37-km grid across all modelled years, is shown in Figure 181. This map confirms that the particle trajectories during this modelled period for 2011–2016 typically backtrack to the western most extent of the model and that particle tracks can occur most frequently across the shelf and shelf break of the continental margin.

The backtrack summer model iterations (January, February, March) exhibit very different particle trajectories to those produced for the winter backtracks. There are a number of general trends that can be observed in the data:

a) General southward movement of particle backtracks;
b) Eyre Peninsula southward backtrack trajectories in coastal waters;
c) Entrainment in eddies to the west of Kangaroo Island and Limestone Coast; and
d) Re-encounter with shoreline.

Particle trajectories from the backtrack beach seeding locations for 2014 (Figure 178), 2015 (Figure 179), 2016 (Figure 180) all show that the combined surface currents and Stokes drift can lead, over the three-month period, to many of the particles encountering the deepwater southern boundary of the modelled area. Many of the modelled particles released from the beaches re-encounter beaches further to the south, and this is suggestive of a possible mechanism for reworked materials to travel north during summer months. Many of the backtrack particle trajectories become trapped in eddies that circulate along the shelf break to the west of Kangaroo Island, especially those released from the Eyre Peninsula and Kangaroo Island.

As with the prior BRAN2015 models, the spring (October, November, December) trajectories display some similarity to those observed in the summer model, although there are key differences. The backtrack trajectories in these model realisations typically are closely associated with the coastline and can include a westerly orientation towards the end of the model, suggesting that the winter processes are becoming more dominant.

To illustrate the average October–March trajectory patterns across years, a cumulative heat map, which sums all particle trajectories across a 37-km grid across all modelled years is shown in Figure 182. This reveals that the backtrack trajectories are strongly constrained to the eastern side of the GAB, particularly along the Eyre Peninsula. A higher number of backtracks also occur over the Duntroon, eastern Ceduna and Morum sub-basins.

The interpretation of the results from this model differs as the final positions of all of the particles in the model are a function of its run time and not the proposed offshore release point. Certainly, a release point of asphaltite or waxy bitumen from the abyssal seafloor of the GAB in the Recherche sub-basin is highly unlikely. The model results, however, do permit the identification of areas over which particles, seeded from key beaches, may pass, which may have a higher likelihood of being the origin locations for potential GAB-sourced coastal bitumens.

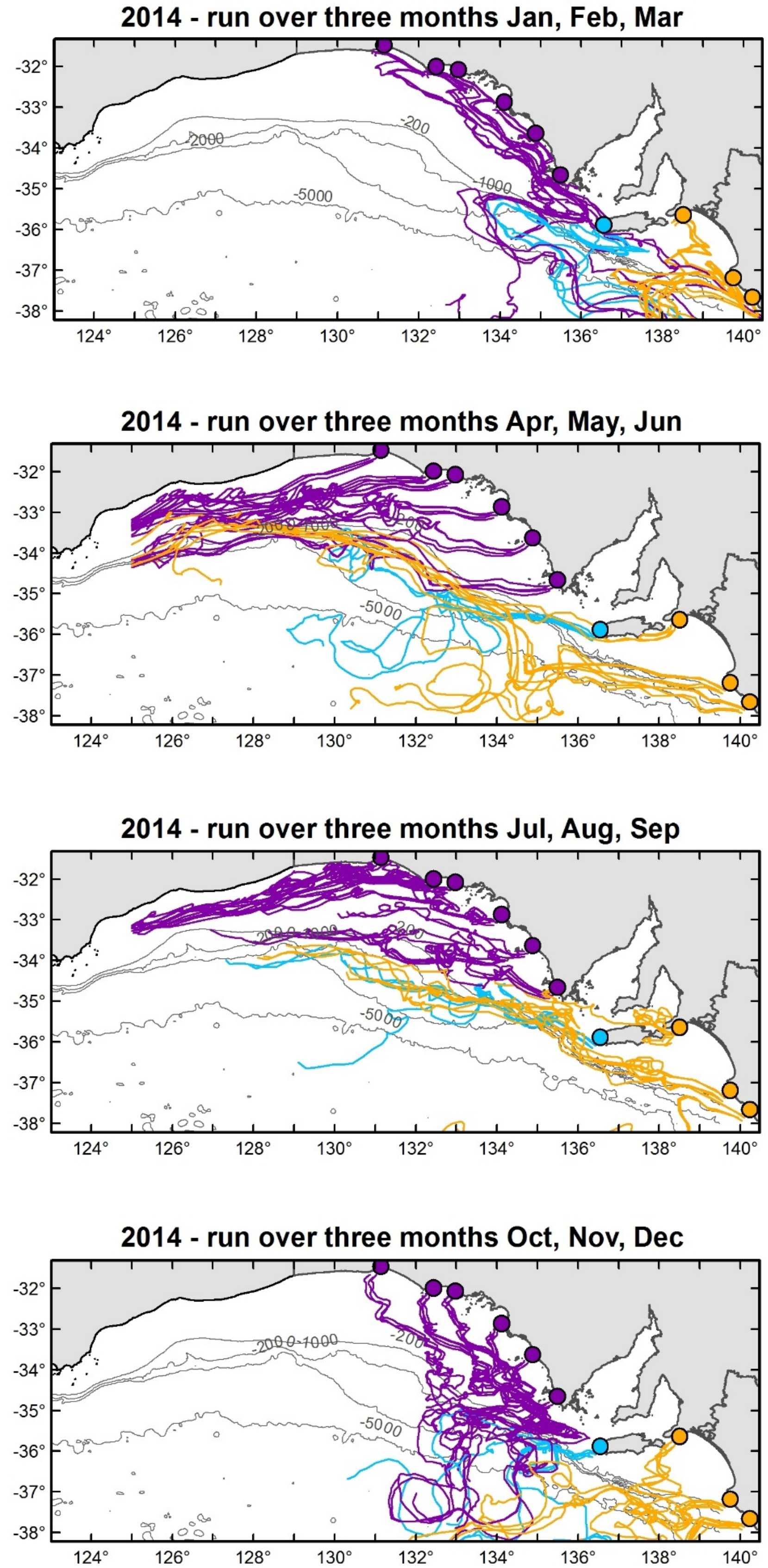

Figure 178: BRAN2015 three-monthly backtrack particle trajectories combining surface currents and Stokes drift for 2014.

