Highlights and Implication of a Deep-Crustal Seismic Reflection Survey in the Arafura Sea Region

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Abstract

A regional 2-D reconnaissance seismic survey, ArafuraSPAN™, provideS pre-stack depth images down to 40 km, allowing new interpretations of the basement structure and its influence on the overlying sedimentary cover of at least seven geological provinces. In the Arafura Sea, the new data have revealed an enormous two-part Proterozoic supracrustal section comprised of a some 15+ km thick Arafura Basin and an underlying additional 15+ km McArthur Basin equivalents. The stratigraphic thicknesses of these rocks make up virtually the entire crust under the Arafura platform. Stratiform reflections are interpretable to a depth of over 30 km, an imaging first and a game changer in terms of understanding the regional geological framework. The best available interpretation of this section is that it represents a peri-cratonic large igneous province of Proterozoic age, preserved as virtually the entire crust. In the Banda Sea, structural relationships between the Tanimbar accretionary prism, the Weber Deep, and the platform suggest that the Weber Deep initiated as a forearc extensional event the severed the accretionary prism from its hard volcanic core, and then evolved into a major basin within the Banda Basin. The Seram thrust belt is shown to lie above a strike-slip system that separates the Banda microplate from the Bird's Head, and forms the plate boundary in that area.

Introduction

The deep crustal imaging programs conducted by ION/GXT, many of which penetrate to 40 km, commonly provide new insights into the geology of and address some of the fundamental geological problems in their subject areas. They consist of PSTM and PSDM (pre-stack time and depth migration) lines located specifically to highlight geologically significant transects. The crustal reflection survey under consideration here is no exception. The ArafuraSPAN survey (Figure 1) spans a remarkable variety of tectonic environments: a long-lived, stable Precambrian craton under the Arafura Sea itself, an active margin involving subduction of young oceanic crust along the eastern rim of the Banda Sea, an active collisional margin between micro-continents and Australia at the Seram Trough, the passive margin along the northern coast of Australia in collision with the Banda Arc, and intra-plate effects of the greater north Australia-Asia collision.

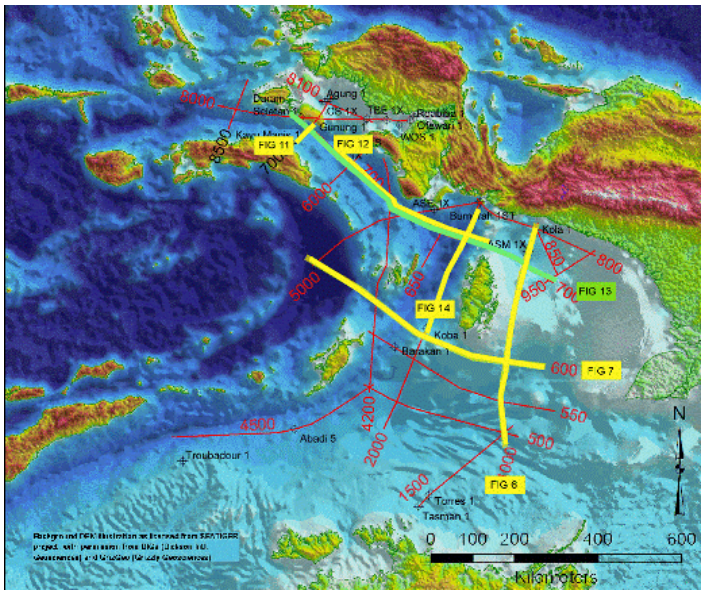


Figure 1. *Location map of seismic lines shown in this article. ArafuraSPAN grid is shown in finer red lines.*

The SPAN™ surveys were conceived in the early 2000s in response to an industry need for new regional datasets that overcome limitations of legacy seismic and to provide a crucible for new exploration concepts. They do this by providing a regional crustal-scale framework of data that stimulate new insights into the architecture of hydrocarbon-bearing basins and their petroleum systems and can facilitate basin modeling. Until the SPAN surveys, deep reflection imaging programs were primarily academic, such as COCORP and ANSIR, and based on 20 year old technology (Brewer and Oliver, 1980; COCORP, 2009; ANSIR, 2009). SPAN surveys have been acquired to date in offshore SE Asia, southern Australia, and many other continental margin areas worldwide (ION, 2010).

Similar to many of the other surveys, the ArafuraSPAN survey is comprised of nearly 7,000 line kilometers of 2-D data acquired with a 50 m shot interval, 25 m group interval and maximum offset of 9,130 m. The record length is 18 seconds TWT and the data have been processed to prestack time images of 16 seconds and prestack depth images of 40 km (or more) record length. The lines capture key features of the geologic framework of the Bird's Head, Arafura Sea, Seram Trough, and Banda Sea, while tying to sparse petroleum exploration wells for stratigraphic control.

