Hydrocarbon Generation and Seepage in an Emerging Fold-and-Thrust Belt, Cenderawasih Bay, Indonesia

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ABSTRACT

Cenderawasih Bay, a triangular embayment located at the western end of the island of New Guinea, lies within the Eastern Indonesia region of complex and rapid neotectonics. In Cenderawasih Bay, the Yapen Fault marks the boundary between the oceanic Pacific plate and continental material of the Australia tectonic plate. A fold-and-thrust belt is developing in response to left-lateral strike-slip movements on the Yapen fault system. Geochemistry from sea bottom core samples the presence of an active petroleum system within the emerging fold-and-thrust belt.

Keywords: *Deepwater depositional systems, Oil seeps, SeaSeep, Neotectonics*

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INTRODUCTION

SeaSeep is a quick-look basin evaluation methodology for hydrocarbon prospectivity using multibeam bathymetry, backscatter, coring, hydrocarbon geochemistry and regional 2D seismic to mitigate kitchen, source, timing and migration risk in frontier basins. The multibeam bathymetry and backscatter provide the basis for seep identification and targeted core acquisition (Orange et al., 2008).

The term "SeaSeep" was first used by the authors of this paper for the exploration technique applied to a large multi-client frontier basins program offshore Indonesia in 2008–2011. Exploration data acquired during the program consisted of approximately 400,000 sq. km. of multibeam bathymetry and backscatter data, 100,000 line-km of gravity/magnetics and 1,188 piston cores, as well as 34,000 line-km of 2D seismic data. These data were acquired in ten basins throughout the Indonesian archipelago. The results of a geochemical suite of analyses on the cores showed that 11% contain evidence of migrated liquid petroleum, and 46% contain thermogenic gas (Bernard et al., 2008). The success of this program significantly impacted the risk through demonstration of source, maturity and migration (Orange et al., 2008, 2009).

The authorship of this paper comprises the team members involved in the development, acquisition and marketing of the various elements of the project. In this paper we present results of that work carried out in Cenderawasih Bay, the easternmost of the ten basins studied in the project. Cenderawasih Bay (Figure 1), is a triangular deep embayment located at the western end of the island of New Guinea. The bay is about 350 km in E-W

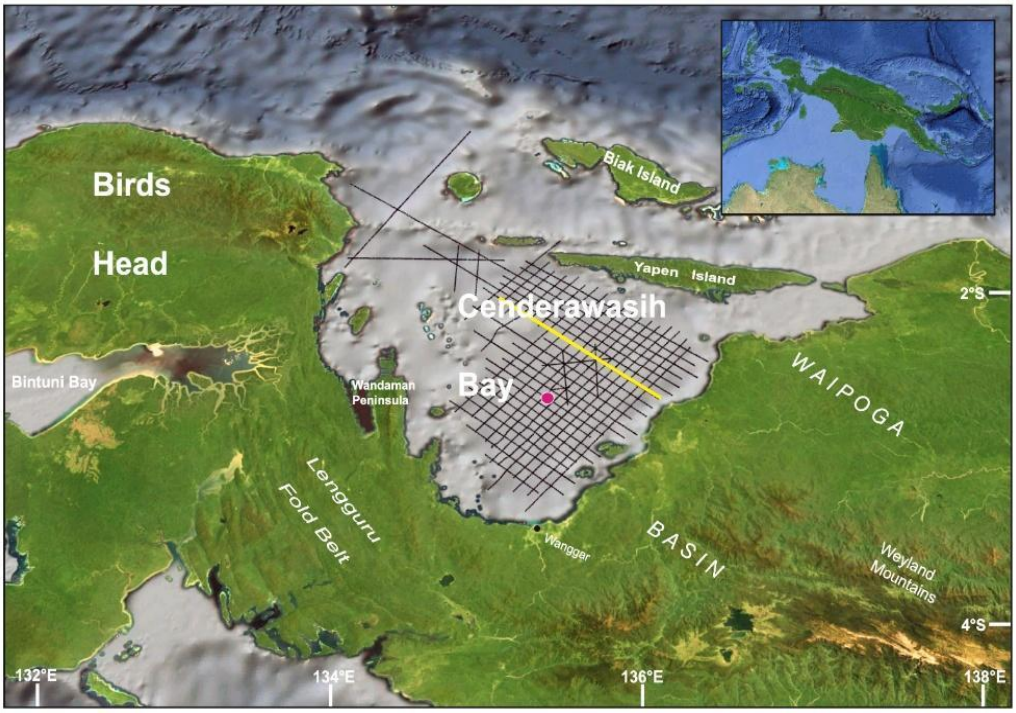


Figure 1: *Locality map (source: Google Earth) of Cenderawasih Bay with seismic lines indicated. Yellow line shows position of Figure 4. Red dot shows location of the Elang-1 exploration well. Inset shows the island of New Guinea; Cenderawasih Bay is near western end, east of the "Birds Head".*

extent immediately south of Yapen island and 180 km in the N-S direction. Water depths range from shelfal with numerous small islands to around 2000m in the centre of the bay.

REGIONAL GEOLOGY

To understand the complex regional setting and the basin history of this vast area, sequence stratigraphic method was used to interpret the seismic data and correlate each of the areas. This method allowed us to independently understand the geological relationship of each of the areas, starting from the pre-break up of Gondwanaland, the breakup, post break up and the influence of other tectonic events and plate movements that changed the configuration of the basins.

Eastern Indonesia and the island of New Guinea is a region of complex and rapid neotectonics. Convergence of the Australia Plate (in this paper we refer to "Australia Plate", in reality the continental part of the larger composite Australo-Indian Plate) and the Eurasia and Pacific tectonic plates (e.g., Hamilton 1979; Hall 2002, 2012; Bock et al., 2003) results in both contraction and extension from subduction hinge rollback, lithospheric delamination and slab break-off (e.g., Spakman & Hall, 2010; Hall, 2012). Multiple phases of deformation have occurred within the last few million years (White et al., 2018).

In general terms, the geological evolution of the region may be considered in terms of building blocks formed during Proterozoic and Palaeozoic times, Mesozoic continental breakup and Neogene collision of Australia and the Indonesian Sunda archipelago.

Different mechanisms have been proposed for the tectonic origin and evolution of Cenderawasih Bay – the bay has been variously interpreted as being floored by continental, oceanic, and transitional crust (Dow & Hartono, 1982; Hamilton, 1979; Baillie et al., 2004; Decker et al, 2009).

Like the onshore sector of the Waipoga Basin in the east (Figure 2), the bay straddles the Yapen Fault, an important element of a system of left-lateral mega-shear (Sorong Fault System) along the entire north coast of New Guinea. The Sorong Fault System, the southern boundary of both the Molucca Sea and the Philippine Sea plates with the Australia Plate (Hall & Wilson, 2000), is one of the most important structural elements of Southeast Asia. The fault has been responsible for translation of continental fragments from the northern margin of the Australian Plate (that is, the "Bird's Head" of the bird-shaped island of New Guinea) into the outer edge of Sundaland (Pigram & Panggabean, 1984; Hutchison, 1989). This fault system was initiated with a change from a subduction margin around 25 million years ago and continues to the present day (Hall, 2002, 2012).