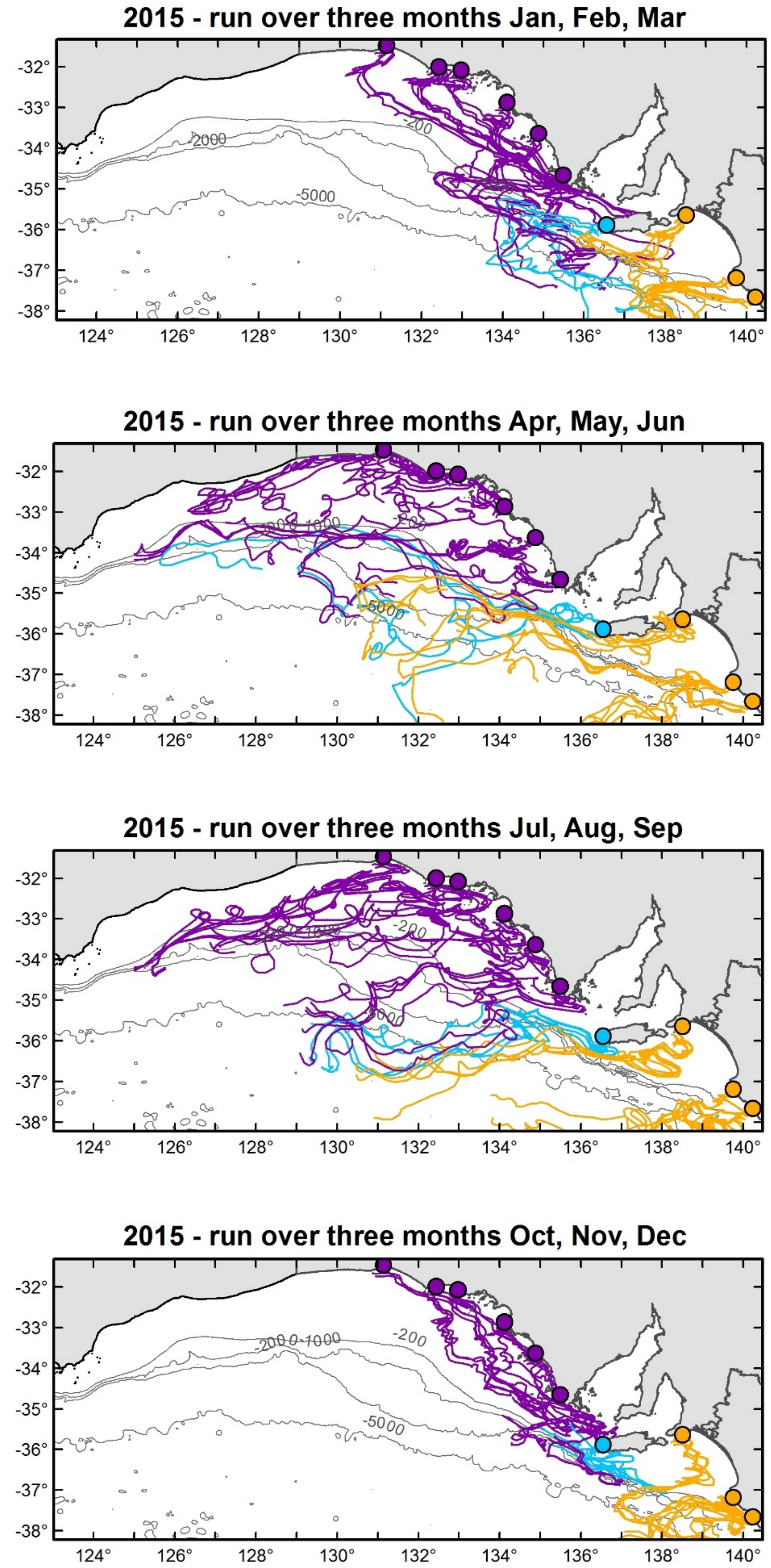

Figure 179: BRAN2015 three-monthly backtrack particle trajectories combining surface currents and Stokes drift for 2015.

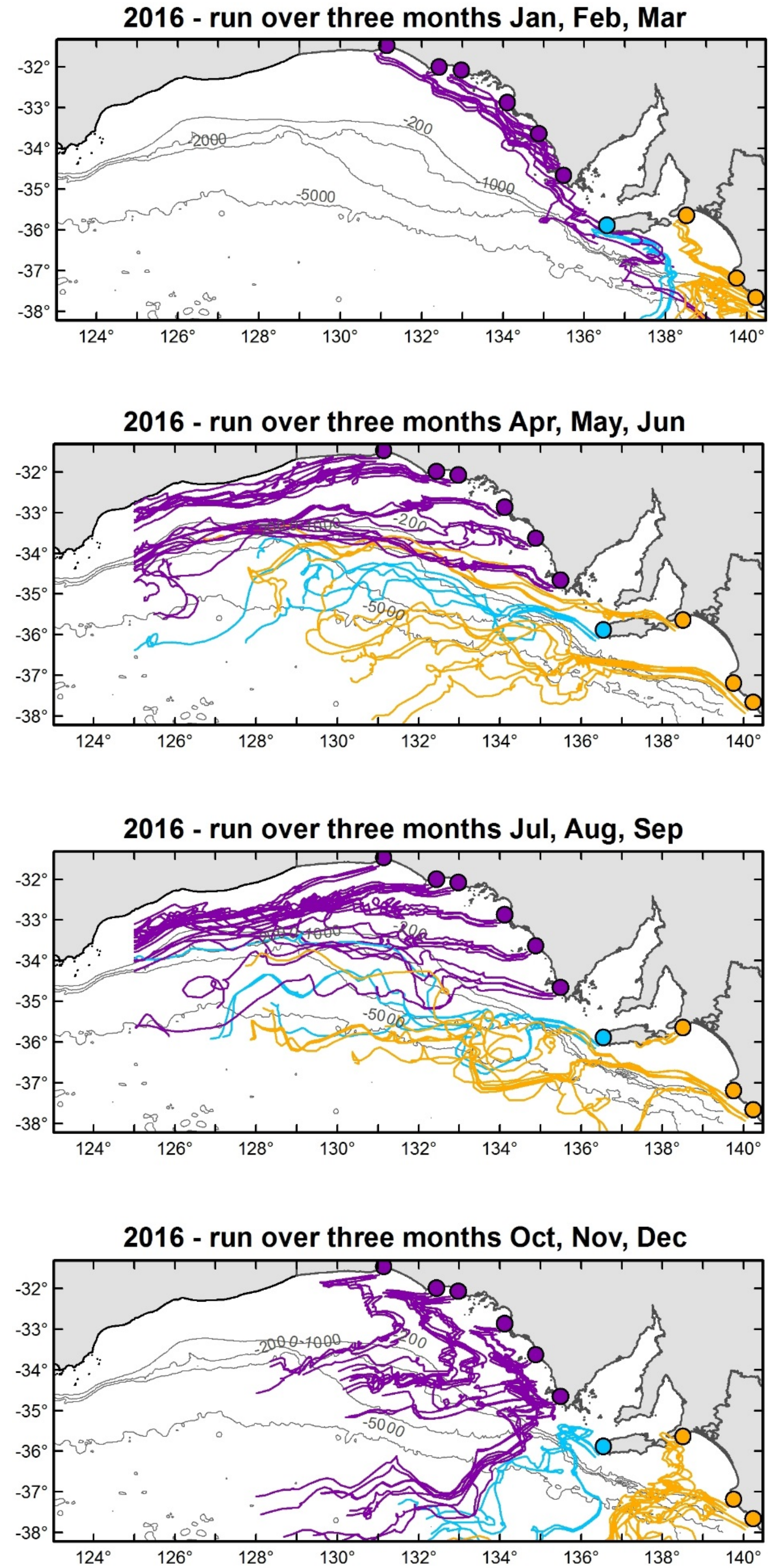

Figure 180: BRAN2015 three-monthly backtrack particle trajectories combining surface currents and Stokes drift for 2016.

For particles seeded on the Eyre Peninsula beaches and Head of the Bight (purple points), these backtrack trajectories during winter conditions originate in the west. For those particles that are seeded from the northern beaches and the Head of the Bight, these trajectories track across the GAB shelf; whereas particles seeded on the southern beaches of the Eyre Peninsula have trajectories which pass over the Eyre sub-basin and along the shelf break associated with the northern extent of the Ceduna sub-basin. During summer conditions particles from these seeding locations travel along the coast southwards and frequently re-encounter the shoreline or circulate to the west of Kangaroo Island, over the Duntroon and eastern Ceduna sub-basins. Whilst the origin of Indonesian-sourced coastal bitumens can readily be explained for these particles, these data suggest that a local source of coastal bitumen would be restricted to a region west of Kangaroo Island.

Particles seeded from the beach on Kangaroo Island (blue points) have winter backtracks that originate in the west. These trajectories pass along the shelf break over the northern part of the Ceduna sub-basin and the Eyre sub-basin. During summer conditions these particles frequently circulate to the west of the island over the Duntroon sub-basin, and to the south of the island, into deep water. Some of the particle backtracks also occasionally move to the southeast and travel over the Morum sub-basin. Whilst Indonesian-sourced coastal bitumens can be readily explained by the winter west-east trajectories, a local source of coastal bitumen would again suggest a source predominantly to the west of Kangaroo Island.

The particles seeded from the beaches on the Fleurieu Peninsula and Limestone Coast during winter conditions, as with the other particles in the model, can originate from the west and cross the Eyre, Ceduna and Duntroon sub-basins, all with hydrocarbon potential in the GAB. Once again, these patterns readily explain the arrival of Indonesian-sourced oils on these beaches via the Leeuwin Current. During summer conditions the backtracks show that particles are typically trapped in the near offshore in the vicinity of the Morum sub-basin, before travelling south and outside the modelled area. This would suggest that any locally-sourced coastal bitumens would either be sourced exclusively from the Morum sub-basin in the summer, or from any of the aforementioned sub-basins in the winter.