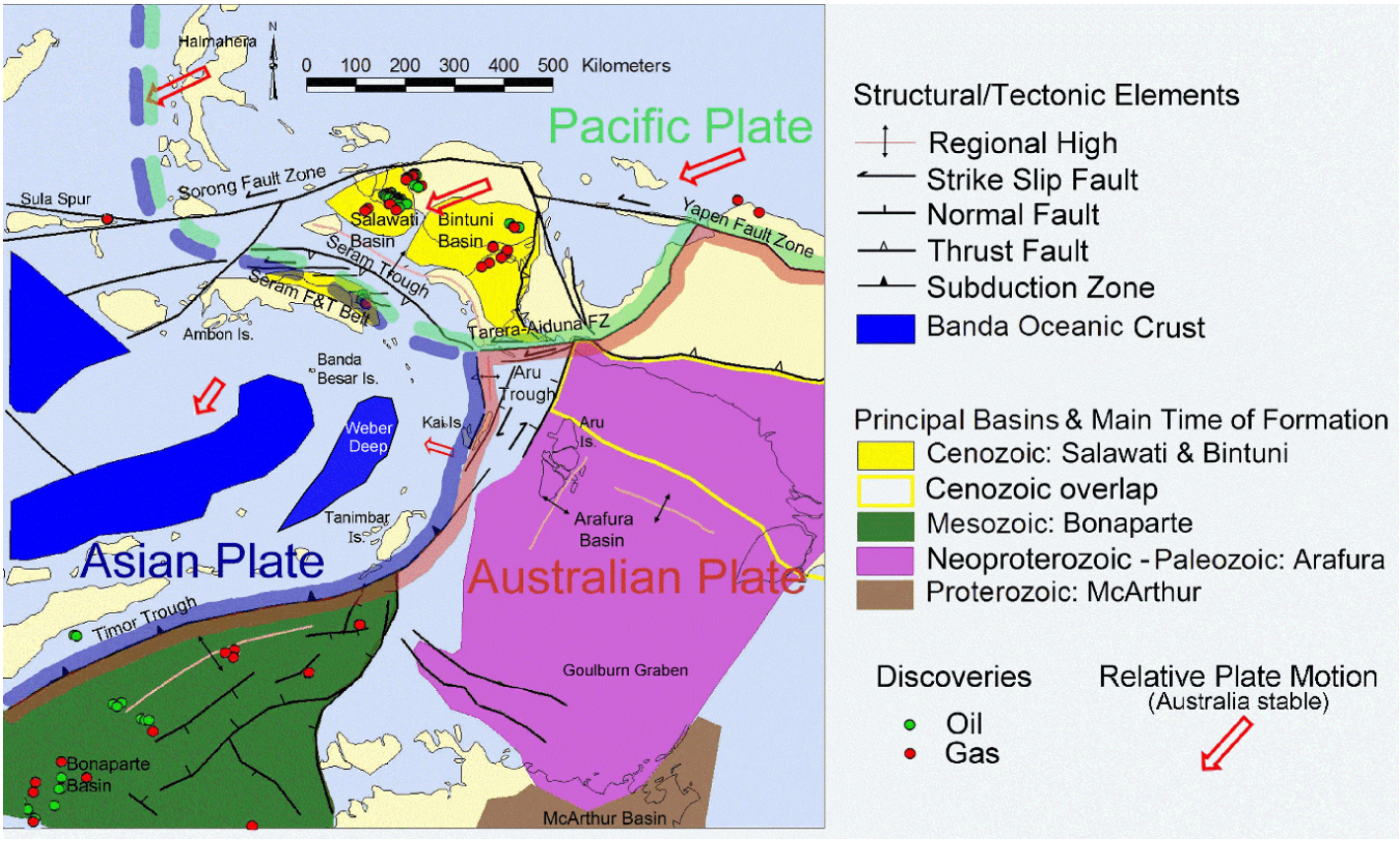


Figure 2. *Tectonic elements in the ArafuraSPAN area. Red arrows are GPS vectors derived for motion of the locations near the but of the arrow. Plate boundaries in broad green (Pacific), brown (Australia), and blue (Asia) stripes. Dashed where problematical. Constructed in ArcGIS.*

Any available seismic refraction surveys and available gravity and magnetic data, both public domain and gravity data gathered during the seismic acquisition, are typically used to constrain the seismic processing stream for the deep crustal structure imaging and interpretation. In this particular case, Hayes (1978) was used to supplement the data collected in connection with ArafuraSPAN. Such an approach places limits on the velocities of the deeply buried sedimentary and non-sedimentary rocks that are critical to the PSDM processing workflow. The resulting 40 km depth sections are used for interpretation, and the time sections are used to connect the surveys to legacy industry data. The regional extent and depth of these images requires a different mindset from that of interpretation of conventional data, not the least of which is an appreciation of the scale of the observations.

Regional Geology

The ArafuraSPAN survey is located at the junction of three major tectonic plates, the Pacific, Australian and Southeast Asian (Figure 2). The Australian Plate is a long-lived continental block, in contrast to the SE Asian and Pacific plates, which are amalgams of continental and mixed-affinity terranes along with oceanic crust. The Arafura platform is located on the northern, leading edge of the Australian plate where its surface lies just below sea level and forms the geological connection between New Guinea and Australia. Its northern rim is involved in the Neogene New Guinea collisional orogen, and was previously overprinted by the northern extent of the Paleozoic Tasman orogen (Figure 3).

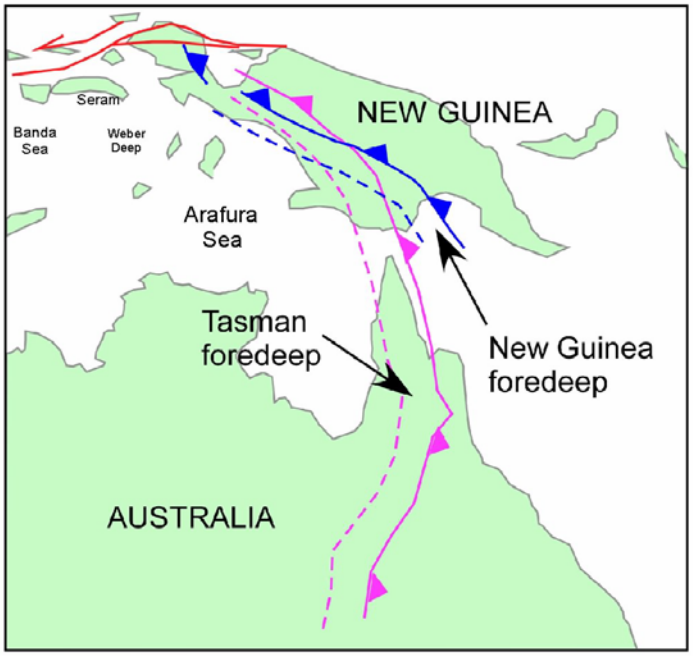


Figure 3. *Locations of the major foreland basin troughs in the ArafuraSPAN region. the Paleozoic Tasman in pink and the Cenozoic New Guinea in blue*

The earliest evolution of the area involves the cratonization of parts of northern and western Australia, interpreted as the deepest crystalline basement in the ArafuraSPAN data set. This basement is comprised of late Archean to Paleoproterozoic cratonic blocks and intervening orogenic

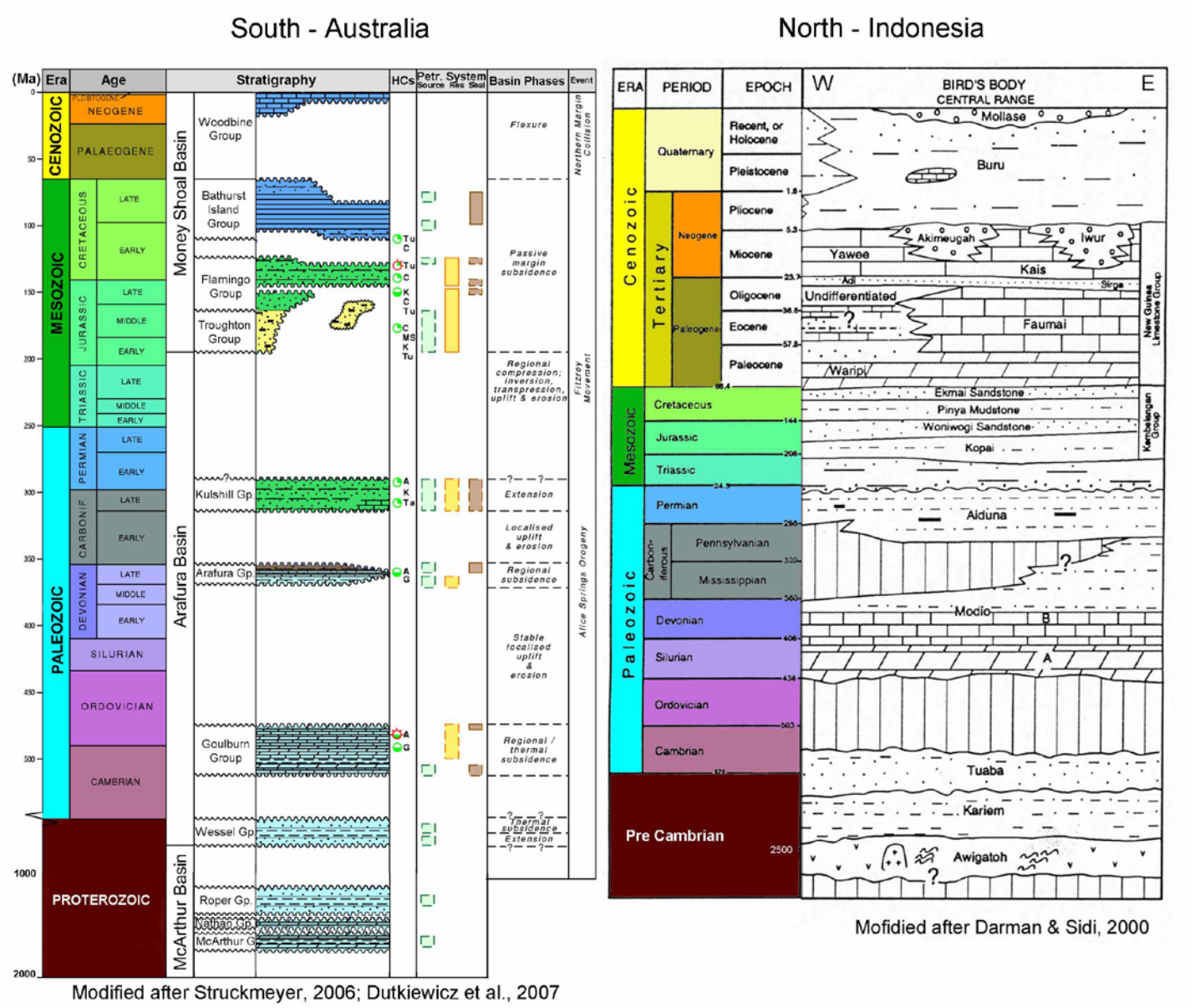


Figure 4. Generalized stratigraphy of the region.

belts (Cawood & Korsch, 2008). The main basins are built upon this amalgamated Precambrian framework.