The Bird's Head has had a complex geologic history but internally is a relatively stable piece of the Northwest Shelf of Australia. Plio-Pleistocene transtensional basins, such as the Waipoga Basin, and deformational zones surrounding the Bird's Head are possibly the consequence of counter-clockwise rotation of the Bird's Head northward from the Northwest Shelf in the past 7 million years (Decker et al., 2009).

The Waipoga Basin (Figure 2), comprising the low-lying area east of Cenderawasih Bay and the eastern part of Cenderawasih

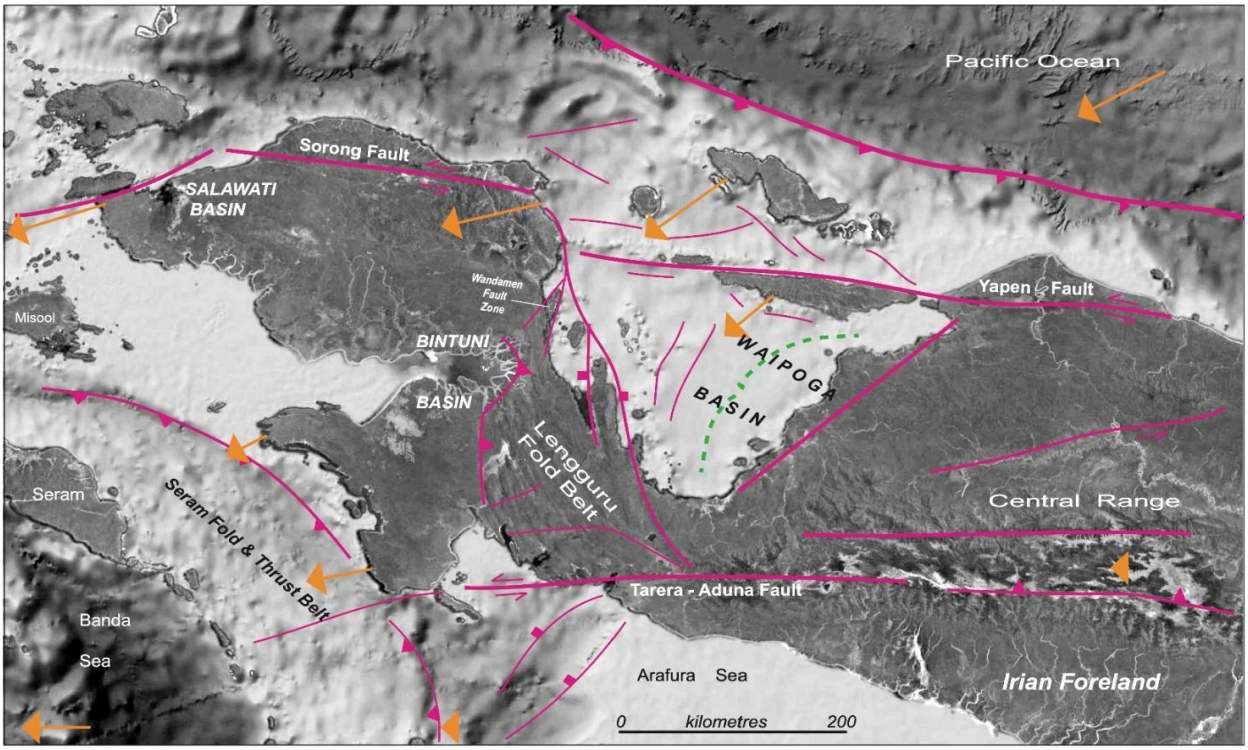


Figure 2: *Simplified regional structural map. Base image from Google Earth; main plate boundaries and faults in lilac, GPS vectors in orange. Limit of surface expression of developing fold-and-thrust belt shown as dashed green line (after Teas et al., 2008). Compiled from several sources, primarily Bailly et al. (2009), Decker et al. (2009) and Sapiie et al. (2010).*

Bay itself, occurs in the northern Australia collision zone in a region of complex deformation between continental Australian Craton on the Australian Plate and the oceanic Pacific Plate. It belongs to a large Plio-Pleistocene post-collisional clastic basin complex which extends across the northern part of the island of New Guinea. The basin contains Miocene to Pleistocene successions which attain offshore an estimated thickness of over 8,000m (sediments overlying the economic basement reach a seismic thickness of six seconds TWTT in Cenderawasih Bay, see Figure 3 and discussion below). Plio-Pleistocene deposits are interpreted as clastics deposited in a deep marine to a near-shore environment whereas older sediments are interpreted as fluvial-shelfal sands (Dow & Sukamto, 1984; McAdoo & Haebig, 1999).

The west coast of Cenderawasih Bay is dominated by mountains, rocky peninsulas and islands, where a variety of magmatic and sedimentary rocks is exposed (Pieters et al., 1983; Pigram et al., 1983; Dow et al., 1985; Ratman, 1999; Hill et al., 2001). The Wandamen Peninsula (Figure 1) consists of multiply deformed medium-high grade metamorphic rocks recording multiple deformation events that occurred within the last six million years (White et al., 2019). Metamorphic zircons dated between 5.61±0.04Ma and 8.1±1.1Ma attest to rapid subduction and exhumation (François et al., 2016).

The Wandamen fault zone (Figure 2) is a series of fault wedges of Paleozoic crystalline basement rocks and overlying Mesozoic and early Tertiary platform and