If there is an offshore origin of coastal bitumens in the GAB, the results of these backtrack models corroborate those observed in the forward models and suggest that those arriving on the coastlines of the Eyre Peninsula during the summer months are most likely to originate from the eastern-Ceduna or Duntroon sub-basins. The backtrack models also show that winter conditions can deliver asphaltite and waxy bitumen to the beaches close to the Head of the Bight but these materials are required to originate to the west of the study area (i.e. in Indonesian or other Western Australian basins).

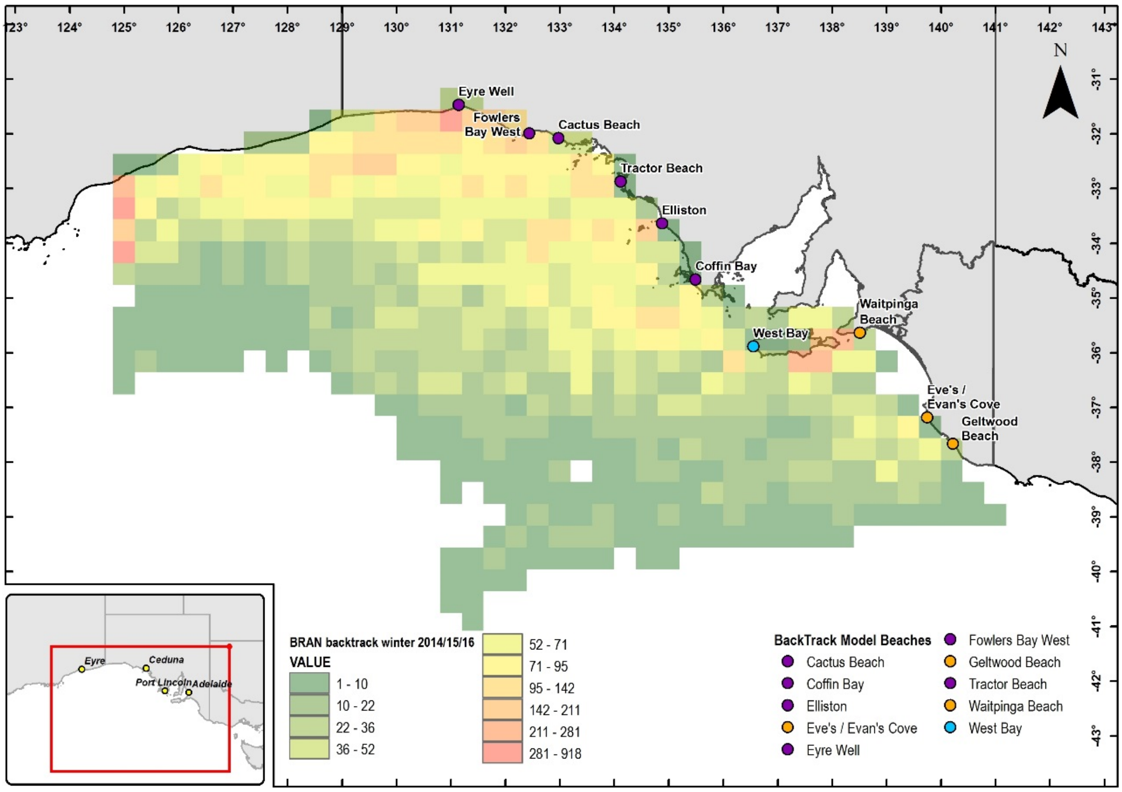

Figure 181: Heat map showing cumulative offshore seeded particles location for 2014–2016 April–September using BRAN2015.

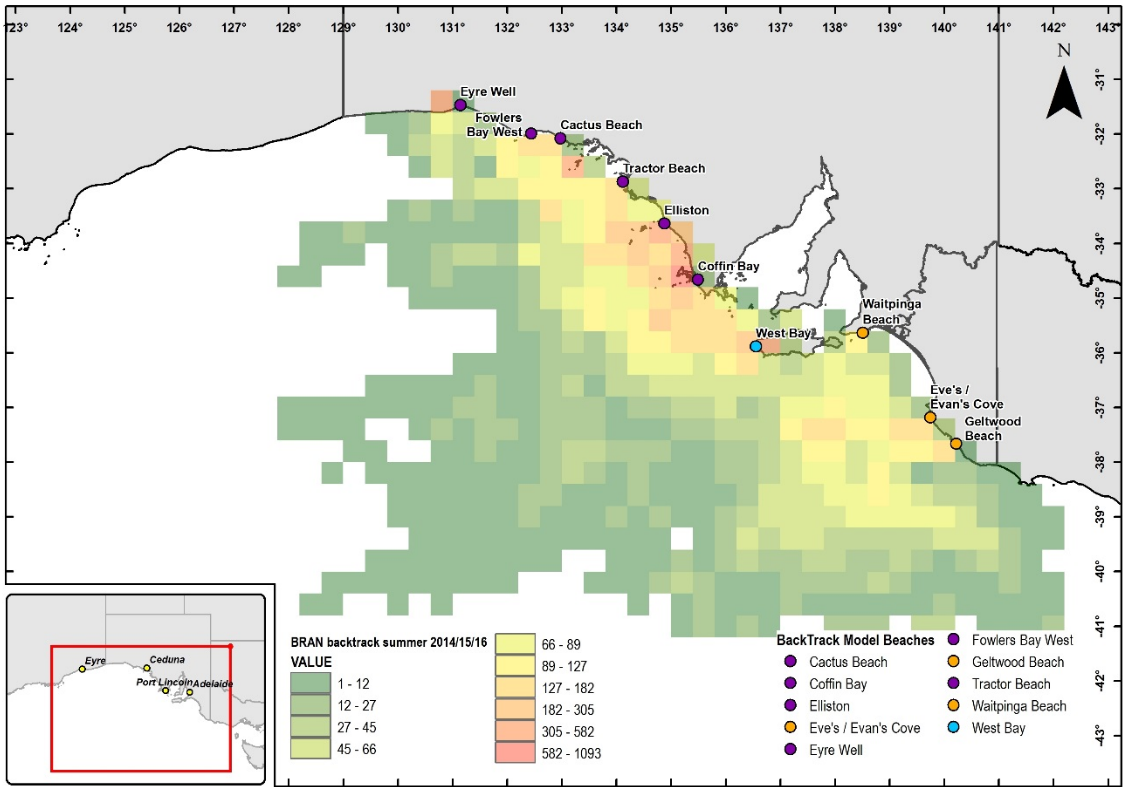

Figure 182: Heat map showing cumulative offshore seeded particles locations for 2014–2011 October–March using BRAN2015.

Discussion of oceanographic modeling results

The oceanographic models described above have, for the first time, described the likely sea-surface migration routes for coastal bitumens arriving on the South Australian shoreline. These models have shown that without the incorporation of Stokes drift in the models, it is not possible to account for the observed stranding of locally-sourced materials on many of the beaches of the Eyre Peninsula. The incorporation of Stokes drift permits the delivery of such materials to the beaches of the Eyre Peninsula during the summer months. This also shows that any locally-sourced coastal bitumens need to be either surface or near-surface drifters; the movement of which is affected by Stokes drift (i.e. positively buoyant).

Whilst the models were never intended to delineate areas of potential local origin of asphaltite and non-Indonesian-sourced tar balls, the combined forward and back-track trajectory models using BRAN2015 do provide several key insights summarised in Figure 183 and below:

- 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 observations of Indonesian-sourced waxy bitumens occurring at all the beaches sampled.
- The winter modelled conditions show that there is a low probability of coastal bitumens sourced in the Ceduna or Duntroon sub-basins reaching the Head of the Bight and northern Eyre Peninsula coastlines.
- Throughout all seasons of the year there is a low probability of any materials sourced in the Morum sub-basin travelling to the west of Kangaroo Island and reaching the ocean beaches of the Eyre Peninsula.
- The area with the highest frequency of particle tracks lies to the west of Kangaroo Island and overlies the Duntroon sub-basin and eastern extremity of the Ceduna sub-basin.
- Any origin of locally derived materials within this area can encounter all beaches in the study area.

When the Duntroon sub-basin geology is considered in more detail there are a number of geological features which can typically be interpreted as being related to subsurface fluid escape. An example of these commonly occurring features is shown in Figure 184. These features and many others with similar attributes show chaotic amplitudes at depth in the sequence associated with faults that intersect key potential reservoir units. These faults extend to seabed suggesting recent reactivation. These indicators alone are not sufficient for unequivocal identification of seepage but they, combined with the oceanographic modelling results, warrant further investigation.