In general terms, three major basin-forming tectonic cycles of assembly and breakup reworked the crust subsequent to the initial establishment of cratonic crust:

- Columbia (Paleo-Mesoproterozoic, ca. 1900-1300 Ma) associated with formation of the McArthur Basin;
- Rodinia (Meso-Neoproterozoic, ca. 1300-600 Ma) associated with the formation of the Arafura Basin; and
- Gondwana, associated with the upper Arafura and Australian NW Shelf basins such as Bonaparte.

Gondwana began to assemble at about 650 Ma, was formed by the end of the Cambrian, sutured with Laurasia to form the southern half of Pangea in the early Devonian, and was fully amalgamated by ca. 320 Ma (Carboniferous). Subduction along the southeastern convergent margin of Gondwana produced the Tasman fold belt, with some of these Lower Paleozoic metasediments forming the basement rock of the Kemum Terrane of the Bird's Head in western New Guinea.

A collection of terranes fragmented from the northern divergent margin of Gondwana in the Devonian, Permian and Jurassic. They were later sutured to Asia to form various parts of Indochina and Sunda. The Devonian episode of extension is associated with formation of the Petrel Sub-basin of Bonaparte and other basins to the southwest, and the Permian episode formed the Westralian Superbasin along the entire northwestern margin of the Australian Plate. The last breakup event began about 185-160 Ma (Early-Middle Jurassic), when rifting overprinted and enhanced the precursor Westralian Superbasin to form the basin structure of much of the Australian NW Shelf. This last event culminated in the current seafloor and formation of a drift margin along the northwestern Australian plate margin. In the Neogene, this margin impinged on SE Asia while portions of the Pacific Plate (e.g. the Caroline microplate) collided from the northeast. In broad terms, the resulting compression folded, thrusted and uplifted Timor, the Banda accretionary arc, and the Seram, Lengguru and Central New Guinea fold/thrust belts. Erosional products from the rising fold belts accumulated in foreland basins such as Bintuni, and the

present day convergent plate setting was established (Figures 2 and 3).
The basins in the region developed through many episodes of subsidence and uplift/deformation, overlapping older basins in a variety of configurations. They are shown in Figure 2 with color keyed to their primary time of formation. Phanerozoic stratigraphy is shown in Figure 4. Adjacent basins have similar Upper Paleozoic-Recent strata although often the nomenclature varies.

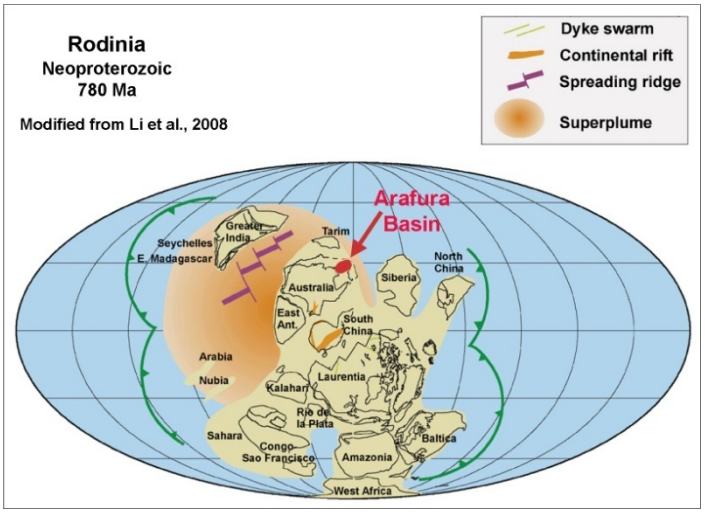


Figure 5. Position of the Arafura Basin in relation to the Rodinia reconstruction, for 760 Ma.

Precambrian underpinnings of Arafura Sea

Arafura Basin. ArafuraSPAN images two basins containing impressive Precambrian sedimentary sections, the Arafura and McArthur Basins, primarily known from onshore in northern Australia. The younger of the two basins, the Arafura Basin formed on the Rodinia supercontinent in temperate latitudes (Figure 5). It was initiated in the Neoproterozoic as an intracratonic basin during upper crustal extension (Struckmeyer, 2006) but persisted into lower Paleozoic time as a broadly subsiding basin with little internal structure to drive the subsidence. Wessel Group sediments comprise the bulk of the basin fill, spanning the Neoproterozoic to the Eocambrian. The Wessel is known in Australia (Struckmeyer, 2006) from the Arafura-1 well and outcrops in the Wessel Islands, where it consists mainly of shallow marine sandstones, siltstones and mudstones with minor conglomerates and carbonates.

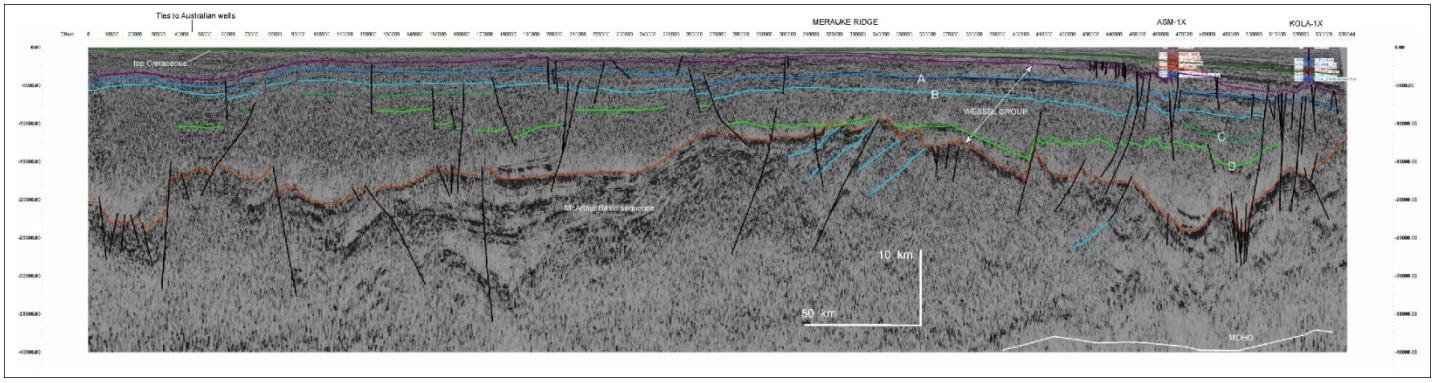


Figure 6. Line 1000 of the ArafuraSPAN data set, north to the right. Line is shown in a black to white color bar and in an average energy display. The display is an IHS Kingdom Suite option generated by squaring the average amplitude within pixelated areas down each trace of the data, the length vertically is the size of the seismic wavelet. It is useful in that the display tends to sharpen features within the crust.