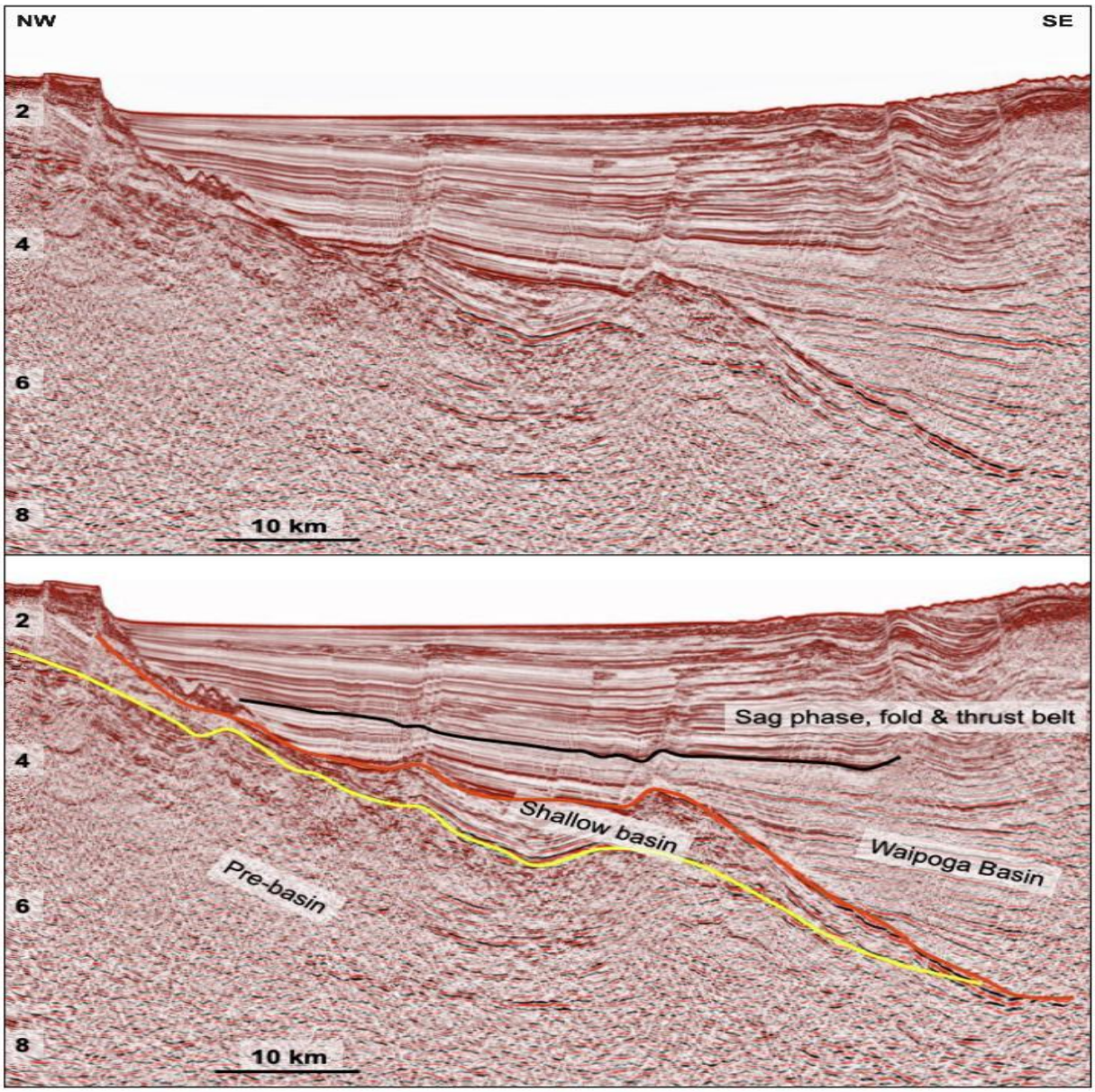


Figure 3: *Representative seismic section, Cenderawasih Bay location of line indicated on Figure 1, vertical scale seconds TWT; (A) uninterpreted; (B) interpreted.*

trough-type sediments that are strongly folded along narrow tectonic zones (Dow and Hartono 1982).

DATA

As part of the regional program over Indonesia's deep-water areas approximately 19,000 sq km of multibeam data, 4,836 km of 2D seismic data, 111 piston cores (resulting in 293 petroleum geochemical analyses), 6,088 km of gravity and magnetic data and six heat flow measurements from 6 sites were acquired in Cenderawasih Bay area (Figure1 and 4): this was the first multichannel seismic data acquired in Cenderawasih Bay.

A multibeam bathymetry image of Cenderawasih Bay is shown as Figure 5 and clearly shows the Yapen Fault, contiguous with the northern margin of Yapen Island, which marks the plate boundary between the Pacific and Australia plates (it should be noted that

although part of the same great strike-slip fault system which extends through all of East Indonesia, the Yapen and Sorong faults are not contiguous).

A more detailed image of the bathymetry around the plate boundary (Figure 6A) shows the development of an ovoid transtensional basin immediately south of the fault; a large volcanic feature about 8 km in diameter, is present near the western extremity of the basin. The feature has "rubbly" appearance due to the presence of abundant rock fragments and is interpreted as volcanic in origin. Petrology from three cores were taken and showed that the clasts were volcanic, comprised predominantly of amphibole, pyroxene and olivine.

Also clearly imaged is an emerging fold-and-trust belt in the southeast of the bay (Figure 6B). The edge of the fold-and-thrust belt is clearly defined (indicated on Figure 2), and the development of drainage channels is shown to be controlled by the developing folds. Bending of folds can also be observed. Two areas based on general morphology related to the interplay between deposition and deformation can be recognised: (a) a north-eastern low-gradient zone characterized by numerous anticlines, shallower seafloor, numerous fill-and-spill mini-basins, and (b) a deeper south-western zone with fewer anticlines, few mini-basins and a higher gradient bypass depositional system.

A representative seismic line is shown as Figure 3 and illustrates the rapid thickening of the Plio-Pleistocene section to the southeast to greater than six seconds TWT. There is a marked unconformity between the Plio-Pleistocene and underlying 'basement' rocks which are interpreted as continental crust with some volcanics sometimes with relatively thin Late Oligocene–Miocene carbonate successions in the upper part (see also Noble et al., 2016).

Faults tend to propagate from basement highs and appear to be the locus for hydrocarbon migration as sediments near the faults display amplitude enhancement ('flags') indicating migration of hydrocarbon fluids (Figure 3).

An interpretation of the seismic data was given by Sapiie et al. (2010) who concluded that Cenderawasih Bay is asymmetric syn-orogenic basin with more than ~6 seconds (two-way travel time) of Plio-Pleistocene sediments in the south-eastern sector. The basin is controlled by several major structures with normal faults trending E-W becoming NE-SW in the northeast part of the bay near Yapen Island. There is also a series of N-trending normal faults parallel to Wandaman Peninsula. NE–SW normal faults cut through the Plio-Pleistocene succession.

Thick Plio-Pleistocene successions were deposited and experienced compressional deformation forming a NE-trending thin-skinned fold-and-thrust thrust belt verging to the southeast (Sapiie et al., 2010). The deformation is occurring at the same time as sedimentation and is probably related to movements on the Yapen-Sorong strike-slip fault system and associated counter-clockwise rotation of the Bird's Head, as suggested by Decker et al. (2009).

Basement in Cenderawasih Bay is likely to be a mixture of oceanic (including ophiolites) and continental crust, similar to the variety of rock types observed around the bay.