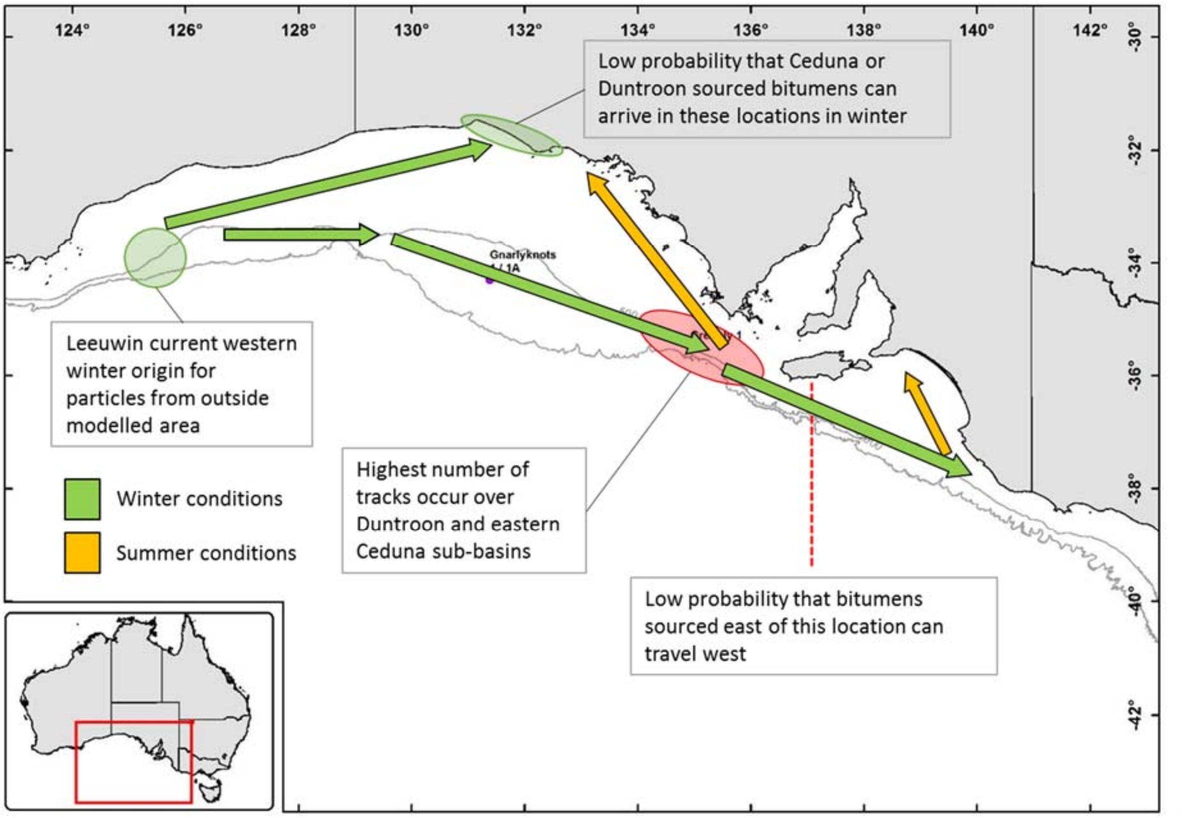

Figure 183: Key observations from oceanographic forward and backtrack models incorporating Stokes drift.

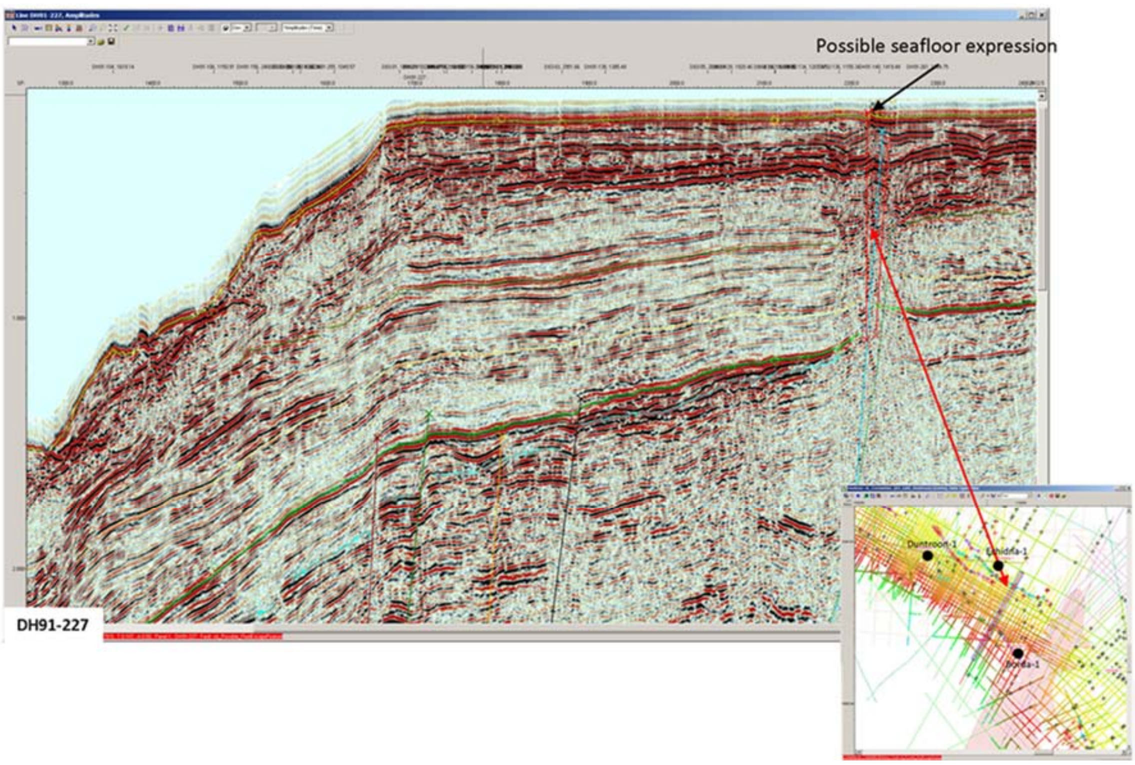

Figure 184. Example 2D seismic line (DH91-227) from SW-NE showing typical fluid escape features.

Oceanographic modelling summary and conclusions

Whilst the oceanographic models employed in this study have inherent uncertainties, they can be used to better understand the major processes driving circulation in the GAB and likely to affect any bitumens floating in the area.

The parameterisation of the models used here have assumed that the coastal bitumens, asphaltites and tarballs, are surface drifters. This assumption was based on the hypothesis that the sample densities of the asphaltites represent the weathered end member of the lower density originating material, which is more likely to be a near surface boyant drifter. Seafloor drifters were modelled by SARDI using a ROMS seafloor release 70 day model realisation using neutrally buoyant drifters (pers comm John Middleton, Figure 185). These models show similar trajectories to the winter surface drifter ROMS models, with a low likelihood of an Eyre Peninsula encounter.