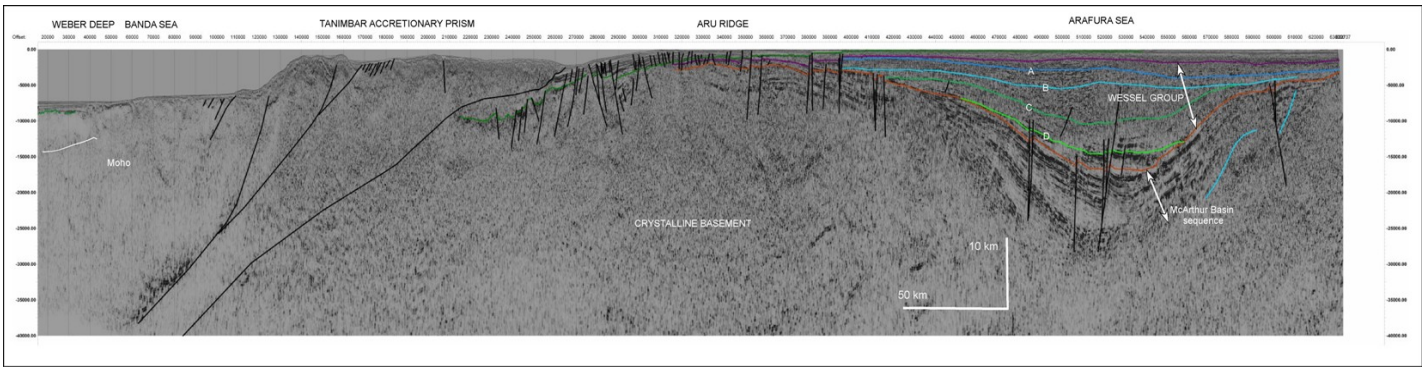


Figure 7. Line 600 of the ArafuraSPAN data set, east to the right. Line is shown in a black to white color bar and in an average energy display. The display is an IHS Kingdom Suite option generated by squaring the average amplitude within pixelated areas down each trace of the data, the length vertically is the size of the seismic wavelet. It is useful in that the display tends to sharpen features within the crust.

The lowest stratigraphic units onshore in New Guinea are termed the Kariem Formation which is composed of sandstone and shale both in outcrop and in Indonesian wells; it lies above the Awitagoh mafic volcanics in outcrop in southeastern Papua Province (Visser & Hermes, 1962) and together they appear to constitute a lowermost or pre-Paleozoic section. Nearshore wells have intersected the upper part of the Kariem Formation. Darman & Sidi (2000) dated the Kariem in New Guinea as correlative to the top of this Wessel Group, and thus it forms the uppermost part of the Wessel equivalents on the north side of the Arafura

Sea, where it caps a section that is as much as 10 km thick in places on the survey lines.

ArafuraSPAN stretches from the Goulburn Graben in the southeastern extreme of the survey (Figure 2) across the

Arafura Sea toward New Guinea. As such it images the entire Arafura Basin, and hence the Wessel Group can be traced on the ArafuraSPAN data without interruption from Australia to New Guinea. Several long lines (e.g. Figures 1and 6) are tied to the Indonesian wells, and show the Wessel section to approach 20 km in thickness. Figure 6 runs N-S, while Figure 7 shows a generally E-W section, 40 km in depth from the Weber Deep in the Banda Basin, across the Aru Ridge into the Arafura Basin. Both sections contain Wessel sediments that extend from about 2 km to 18 km depth. Note the vertical exaggeration of the section is about 5:1, the lack of large structures affecting the Wessel Group in these figures, particularly the broad blanket character of the Wessel Group in Figure 7 with little internal structure.

Correlations across this thinly covered platform are fairly easy, and indicate that the Phanerozoic is underlain along the entire length by the Wessel Group. Four key horizons that can be correlated across large distances were picked in the Wessel Group (Horizons A through D are annotated Figures 6 and 7), and have been used in this project to characterize the high-level subdivisions within the Wessel Group. There appears to be very little fault-controlled expansion of the stratigraphy above the basal unit: faulting is important in the basal unit D, which is affected by half-graben extension. Struckmeyer (2006) related the half-graben formation to NW-SE upper crustal extension associated with back arc processes between the Tarim Block and northwestern Australia during the breakup of the supercontinent Rodinia. We would agree that extension is confined to the lower part of the group. The basal unit is succeeded by horizon C, and this interval may be a sag phase in the conventional sense of the word. The upper Wessel sediments (the top of the Wessel Group to the top of the horizon C) form a regional blanket as much as 6 km thick, apparently unrelated to any known tectonic phase.

The Wessel Group as a whole forms the bulk of the section in the Arafura Basin, with the Paleozoic of lesser thickness (see below). The Wessel Group spans an enormous amount of time (300 m.y.), from Neoproterozoic to the Eocambrian, a remarkably long-lived history of sedimentation involving a number of different phases of platform evolution with only mild intracratonic tectonics. Figure 6 shows the section across 500 km of the shelf with a variation in the Wessel Group thickness from about 12 km to a maximum of 18 km. For typical continental crust of 40 km thickness, this means that over broad areas of the craton the Wessel represents 45% of the crustal thickness.

McArthur Basin. Even more remarkable is the appearance of the McArthur Basin under the Wessel group in the ArafuraSPAN survey. Unable to separate units within this section we equate the seismic interval to the totality of the

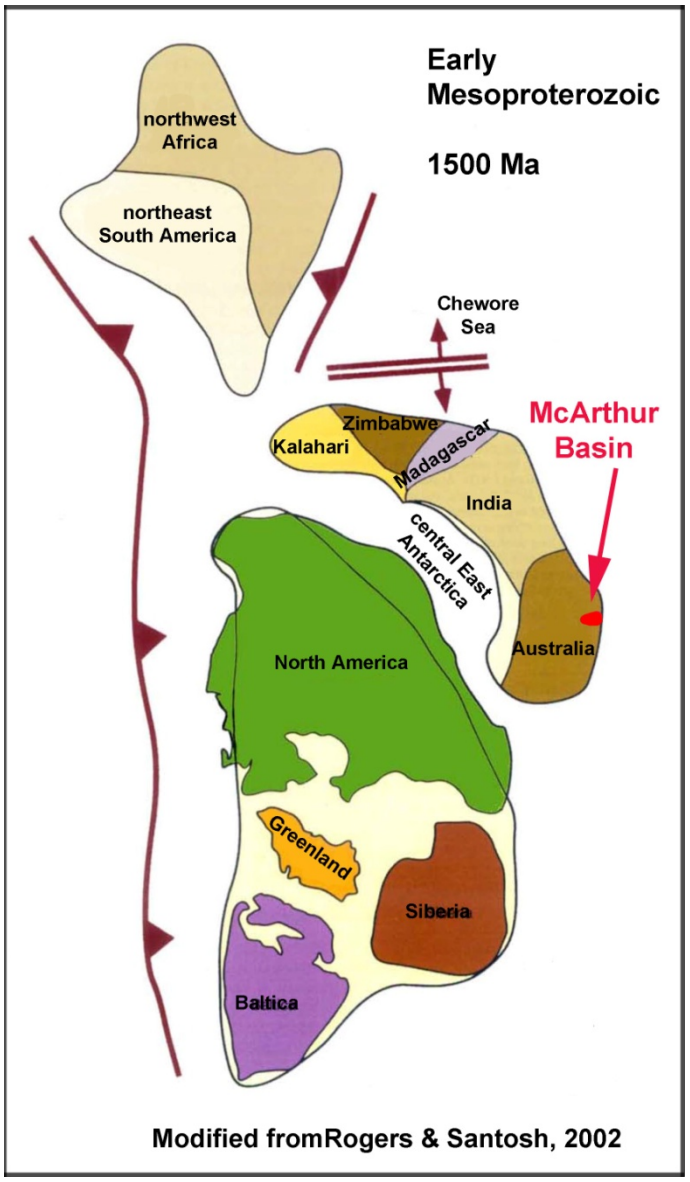


Figure 8. Position of the Arafura Basin in relation to the Columbia reconstruction, for 1500 Ma.