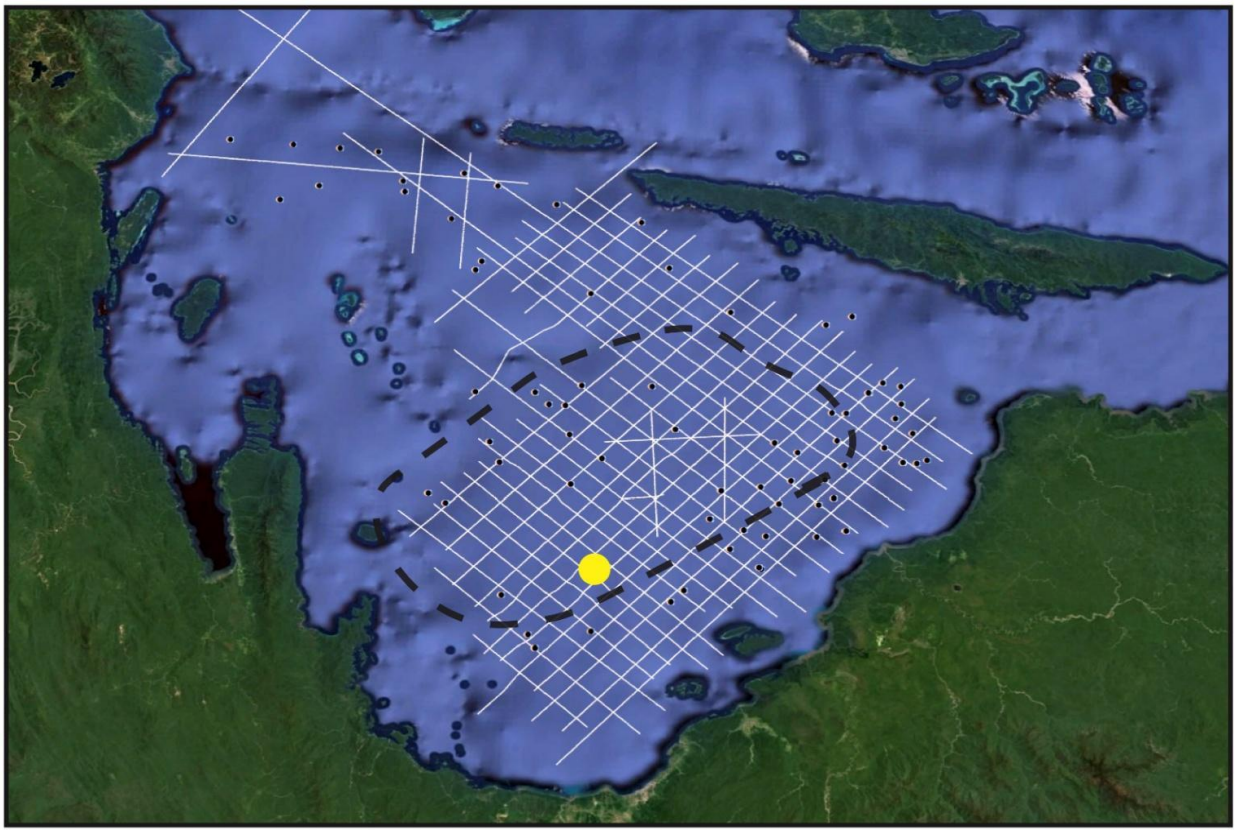


Figure 4: *Location of seismic lines and core sites (source: Google Earth) with location of interpreted oil seep shown as yellow dot. Areal extent of interpreted hydrocarbon seepage indicated by black polygon.*

SEEPAGE INDICATOR

Natural hydrocarbon seepage out of the seafloor can alter the physical and biological characteristics of the sediment-water interface. Specifically, the presence of seep-related biologic communities and authigenic carbonate or gas hydrate can increase acoustic impedance, roughness, and volumetric heterogeneity down to several meters below the seafloor at seep sites. These characteristics increase the backscatter energy recorded by the multibeam system (Orange et al., 2009 and references therein) which allows us to recognise and map the distribution of seep-related features at the sea bottom. Seepage can also lead to local bathymetric highs (mounds, mud volcanoes), and lows (pockmarks). Seepage may also occur preferentially along bathymetrically expressed fault traces at the sea bottom (Orange et al., 2008, 2009).

The primary goal of SeaSeep exploration is to map the seafloor at very high resolution – both bathymetrically (generally at a grid size of 15m) and with acoustic backscatter (generally at a pizel density of 5m) – and identify locations of potential natural hydrocarbon seafloor seeps to be sampled by surface-deployed piston cores. The cores can then then be analysed geochemically for the signature of natural hydrocarbons (Bernard et al, 2008; Orange et al., 2009).

CORE SAMPLE GEOCHEMISTRY

Primarily on the basis of anomalous backscatter, a total of 91 sites were identified and cored in Cenderawasih Bay.

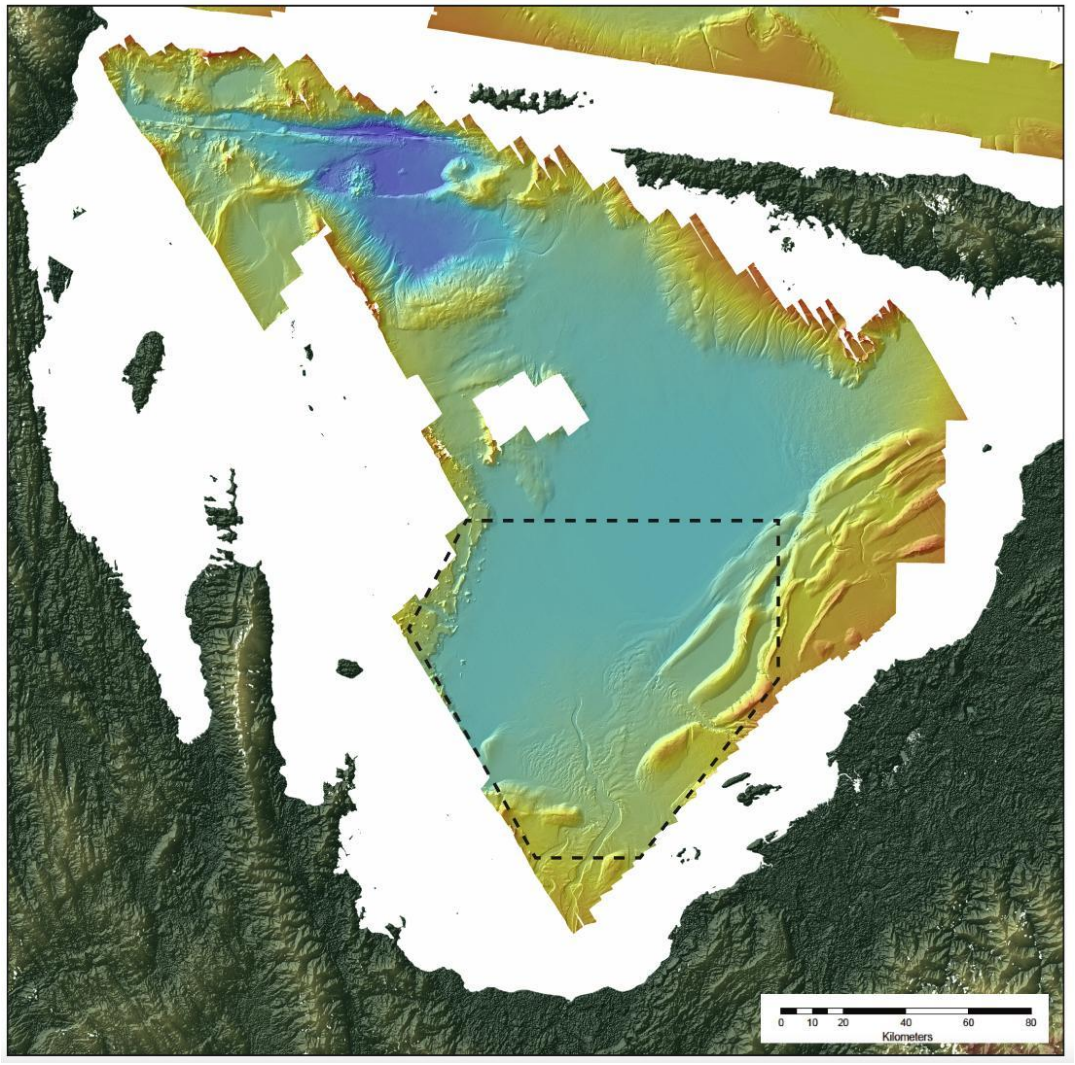


Figure 5: *Bathymetric image of Cenderawasih Bay. Shaded relief topography after SRTM; artificial sun from the NW.*

Core locations are shown on Figure 4 and some details are presented as Figure 7. To interrogate these potential seep sites, a standard 6–9m piston corer equipped with an Ultra-Short Baseline (USBL) positioning beacon was deployed to sample features of interest (Orange et al., 2009).