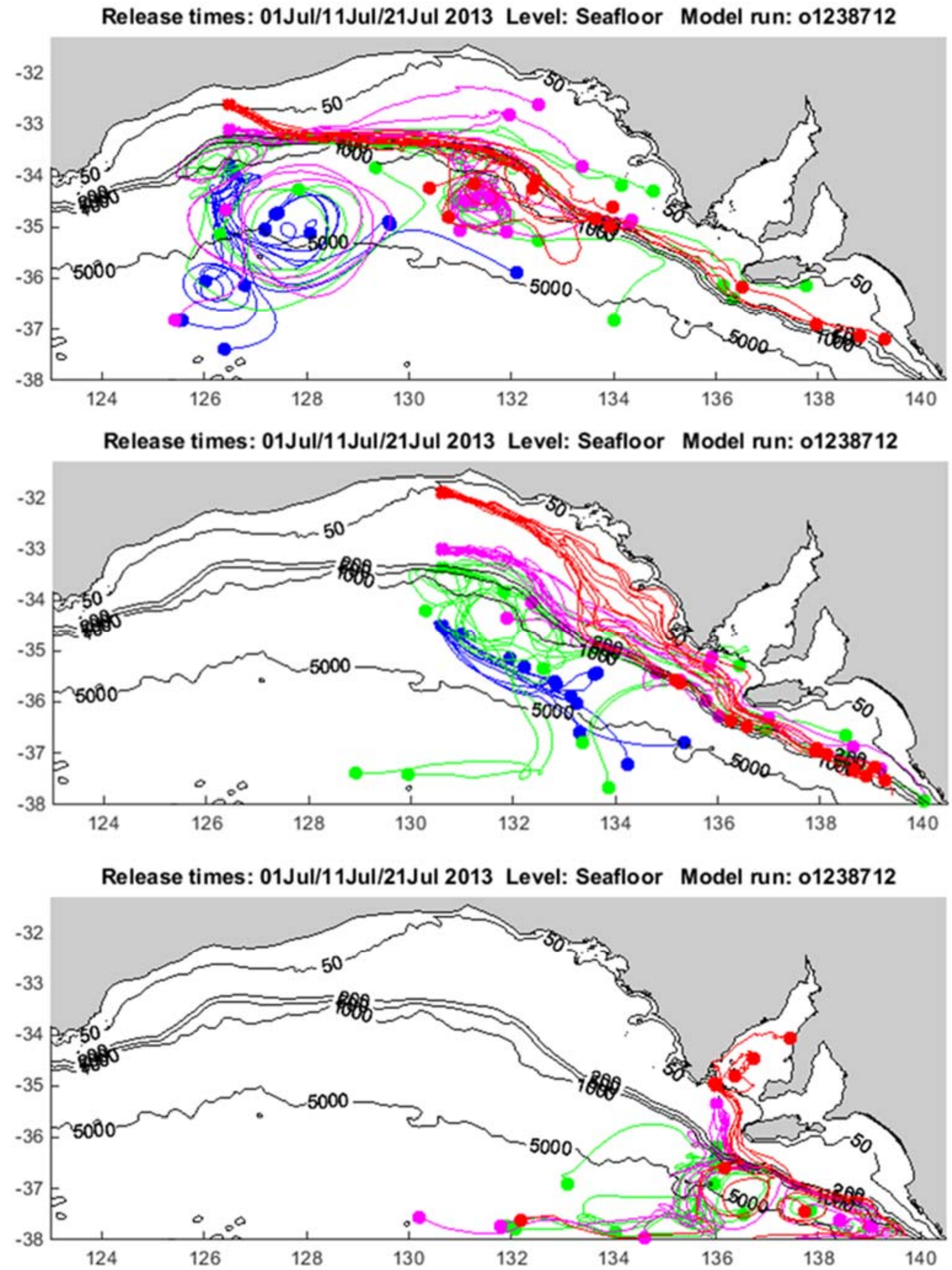

Figure 185: ROMS model (70-day duration) of seafloor release of neutrally buoyant particles (John Middleton, pers comm.).

The insights gained from the study and modelling of the physical oceanography and meteorology of the Great Australian Bight are summarised below:

- Weather in the GAB is dominated by storms with westerly winds during the winter and strong north to north-westerly winds in the summer.
- Water circulation in the winter is dominated by the eastward flowing southern boundary Leeuwin Current.

- Regional and global oceanographic models were used to simulate the trajectories of surface drifters across the GAB.
- Oceanographic models which simulate currents alone do not adequately account for the observed stranding locations of tarballs and asphaltites.
- Models which simulate both currents and Stokes drift can 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.

Part 5 Conclusion

CONCLUSIONS

This report presents the collated findings of research conducted for Project 5.2 (Asphaltite and tarball surveys) of Theme 5 (Petroleum Geology and Geochemistry) of the Great Australian Bight Research Program.

The thorough beach survey approach, geochemical characterisation and oceanographic modelling have led to new insights and understandings of the processes, origin and spatial extent of bitumen strandings on the coastline of South Australia.

The objectives of the study were to:

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

This objective has been addressed through the study of 31 beaches over three yearly surveys covering the entire South Australian coastline (with the exception of the St Vincent and Spencer Gulfs). This has established the contemporary natural hydrocarbon loadings of the South Australian coastline. In the study of these beaches, and through the collection of an array of data types, the nearshore and shoreline processes leading to coastal bitumen stranding have been explored in detail, arguably for the first time.

2. Describe 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.

This objective has been achieved through the beach surveys. These surveys have revealed that the sites of most frequent present day stranding are consistent with historical studies. The surveys have also shown that the spatial distribution of coastal bitumens is more widespread than previously identified and this has provided valuable insights when attempting to understand their potential GAB origins. Oceanographic modelling of the coastal bitumen transport has been undertaken for the first time and has defined not only important transport mechanisms but also enabled potential GAB origin locations to be eliminated whilst highlighting others.

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

The molecular characterisation of a very large cohort of tarballs and asphaltites has led to an unparalleled understanding of their geochemistry. Detailed data interrogation and interpretation and comparison with historical study results permitted weathering end members to be identified and elucidated a much greater knowledge of potential hydrocarbon sources.

This detailed analysis of the tarballs and asphaltites has allowed the definition of larger number of distinct oil families and the identification of likely source basins within the Indonesian archipelago. Several new oil families have also been discovered along the South Australian coastline with a non-

Indonesian origin that have potentially important implications for the prospectivity of its offshore sedimentary basins.

This research has significantly expanded the understanding of the coastal bitumens of South Australia. It forms an important, and continuing, baseline for hydrocarbon loadings on the beaches of South Australia and has occurred before renewed exploration in the GAB. 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.

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Part 6 Appendices

APPENDIX 1: DATA MANAGEMENT

Raw datasets created

Field data was collected in a Microsoft Access database. Tables provide data for the following:

- Beaches
- Beach visits
- Beach segments
- Beach transects
- Photographs
- Samples
- Sample analyses
- Observations
- Debris
- Survey team

See the separate document Ross et al. (2017b).

Data processing and derived datasets

After bitumen samples were analyzed, data was received in the form of MS Excel spreadsheets. This raw data was compiled into a single Excel workbook and is included as APPENDIX 7: SAMPLE ANALYSIS DATA.

Analysis results were also reformatted then entered into the database in two related tables tblAnalysisResults (analysis done, how, by who, related images) and tblAnalysisRaw (raw results for each compound / variable plus analysis type and preparation).

Data in these tables, together with location and type details plus any images available were used to create a report for each sample listing all analyses requested and all results received. These reports can be found in APPENDIX 6: SAMPLE REPORTS.

Data curation and archive

Data files (raw data, derived datasets, working files, reports) relating to the project are stored CSIRO's network servers in secure locations only accessible to personnel working in the GAB Research Program.

Backup versions of the databases have been retained before and after each field survey and each major update to the data.

Data access, use agreements and licensing

None required

Publication of datasets

Not published – data included in appendices.

APPENDIX 2: STUDENT PROJECTS

Student name

Alex Corrick

Degree type, project title and institution

PhD- Understanding South Australian Costal Bitumen, University of Adelaide.

Status of student project

Completion of PhD project anctipated June/July 2018

APPENDIX 3: PROJECT PUBLICATIONS

Papers

Edwards, D.S., Vinall, D.R., Corrick, A.J., McKirdy, D.M. (2016) Natural bitumen stranding on the ocean beaches of Southern Australia: a historical and geospatial review. Transactions of the Royal Society of South Australia. 140 (2), 152-185.

Presentations

McKirdy, D., Corrick, A., Gong, S., Trefry, C., Dyt, C., Angelini, Z., Jobin, O., Hall, A., Edwards, D. (2015) Understanding the geographical distribution of historical and modern asphaltite strandings along the South Australian coastline. AAPG International Conference and Exhibition 2015, 13-16 September Melbourne, VIC.