complicated McArthur Basin fill onshore in northern Australia (Rogers, 1996; Pegum, 1997; Worden, 2007; de Vries et al., 2008; Cawood and Korsch, 2008). Formed during the Mesoproterozoic on the outboard edge of the Columbia supercontinent (Figure 8), the basin fill as seen onshore in northern Australia consists of a basal arkose succeeded by three unconformity-separated stratigraphic groups, two of which contain thick, organic-rich shales that have sourced numerous live oil and gas shows in the onshore (Dutkiewicz et al., 2007; Summons et al., 1988).
The older McArthur and Nathan groups are comprised mainly of platform carbonates and evaporites, with lacustrine shales containing up to 10.4% TOC (total organic carbon) in the Barney Creek Formation of the McArthur Group (Jackson et al., 1988). Satyana et al. (2010) provide a possible modern stromatolite analog for these beds. The younger Roper Group is a siliciclastic sequence which contains numerous sandstone units and the Velkerri Formation shales, deposited in a deepwater shelf environment and containing 1-8% TOC with Type I/II kerogen. Sandstones in the Roper Group contain oil and gas shows typed mainly to the Velkerri with some

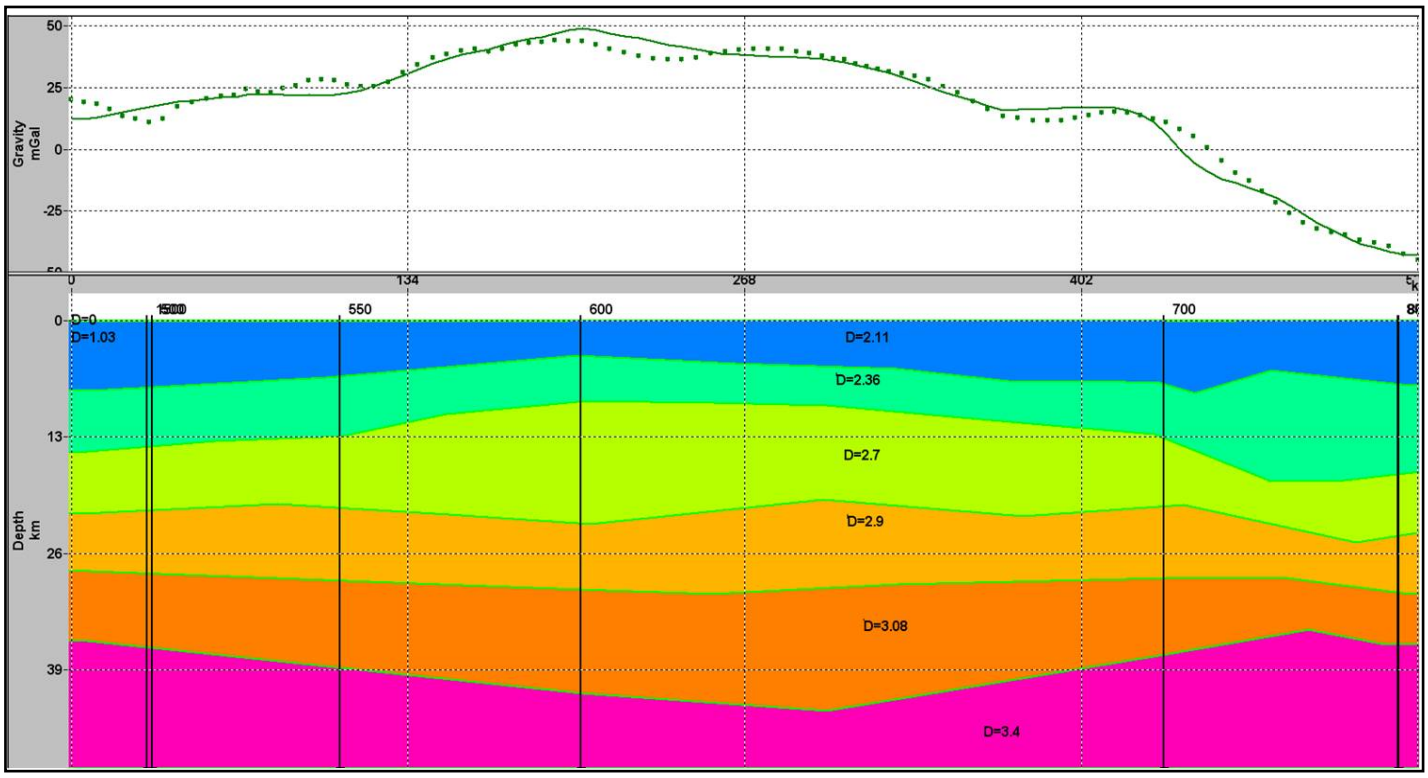
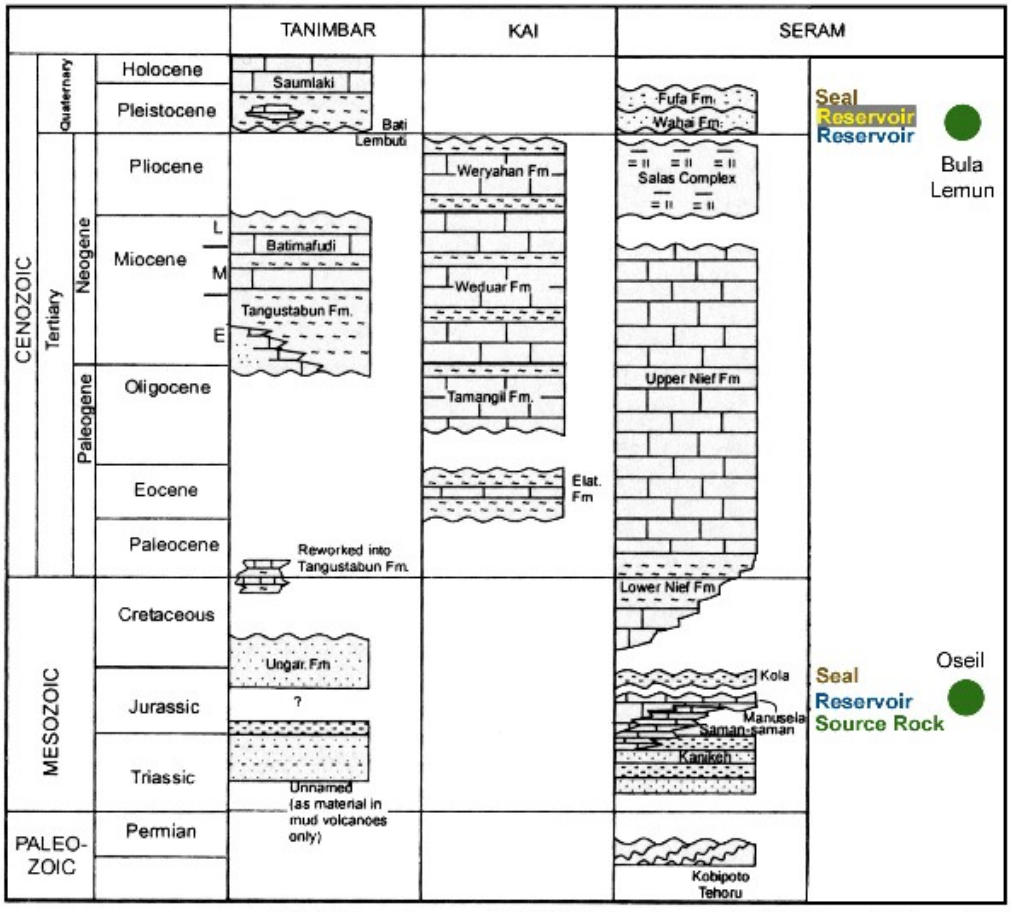


Figure 9. Gravity model for line 1000, showing the density distribution that best matches the observed gravity (solid line). Cross lines are shown in the black vertical lines on the display. Courtesy Bird Geophysical.

contribution from the Barney Creek (Dutkiewicz et al., 2007). Evidently, the crust in the Arafura has experienced a very mild thermal overprint to have a preserved petroleum potential over such a long period of geological time. Similar petroleum system elements may have been present under the continental shelf. In the offshore, of course, this mild thermal overprint could not survive under the massive thickness of Wessel Group rocks described above, but it does serve to illustrate the remarkably uneventful tectonic history or the region.