The recovered cores were visually examined at the surface for indications of hydrocarbons (for example, gas hydrate, gas parting, or oil staining) and then sub-sampled for geochemical analysis. Details of sample collection, laboratory procedures and aspects of thermogenic hydrocarbon recognition were presented by Bernard et al. (2008).

In all, 207 core sections from the 91 cores were analyzed. Initial screening analyses include total scanning fluorescence (TSF), C15+, CO2, and C1-C5. Samples with high TSF values were analyzed further for biological markers, and samples with high gas values were analyzed for carbon isotopes. From the analyses, indicators of migrated liquid or gaseous petroleum hydrocarbons were developed and used to qualify cores and distinguish them from background (Bernard et al., 2008).

Sediment extract indicators include:

- the maximum intensity from total scanning fluorescence measurements (TSF Max Int),
- the mass in µg/g of the unresolved complex mixture (UCM) integrated from the C15+ hydrocarbon chromatograms, and
- the thermogenic/diagenetic n-alkane ratio (T/D Ratio).

Interstitial gas indicators include:

- the sum of the concentrations in ppmV of the alkane gases (ΣAlk Gas) and
- the ratio of the concentrations in ppmV of ethane to ethene (C2a/C2e).

In the study 197 of the 207 extracts analyzed for fluorescence had TSF Max Int below 10,000 intensity units while 10 extracts had between 10,000 and 100,000 intensity units. At one site, TSF values were substantially higher and ranged up to 1.5 million. 178 of the 207 samples (86%) contained background levels of light hydrocarbon alkane gases totaling less than 100 ppmV with the predominant hydrocarbon gas being methane, considered background (Bernard et al., 2008). Nineteen samples contained alkane gases between 100 and 1,000 ppmV, five samples contained alkane gases between 1,000 and 10,000 ppmV and five samples contained alkane gases between 10,000 and 100,000 ppmV.

Oil seep occurrences in Cendrawasih Bay are partially obscured by recent organic matter in the piston core extracts. Nevertheless, one significant oil seep was positively identified on the basin flank (Figure 4) and the biomarker characteristics indicate a marine shale source of Neogene age also reported by (Noble et al. (2009). The sample was a very dark gray, soft, silty clay with gas cracks throughout the core and a strong H2S smell. The presence of C1-C5 gases and carbon isotopes ($\delta^{13}C_1$ = -68 ‰, $\delta^{13}C_2$ = -47 ‰, $\delta^{13}C_3$ = -25 ‰) indicate a mixed biogenic and thermogenic source for the gases. One other oil seep was identified, also near the basin margin.

In the study 197 of the 207 extracts analyzed for fluorescence had TSF Max Int below 10,000 intensity units while 10 extracts had between 10,000 and 100,000 intensity units. 178 of the 207 samples (86%) contained sediment (interstitial) light hydrocarbon alkane gases totalling less than 100 ppmV with the predominant hydrocarbon gas being methane, considered background (Bernard et al., 2008). Nineteen samples contained alkane gases between 100 and 1,000 ppmV, five samples contained alkane gases between 1,000 and 10,000 ppmV and five samples contained alkane gases between 10,000 and 100,000 ppmV.

Alkane gases detected in the sediment samples include methane, ethane, propane, iso-butane, n-butane, neo-pentane, iso-pentane, and n-pentane. Methane, ethane, and propane, and the two alkene (olefin) gases, ethene (ethylene) and propene (propylene), were detected in virtually all samples.

The natural presence of high levels of C2+ alkane gases serve as a good indicator of migrating thermally-sourced gas, because ethane, propane, the butanes, and the pentanes are not locally produced and sustained at more than a few ppmV concentration levels in near-surface marine sediments. On the other hand, the

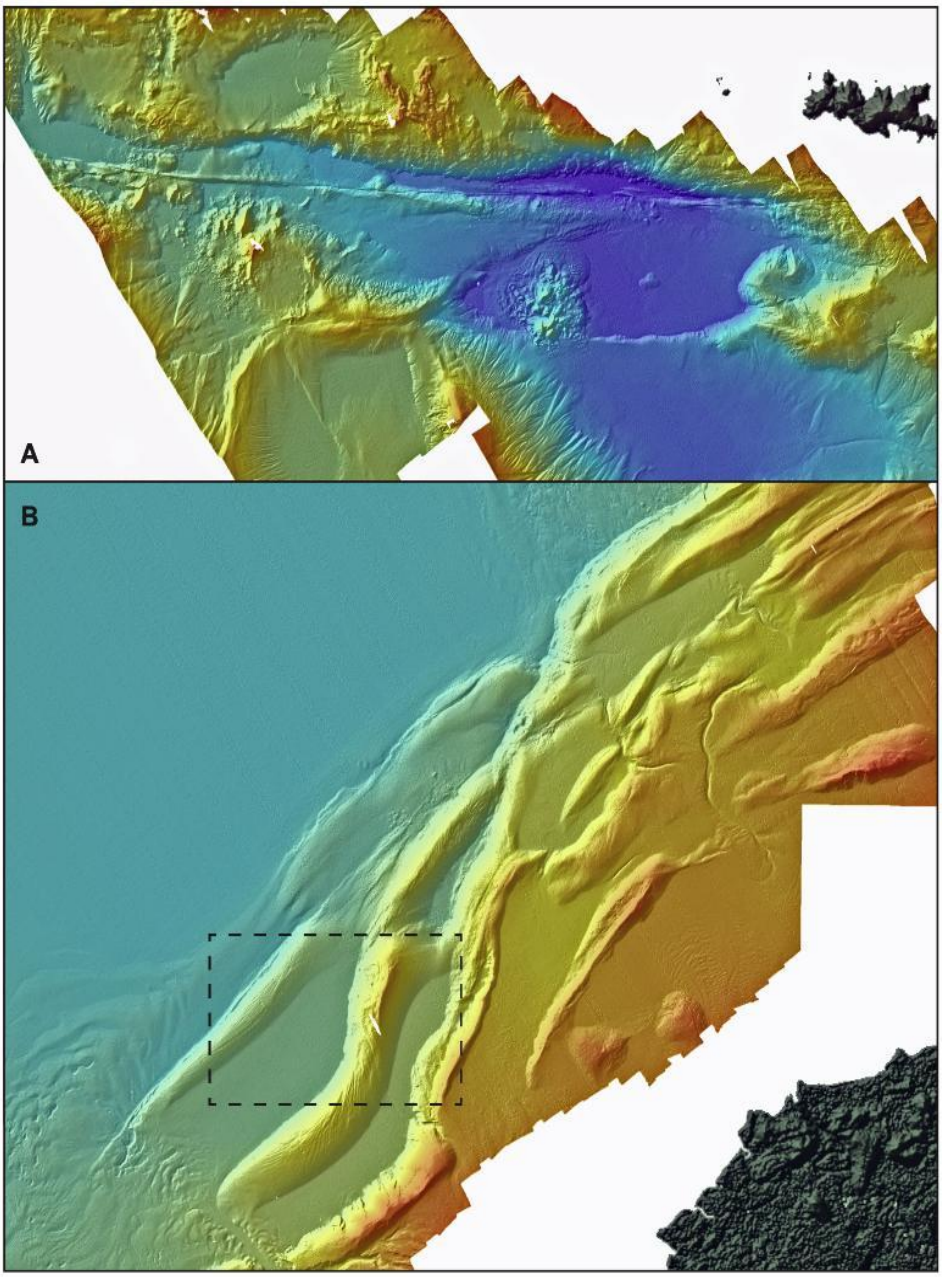


Figure 6: *Higher resolution bathymetric images taken from Figure 2; (A) Yapen Fault (plate boundary between Australian and Pacific plates) with prominent transtensional basin and 8km-diamter mud volcano; (B) emerging fold-and-thrust belt in the Waipoga Basin.*

absence of high levels of the C2+ alkane gases does not necessarily mean that thermogenically-sourced gas is not present.