Corrick, A., Hall, P.A., McKirdy, D.M., Gong, S., Trefry, C., Dyt, C., Angelini, Z., Ross, A., Kempton, R., Armand, S., White, C. (*2016)* A revised oil family classification scheme and geochemical weathering proxies for South Australian coastal bitumen strandings, *Australian Organic Geochemistry Conference, 4-7th December, 2016 Perth.*

Patents

None

Media releases

None

APPENDIX 4: INTELLECTUAL PROPERTY

Unique discoveries

N/A

Action plan

N/A

APPENDIX 5: BEACH DOSSIERS

Please see separate Appendix document Ross et al. (2017c)

APPENDIX 6: SAMPLE REPORTS

Please see separate Appendix, Ross et al. (2017d)

APPENDIX 7: SAMPLE ANALYSIS DATA

Please see separate Appendix, Ross et al. (2017e)

APPENDIX 8: BRAN MAPS FOR 2011, 2012 and 2013

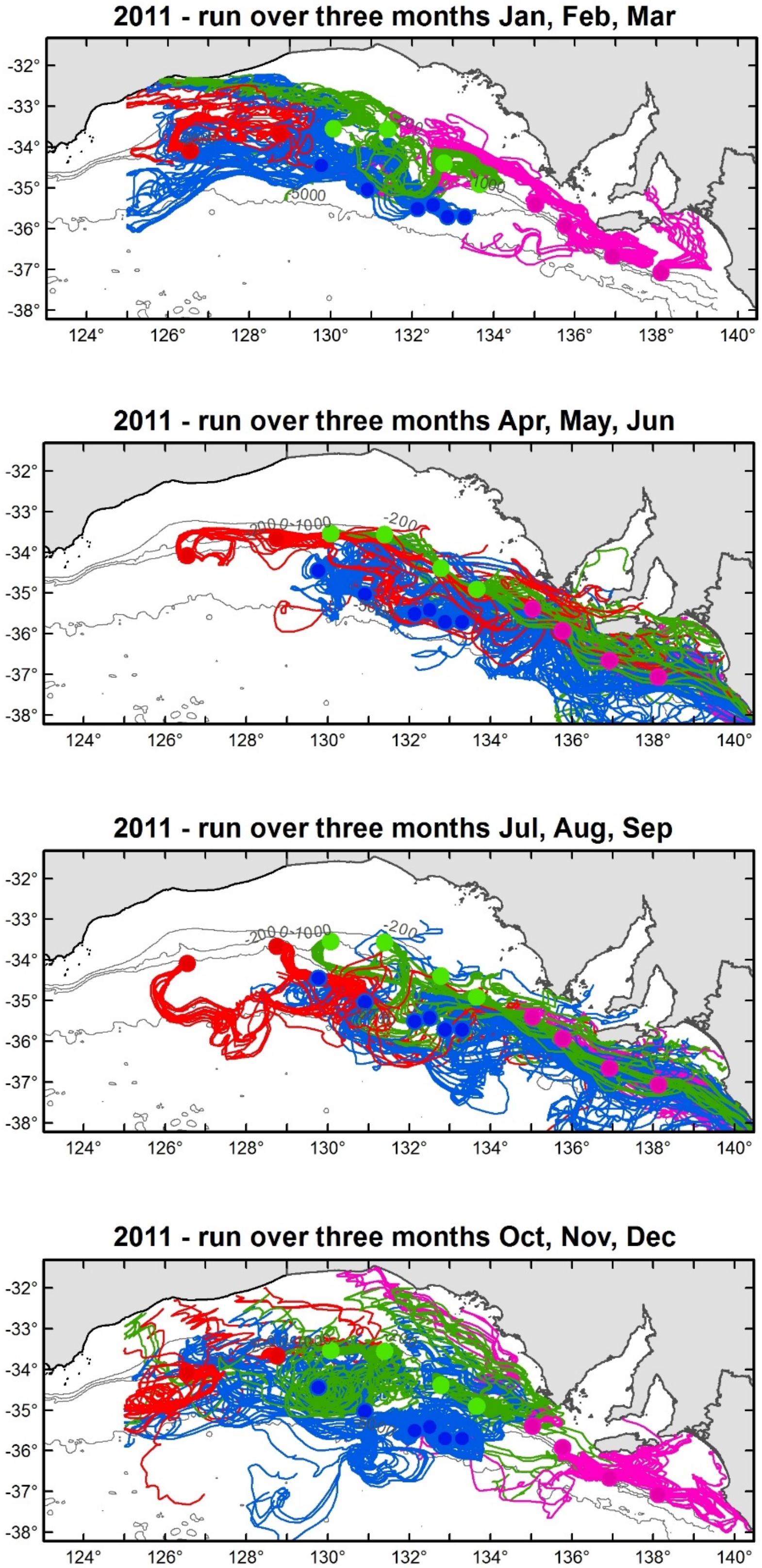

Figure 186 BRAN2015 three monthly offshore seeded particle trajectories combining surface currents and stokes drift for 2011.

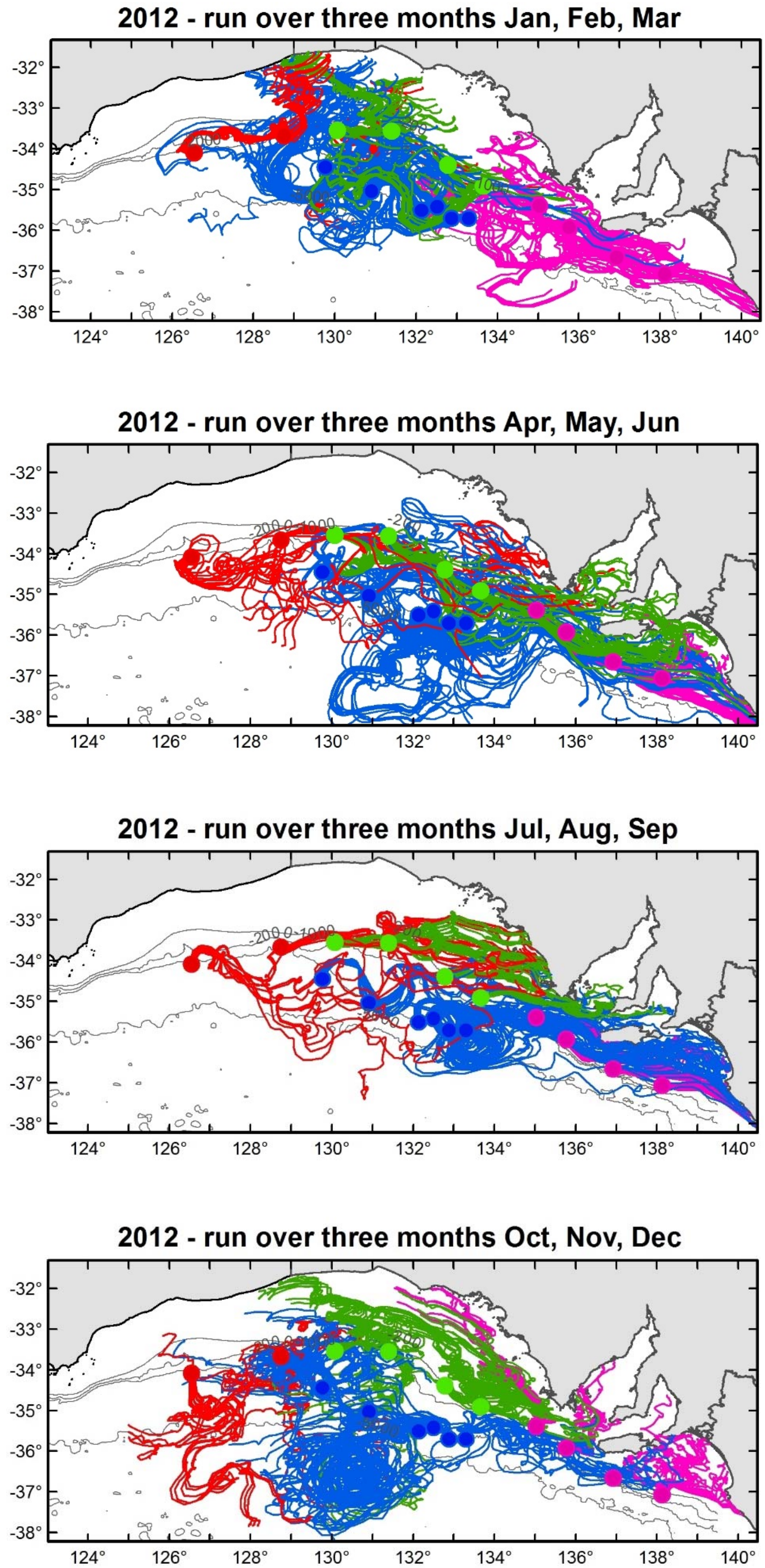

Figure 187 BRAN2015 three monthly offshore seeded particle trajectories combining surface currents and stokes drift for 2012.