The ArafuraSPAN data show that the McArthur Basin



Modified from Darman & Siti, 2000; Courtney *et al.*, 1988; Kemp & Mogg, 1992

Figure 10. Internal stratigraphy of the Seram thrust belt.

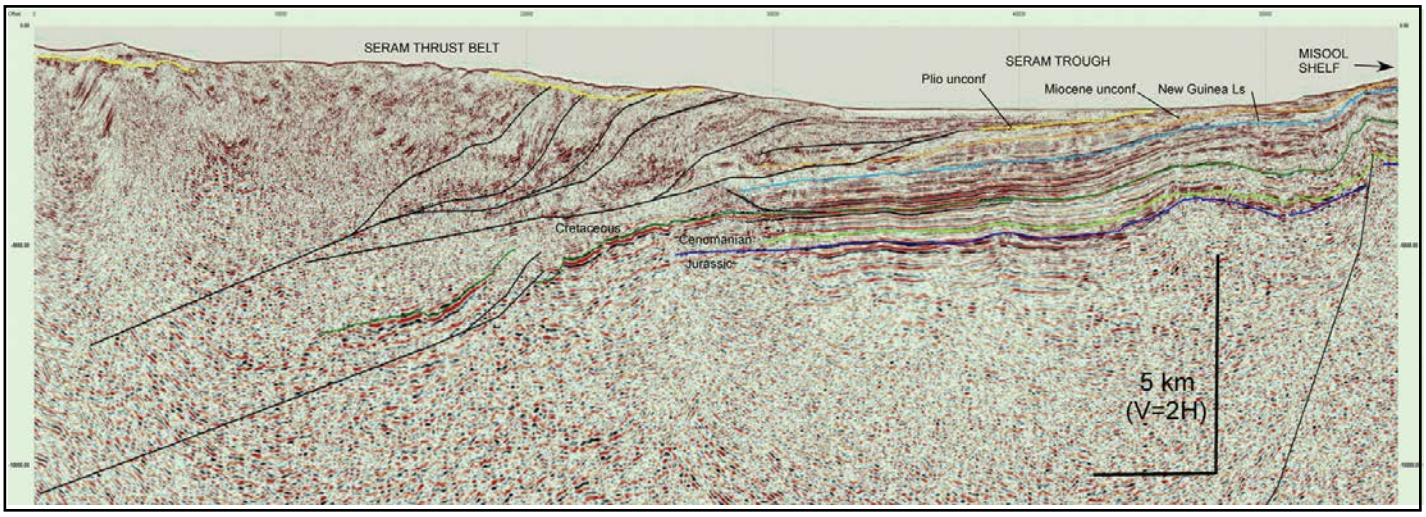


Figure 11. *A portion of line 7000 showing the frontal Seram thrust belt and the Seram trough. The edge Misool shelf is located on the right (North) side of the section.*

strata extend offshore into the Arafura Sea and thicken dramatically below the Arafura Basin. Beneath the Wessel Group, and in many places having a much more prominent seismic character, lies a variably-deformed section of what must be burial metamorphic simply by reason of their present depth (Figures 6 & 7). This section appears to be faulted where Wessel Group is thickened over it. It also appears to dip to the east from the Aru Ridge (Figure 7) and thicken as it does so. Unless this is an entirely new package of rocks we would correlate it broadly to one or more of the many units in the McArthur Basin. Figure 6 shows that this section extends to an astounding depth of 35 km, and that Moho lies below 40 km in this area. The bright reflections in the section and some cross-cutting character suggest that this section is dominated by metavolcanics, as does the gravity modeling inference that the densities are slightly higher than normal continental crust (Figure 9).

We would intepret these relationships to suggest that the continental margin of the McArthur basin is occupied by peri-continental large igneous province similar to something like the Deccan traps in India. The onshore equivalents of this section are much less impressive, and in the literature are usually described in passing as mafic volcanics interbedded with much more interesting sedimentary sections (Rogers, 1996; Pegum, 1997; Worden, 2007; de Vries et al., 2008; Cawood and Korsch, 2008). Which of the volcanic intervals onshore is equivalent to those offshore is at present unknown.

A remarkable thing about this section is that it rests on very thin older continental crust or perhaps even overlaps a Precambrian continent-ocean transition, one that has survived since mid Proterozoic time with little deformation. If so the rocks above the thin crystalline basement themselves form a major part of the crust, and represent a period of continental crustal growth relatively unaffected since the Proterozoic. The craton-margin Proterozoic is deformed only toward the north and east, some of which is shown on Figure 7 as the thrust faults denoted in blue. Part of the explanation of this long survival may be the location of the section on the outboard edge of the craton throughout most of the Proterozoic (Figures 5 and 8) and well into the Paleozoic before the deformation of the continental margin in the Tasman orogenic cycle (Figure 3). To our knowledge a structural situation like this one is unprecedented in seismic reflection studies anywhere in the world.

Archean and/or Paleoproterozoic. The basement of the Aru Ridge, which trends generally NNE-SSW from Aru Island toward Darwin, is internally featureless in seismic character (Figure 7) and may represent the continental core over which the massive supracrustal section of the Arafura and McArthur basins was deposited. This basement may be older Proterozoic metamorphic complexes similar to the Pine Creek Inlier, or more likely they are similar in nature to late Archean inliers onshore in Australia, i.e. the Rum Jungle and Nanambu Complexes (Plumb, 1979; Worden, 2007) with ages of ~2,545-2,520 Ma and ~2,675Ma for the Woolner Granite. Sediments overlying this Archaen basement contain detrital zircons with ages ~2,506 Ma onshore in northern Australia.

Phanerozoic

Post-Wessel Paleozoic sediments are comparatively thin (a few thousand meters) across most of the Arafura Basin and represent relatively short time intervals separated by large hiatuses (Figure 4). The sediments were deposited in intracratonic to continental marginal settings along the northern edge of Gondwana as it drifted southward from subtropical to tropical latitudes during the Early Paleozoic, reaching temperate to cool southern latitudes by the Permian.