Although the carbon isotopic composition of methane in many of the samples appears to approach the "biogenic gas" range, several of the gas samples also contained an unambiguous thermogenic component. These seep gases are perhaps comprised of a mixture of end members of biogenic gas with methane isotopes as light as –88‰ and thermogenic gas with a C2+ fraction of 1-10% and methane at -45‰. This trend of common source mixtures may indicate a low to medium flux of upward migrating thermogenic gas.

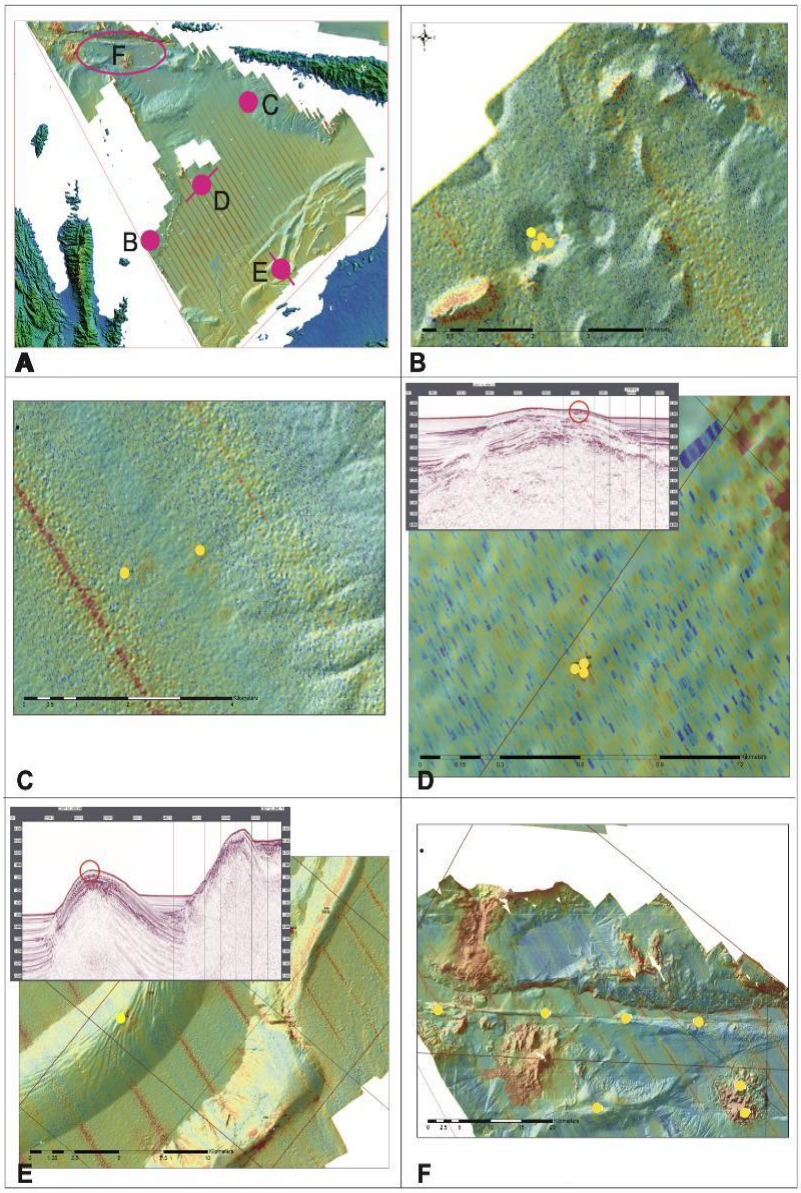


Figure 7: *Cenderawasih Bay geochemistry studies. A: Regional map of multibeam backscatter on shaded relief bathymetry showing the location of Figures 7B through 7F. B: multibeam backscatter image showing 1km-diameter, 40m deep pockmark with a relatively flat floor and moderately elevated backscatter; 7 cores, 21 samples; scale bar 4km. C: multibeam backscatter image with 2 core sites on relatively elevated backscatter area; 2 cores, 6 samples; scale bar 4km. D: multibeam backscatter image showing elevated backscatter patch; 4 cores, 11 geochemical samples; approximate location of seismic line inset shown on regional location map; scale bar 4km. E: multibeam backscatter image in fold belt area of SE Cenderawasih Bay; 1 core, 3 samples; approximate location of seismic line inset shown on regional location map; scale bar 10km. F: multibeam backscatter image showing the locations of 7 cores taken along the Yapen Fault Zone and adjacent volcanic feature; scale bar 20km.*

In summary, thirty cores were determined as containing migrated thermogenic gas. The area in which these cores were located is shown on Figure 6 and corresponds well with the extend of the fold-and-thrust belt where the Neogene sedimentary section is thickest.

RESERVOIR

A modern fan system is present in the south of Cenderawasih Bay (Figure 8) and demonstrates how potential reservoirs might have formed in the Plio-Pleistocene in the Waipoga Basin. The submarine channel system appears to originate which from a river in the Weyland Mountains and flows into Cenderawasih Bay near the town of Wanggar in West Papua (Figure 1). Prominent large sediment waves formed as unchannelised flow adjacent to the main channel. Distal to the submarine channel system, a submarine fan is clearly imaged by backscatter (Figure 8B) and shows an overall aggradation to the northeast. Clean sands were recovered by cores from the fan, together with large fragments of wood and plant material