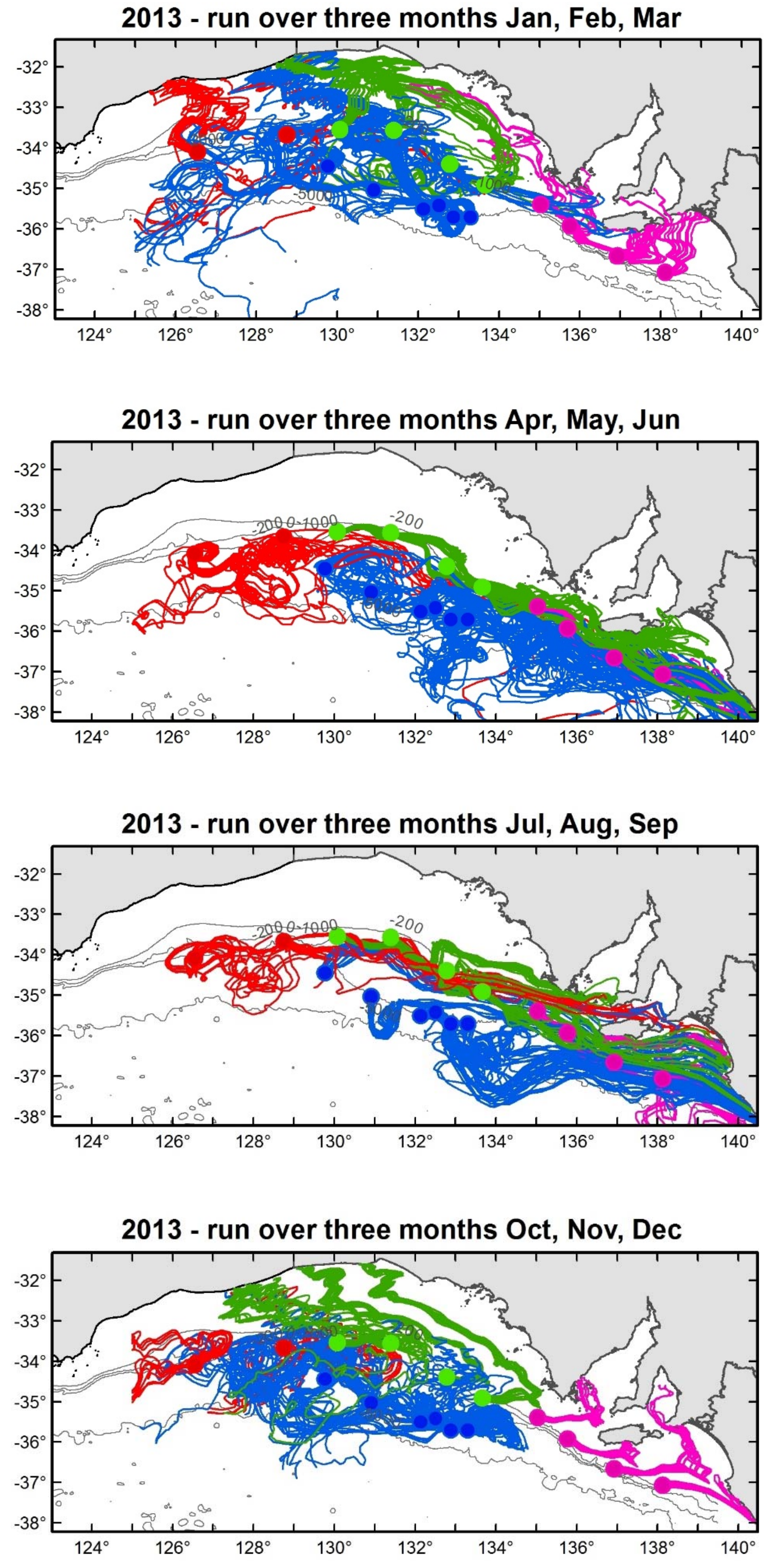

Figure 188 BRAN2015 three monthly offshore seeded particle trajectories combining surface currents and stokes drift for 2013.

Figure 189. BRAN2015 three monthly back track particle trajectories combining surface currents and stokes drift for 2011.

Figure 190. BRAN2015 three monthly back track particle trajectories combining surface currents and stokes drift for 2012.

Figure 191. BRAN2015 three monthly back track particle trajectories combining surface currents and stokes drift for 2013.

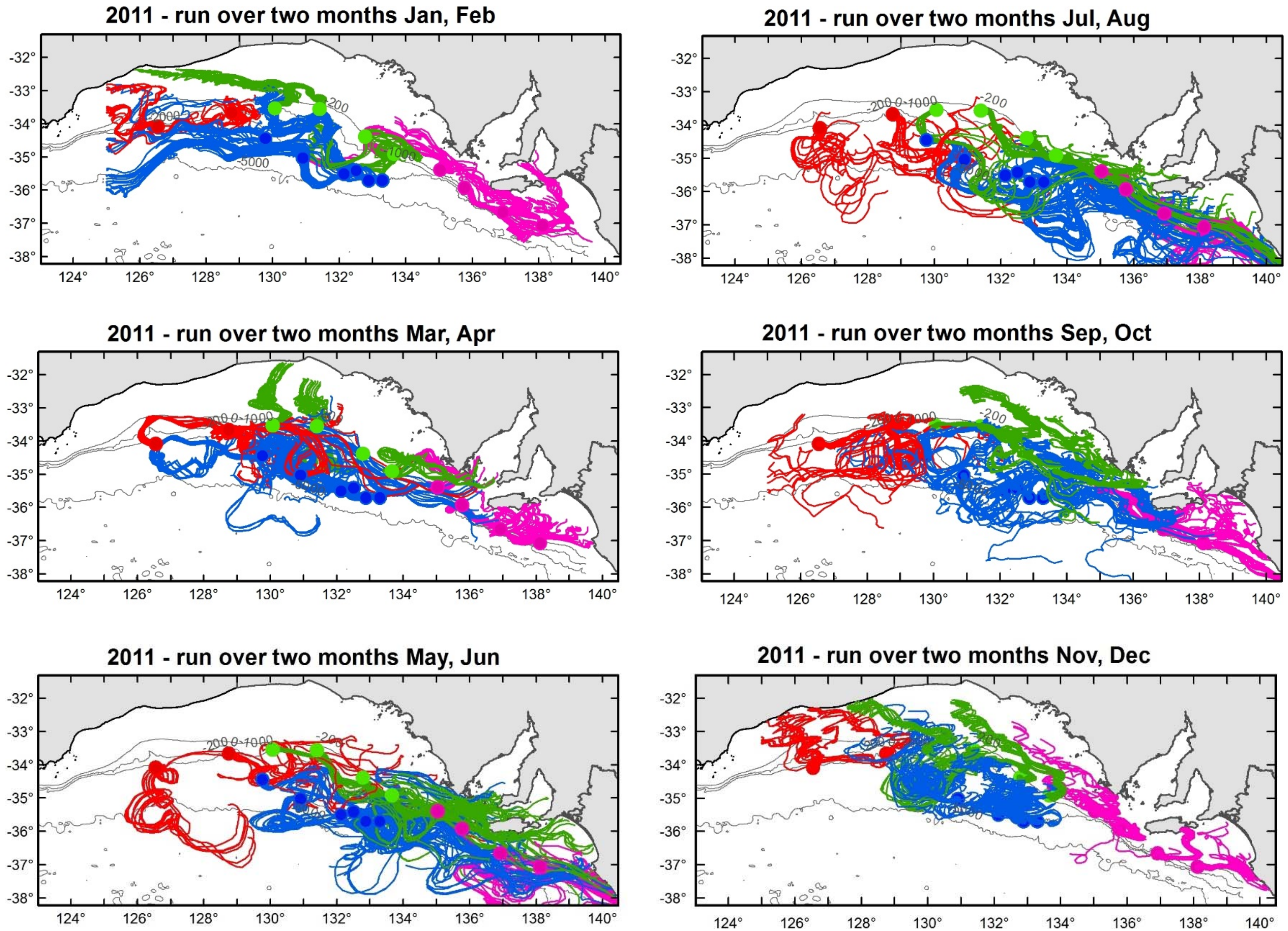

Figure 192. BRAN2015 two monthly offshore seeded particle trajectories combining surface currents and stokes drift for 2011.