The Middle Cambrian-Lower Ordovician Goulburn Group contains a basal Jigaimara Formation consisting of shelfal limestone, shale, and dolomite succeeded by carbonates and siliciclastics. The Jigaimara is correlative with the Middle Cambrian Thorntonia(!) petroleum system of the Georgina Basin onshore northern Australia and geochemical characteristics of oil stains from Lower Paleozoic rocks of Goulburn Graben wells resemble Thorntonia oils. Struckmeyer (2006) therefore considers the Jigaimara

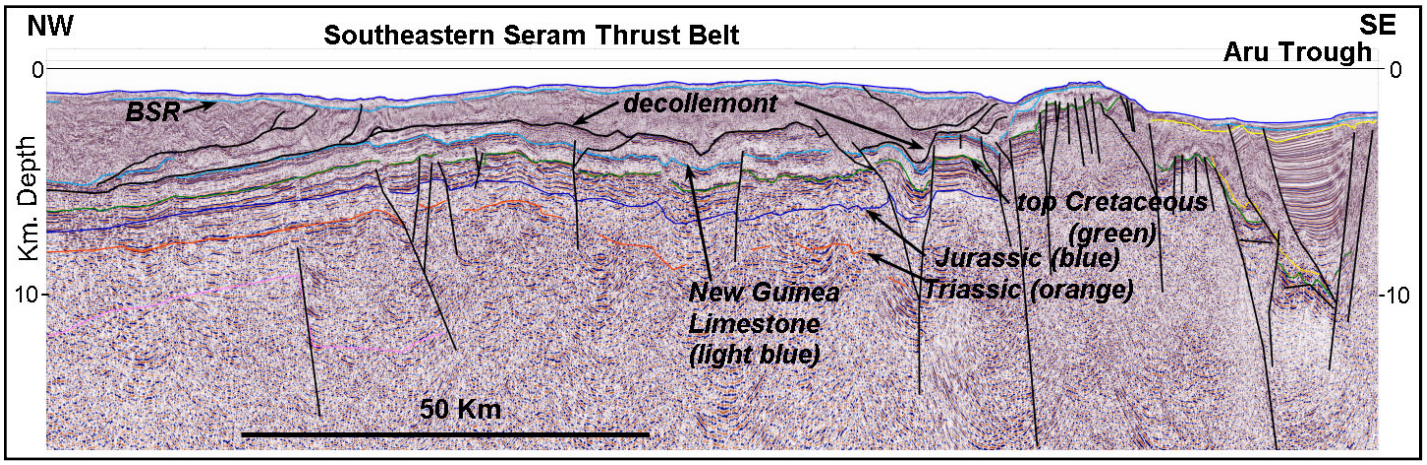


Figure 12. A portion of line 700 showing the decollement of the Seram thrust belt in relation to young strike-slip faults in the Seram trough, the edge of the Arafura shelf, and the Aru Trough on the east side of the line.

Formation the most likely hydrocarbon source for the Arafura Basin. The Goulburn Group is in turn unconformably overlain by the Upper Devonian Australian Arafura Group and correlative ?Siluro-Devonian Indonesian Modio Formation, which contain carbonates and interbedded siliciclastics. Live oil shows were encountered in this section at Kola-1 (Moss, 2001).

The Arafura Group-Modio Formation is unconformably overlain by the Upper Carboniferous-Lower Permian Australian Kulshill Group and correlative Indonesian Aiduna Formation. The section is composed of fluvial-deltaic to marginal marine interbedded sandstone, siltstones and claystone, with some coal and minor dolomite. This section had minor oil shows in Indonesian wells and the coals and carbonaceous shales may be source rocks where more deeply buried there (Moss, 2001; Darman & Sidi, 2000). The upper portion of the Permian section was removed by erosion following Triassic uplift of the Arafura area and local inversion (Struckmeyer, 2006), ending the Arafura Basin sequence. The southeastern-most lines in ArafuraSPAN image the inverted Goulburn graben. Note in Figure 4 that the Carboniferous and Permo-Triassic section is more complete on the northern side of the basin, in Indonesia, where it accumulated in the foreland basin for the Tasman orogenic system (Figure 3).

The post-Tasman section is succeeded over most of the Arafura Basin by onlap of mostly thin Cretaceous and younger cover, and in the north by a more complete Jurassic section capping the Tasman trough and pre-saging the Tertiary rejuvenation of foreland subsidence. Following a thin Paleogene section, also in the north, a thick Neogene section was deposited in the rejuvenated foreland basin peripheral to the rising Central New Guinea range. This section overlaps the Arafura Basin.

Neogene convergent plate boundary region

The gentle tectonics reflected in the Mesozoic and Paleogene history of the Arafura Sea is starkly contrasted with the Neogene orogenesis on the northern margin of the Australian plate. The provinces to the west and north of the Arafura plaform are involved in the complexities of the present day convergence and have diverse formal stratigraphies. As a consequence, our interpretation of the ArafuraSPAN data uses generic time-rock units rather than formational level units (e.g. top Cretaceous, Miocene limestones, etc.) to bring out any correlation commonalities that do exist.

The messy triple junction. In the Neogene, the northwestern passive margin of the Australian plate impinged on SE Asia, while portions of the Pacific Plate (e.g. Caroline microplate) collided from the northeast. In broad terms, the resulting compression folded, thrusted and uplifted Timor, the Banda accretionary arc, and the Seram, Lengguru and Central New Guinea fold and thrust belts. Erosional products from the rising foldbelts accumulated in the surrounding peri-orogenic basins such as the foreland trough in the main part of New Guinea and the Bintuni basin. Beyond that simplistic statement, the geology is controversial. The discussion that follows reflects the authors' point of view on the region, which is influenced by the concept that the area is a youthful triple junction whose component terranes are undergoing rapid rearrangement. Consequently tectonic elements may be playing very different roles in the current kinematic framework than they have in the past, so that some structural relationships may be misleading. This is particularly true of the northern rim of the Banda Sea. We feel that the ArafuraSPAN data help clarify some of the relationships there.

Figure 2 shows the major structural features, which in some cases serve as current plate boundaries. As recent GPS data have shown, the Bird's Head, some islands along the Sorong Fault zone, and Halmahera are all currently moving with the Pacific plate and thus have rapid WSW motion with respect to Australia (Stevens et al., 2002; Bock et al., 2003). Ambon and Banda Besar in the Banda Sea are moving in a distinctly more SW direction at a slower rate with respect to Australia, almost at 90° to the convergence of Asia with Australia, and thus are independent of all three major surrounding plates. We regard Ambon and Banda Besar to lie on an independent microplate, the Banda microplate. It is difficult to place a western boundary for the Banda microplate as GPS data are few from that area.

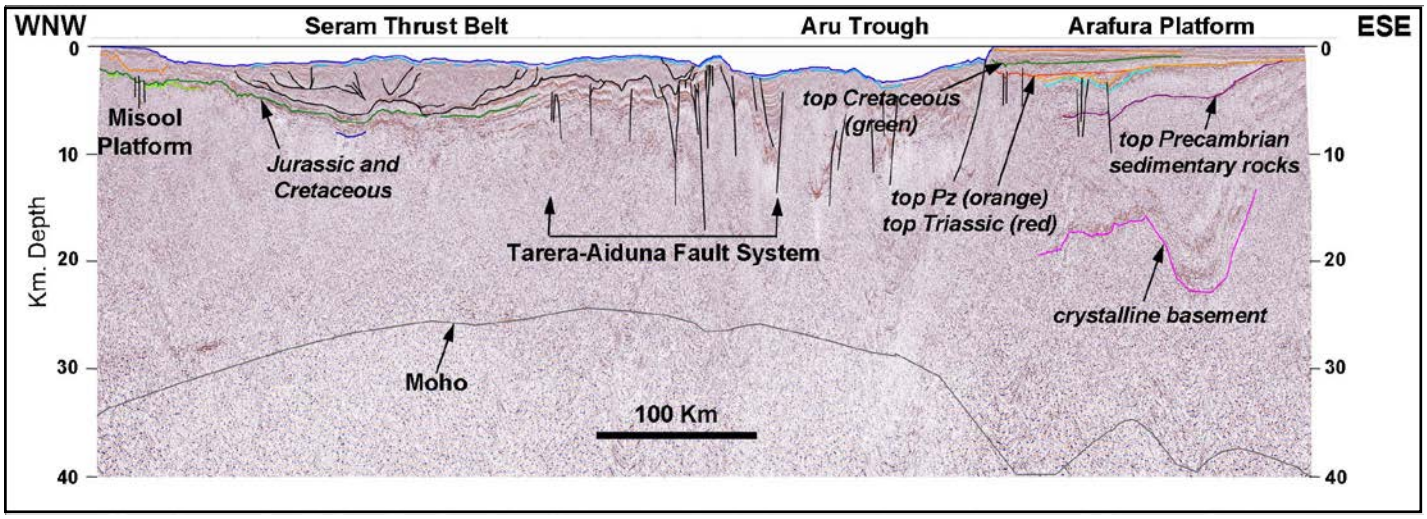


Figure 13. Line 700, rendered in a conventional amplitude display.