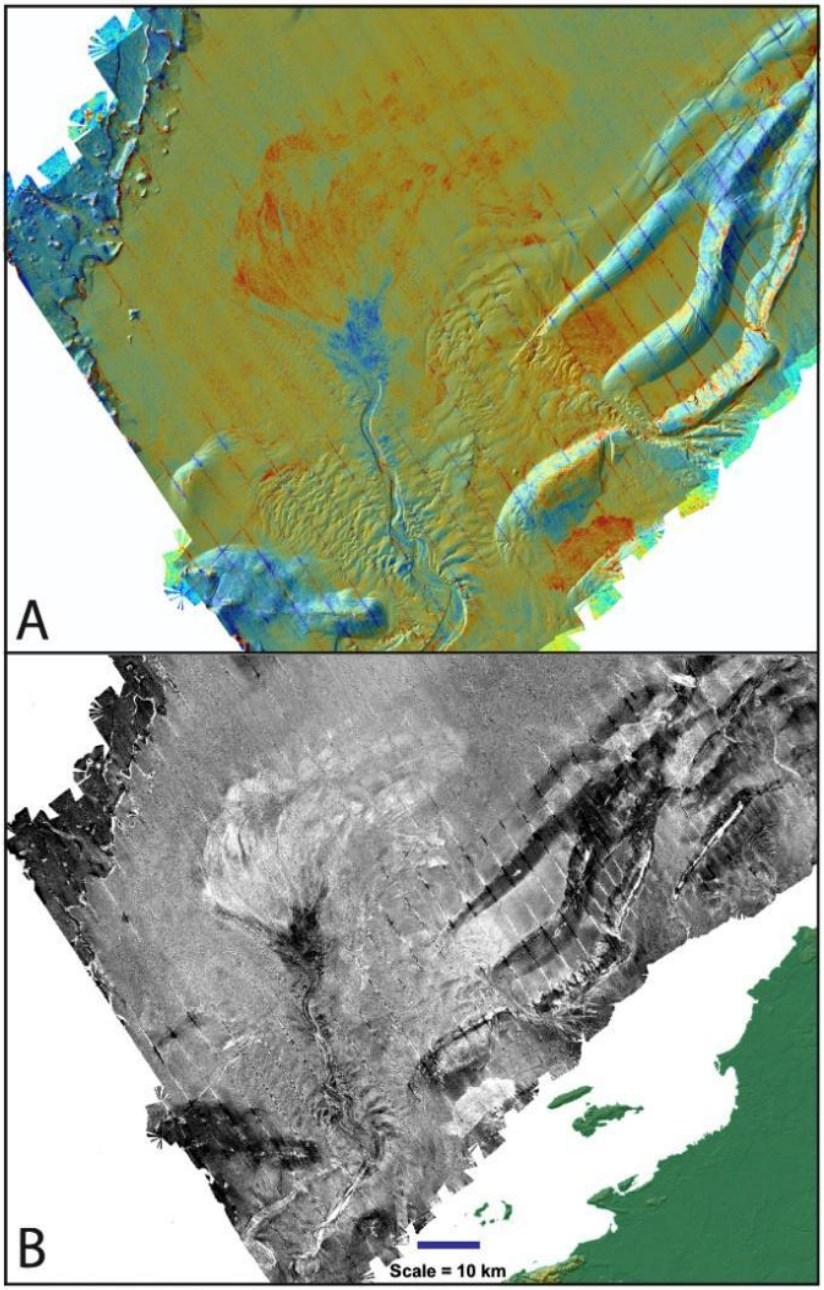


Figure 8: *Backscatter images of southern part of Cenderawasih Bay showing prominent channel and fan system. A: colour image, backscatter draped on bathymetry; high backscatter is red, low backscatter is blue.B: black and white image, backscatter only, high backscatter = white. High backscatter indicates sandier deposits and blue muddier deposits, both confirmed by core samples.*

Similar turbidite reservoirs and potential reservoirs containing abundant plant material in the deepwater Mahakam Delta and adjacent Makassar Straits are also source rocks (Guritno et al., 2003; Saller et al., 2006).

In this area, Teas et al. (2008) showed that active deformation of the sea floor is a key controlling factor for the distribution of sediment in that area and beyond with folds serving to trap sediment or deflect

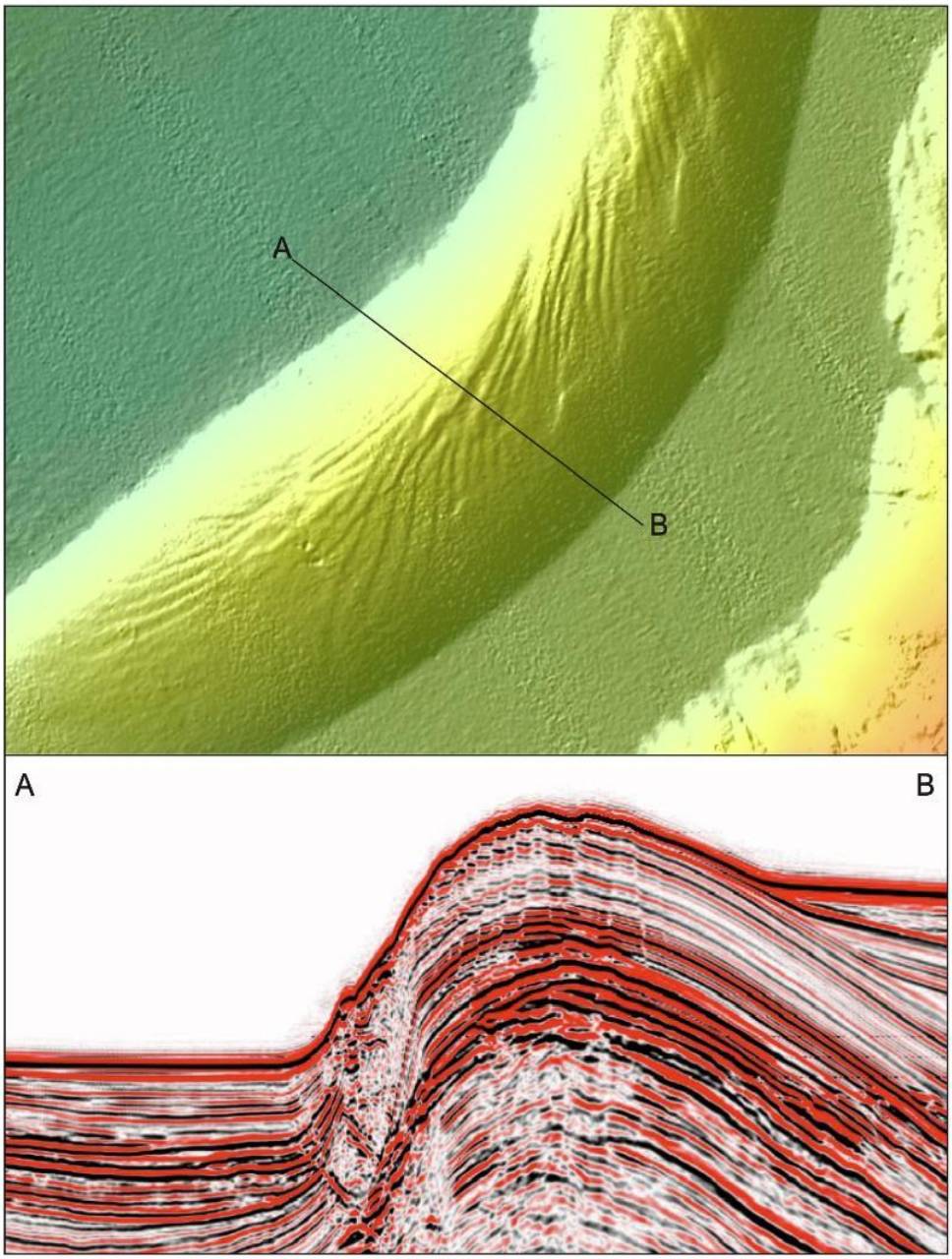


Figure 9: *(A) high resolution bathymetric image of part of fold-and-thrust belt in the Waipoga Basin; note later bending and feather-like fractures in the fold. (B) seismic image across the fold.*

the dispersal system. The main dispersal systems include fill, spill, and drain.