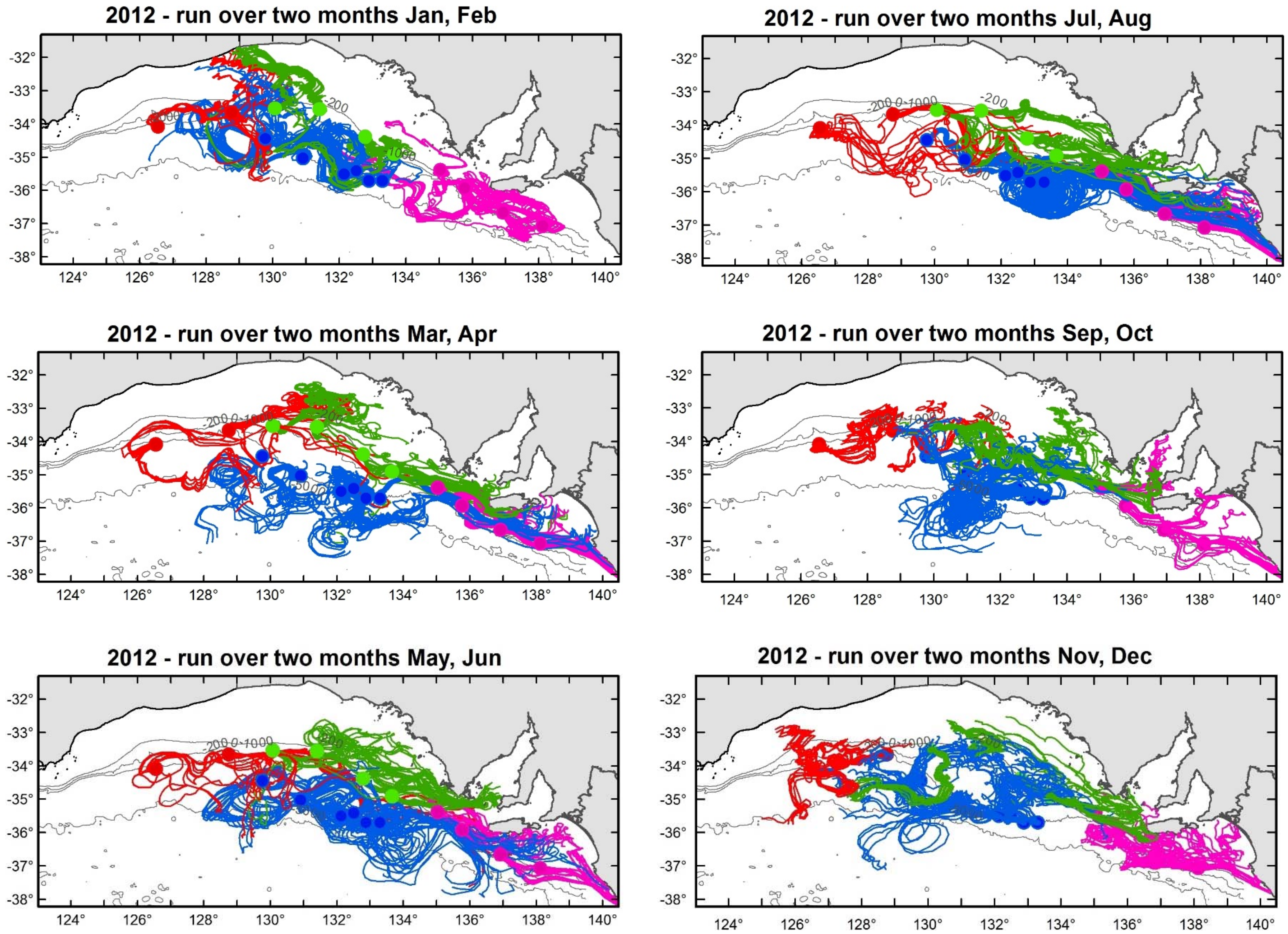

Figure 193. BRAN2015 two monthly offshore seeded particle trajectories combining surface currents and stokes drift for 2012.

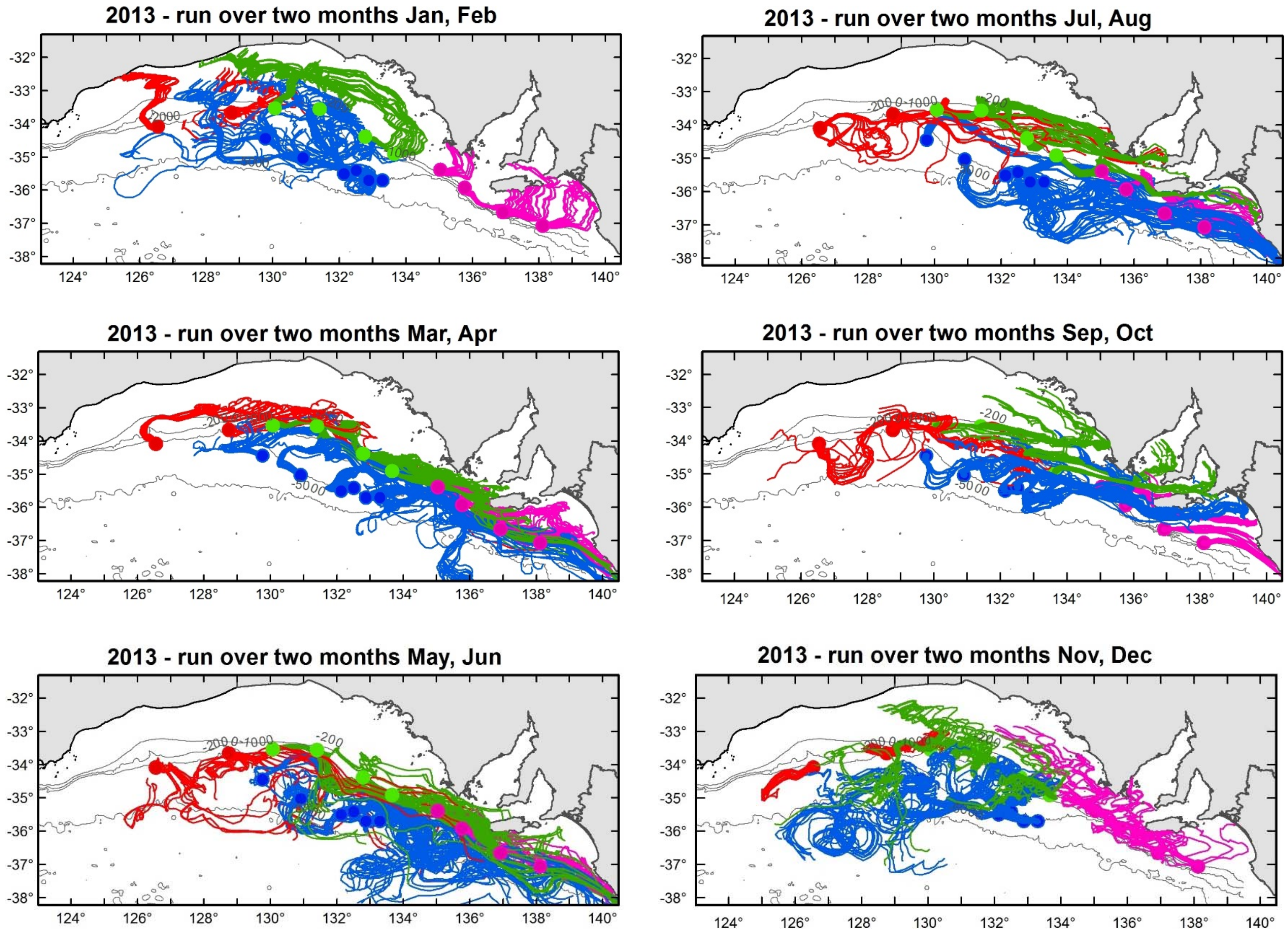

Figure 194. BRAN2015 two monthly offshore seeded particle trajectories combining surface currents and stokes drift for 2013.

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