Two areas based on general morphology related to the interplay between deposition and deformation were recognised: an eastern area characterized by many anticlines, shallower seafloor, numerous mini-basins and a low gradient fill and spill depositional system; and a western system with few anticlines, deeper seafloor, few mini-basins, and a high gradient bypass depositional system. The boundary area between the two domains is generally devoid of modern deposition, with seafloor morphology dominated by structural features and landslides/mass wasting

Cenderawasih Bay is surrounded by variable types of basement, suggesting clastic reservoirs are likely to be variable

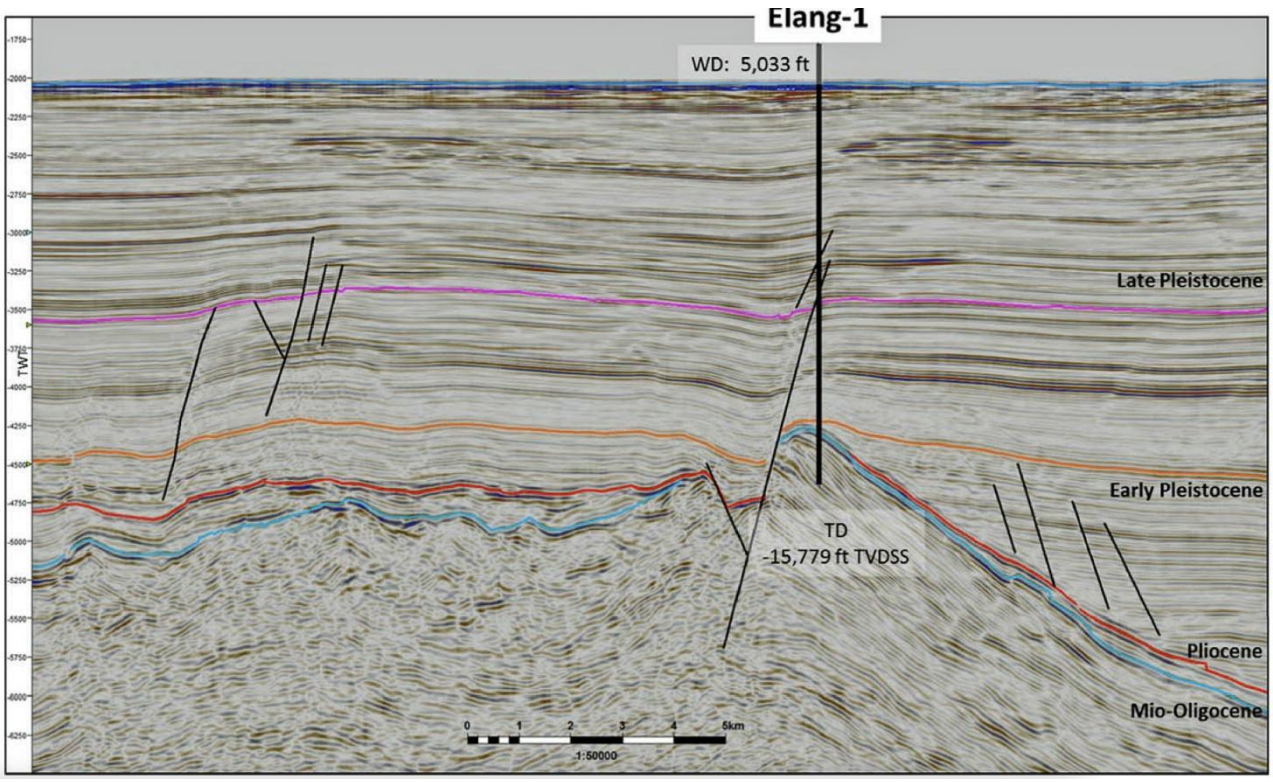


Figure 10: *Seismic section through Elang-1 well in Cenderawasih Bay (after Noble et al., 2016); location of well indicated on Figure 1.*

in composition depending on the geology of the catchment area.

Other potential reservoirs include the Late Oligocene–Miocene carbonate successions immediately underlying the Plio-Pleistocene clastics of the Waipoga Basin. Tertiary carbonate reservoirs are productive in numerous other parts of East Indonesia.

HYDROCARBON MIGRATION IN THE FOLD AND THRUST BELT

As previously noted, the bathymetric image of the fold-and-thrust (Figure 6B) shows that some folds were further deformed subsequent to the main folding phase; a more detailed image is presented as Figure 9A and shows faint lines on the crest of a fold which are interpreted as "keystone" faults resulting from extensional brittle fracture of the fold crest, confirmed by imaging seen on a seismic section across the fold (Figure 9B). The change from ductile to brittle deformation is probably related to temperature and lithostatic pressure (e.g., Wong et al., 2004).

Four cores taken on fold axes in this area show the presence of thermogenic hydrocarbons and it is concluded that the post-folding brittle deformation facilitated the gaseous migration along faults.

DRILLING

The Elang-1 exploration well (for location see Figure 1), drilled by Repsol YPF and partners in Cenderawasih Bay in 2013 (Figure 10), targeted a sedimentary package comprising carbonates and clastics of Tertiary age in a large four-way structural anticline. The well successfully encountered "massive micritic limestone

of Miocene to Oligocene age which was tight, with no hydrocarbon indications" (Noble et al., 2016).

The oil seep noted above was resampled by subsequent coring and conformed to be a substantial oil seep with strong thermogenic composition. We note that the Elang-1well was located away from the oil seep leaving open the possibility that the source of the seep could be feeding the reservoirs in Cenderawasih Bay

DISCUSSION AND CONCLUSION

The Tertiary basins of Southeast Asia invariably contain good source rocks. Hydrocarbons from paralic or deltaic source rocks arise from coals and coaly shales deposited in a variety of fluvial to estuarine lower coastal plain environments, typically in the late synrift and late postrift basin stages. The kerogen is mainly of terrigenous (land plant) origin (Doust and Noble, 2007). Organic matter accumulated in peat swamp, lake and mangrove environments and the resulting source rocks may have TOCs of up to 80%. Critical to the development of a rich charge system is an extensive area of tropical lowland swamp environments (Doust, 2017).

Mangroves occur on all coastlines and in all estuaries and embayments in West Papua where areas most favourable to mangal development include deltaic areas, embayments and deep estuaries that are sheltered from excessive wave action and where mud and silt accumulation are taking place. Mangroves are particularly well developed on the eastern side of Cenderawasih Bay (Johnstone and Frodin, 1982). In more brackish areas of the mangrove swamps (estuarine tidal floodplains) Nipa Palm (Nypa fruticans) is a potential oily source.

The presence of hydrocarbon shows in onshore exploration wells and the proximity of oil and gas surface seeps east of Cenderawasih Bay are indicative of effective source rocks in the region (McAdoo and Haebig, 1999). Sea-floor piston cores from Cenderawasih Bay revealed the presence of significant seepage of hydrocarbon seepage, strongly suggestive of the presence of an offshore active petroleum system. The biomarker characteristics of the oil seep sampled in Cederawasih Bay was interpreted to indicate a marine shale source of Tertiary age (Noble et al., 2009). Maximum thickness of sedimentary section in the Waipoga Basin is certainly sufficient to mature any source rocks deeper in the Plio-Pleistocene and older successions.

SeaSeep provided a rapid and cost-effective tool to undertake frontier exploration in Cenderawasih Bay, a remote underexplored area in Eastern Indonesia where little hard data had previously existed. Good evidence has been presented that an active petroleum system is generating hydrocarbons, including oil. Numerous structural traps remain untested and await further work to reduce reservoir risk and structural integrity.

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multibeam and coring / heatflow programs. Interpretation was carried out by Isis Petroleum Consultants, Perth. The work in Indonesia was carried out in collaboration with PT. Gema Terra and we acknowledge the invaluable help given by Jan Ong and Ibu 'Ika' Mustikawati.

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