So even though it moves differently from the rest of the Asian collage, we have simply lumped Banda microplate with the other Asian fragments in Figure 2. The Pacific-Banda boundary north of the island of Seram is called the Asian/Pacific plate boundary and located along the thrust front as a dashed line in Figure 2, which is its best *surface* location.

Seram. Sitting in the middle of this area, Seram is a key element in the system. ArafuraSPAN images the frontal part of the Seram thrust wedge where only the deformed Neogene is included in the survey at the surface. Farther back in the thrust wedge some of the conventional time-rock units are involved (Kemp and Mogg, 1992; Figure 10 this paper). ArafuraSPAN adds to the understanding of the Seram Trough by improved imaging within the trough and clearly connecting the wells on the north side of the trough in the Bird's Head into the subthrust environment on the south. The data show that the detachment surface, as might be expected, ramps above the Miocene limestones of the area and is onlapped by young Pliocene and younger sediments (Figure 11). Dip lines across the trough show that the frontal part of the thrust wedge itself is composed of finely imbricated sheets of Neogene sediments which do not, at this most frontal position, contain the slabs of older rocks that characterize the onshore thrust belt. Interpretation of these new data place the Jurassic, Cretaceous, and Paleogene, with some Neogene, in a subthrust setting.

The SPAN data confirm that Seram is indeed a fragment of the Bird's Head that has been thrust north over itself (e.g. Pairault et al., 2003), but whether it is currently moving with the Bird's Head or with the Banda microplate (Ambon and Banda Besar) is not clear: its thrust relationship to the Bird's Head is compatible with either interpretation. Furthermore, the thrust belt is intersected in the east by a very young left-lateral shear system that is seen in multi-beam data on the floor of the eastern Seram trough (Teas et al., 2009). This shear is compatible with the Banda-Pacific relative motion if the displacement is partitioned between strike-slip and thrust components. In the center of Figure 12, line 700 of the SPAN data shows that this shear zone affects the lower sheets of the Seram thrust system. This is a new structural relationship to be imaged offshore of the eastern end of Seram. The thrust system appears to interact with the young left-lateral shears. Steeply dipping fault surfaces cut and offset the subthrust and the lower detachment surface (Figure 12). They die out upward, i.e. do not offset shallower thrust planes, and thus appear to represent deformation partitioning between left lateral strike slip on easterly trends and more northerly directed thrusting. This may be where the plate boundary is attempting to stabilize; the nascent Banda-Pacific boundary in this region may be expressed only at depth where it is working its way up from the lower crust through the overlying Seram thrust sheet. The upper part of the Seram thrust belt is 'floating' above and straddling the plate boundary.

North, East, and West of Seram. Elsewhere in the neighborhood, the specific tectonic elements that reflect contemporary motions are similarly not clear, resulting in much of the confusion concerning the tectonics of the region. The Australian Plate is separated from the Bird's Head continental block along the Tarera-Aiduna Fault east of Seram (Figure 13), and along a diffuse boundary through the Cenderwasih region that connects to the clearer, active part of the Yapen Fault Zone of north central New Guinea (Figure 2). The pre-Neogene geology of the Bird's Head of western New Guinea is universally considered of Australian heritage: its Precambrian, Paleozoic, and Mesozoic history as well as that of the rest of New Guinea have much in common with continental Australia regardless of the fact that the GPS data indicate its current location is on the Pacific plate. Hence its past positions and motion is a piece of the regional puzzle, one that is decidedly unsettled. Robert Hall's most recent reconstructions hold the Bird's Head in place along with the islands of the Sula Spur during Jurassic rifting of northern Australia (Hall, et al., 2009), attributing therefore minor and recent motion to the splays of the Sorong system. An animation in the supporting documents to Spakman and Hall (2010) shows this particularly well. Other authors move the Bird's Head north away from the NW shelf of Australia (e.g. Decker, et al., 2009), but that juxtaposes very different basement types:

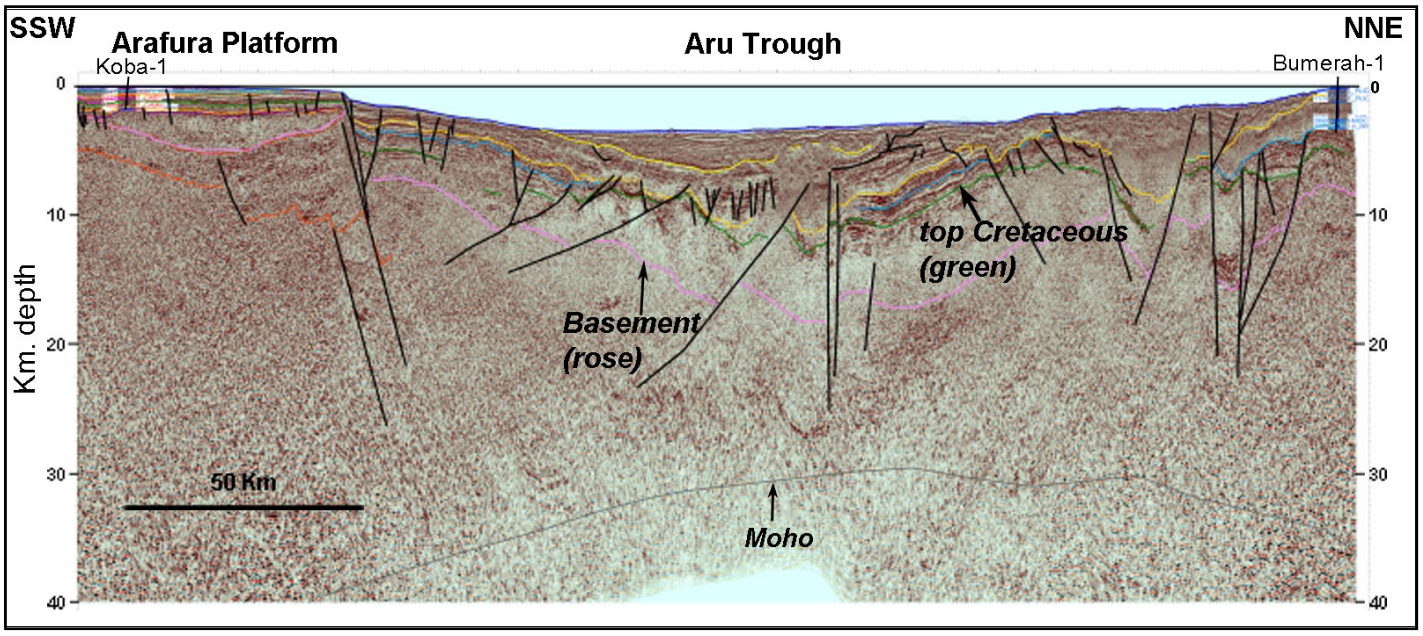


Figure 14. Line 2000, which runs down the center of the Aru Trough from north to south.

the basement that is exposed in the Bird's Head is comprised of early Paleozoic metasediments (Visser & Hermes, 1962; Pieters et al., 1983), and thus has an early history more similar to the eastern Australia Tasman province than to the Northwest Shelf. Similarly the islands of the Sula Spur have stratigraphic and tectonic histories involving Paleozoic dynamic metamorphism and peri-orogenic sedimentation in the late Paleozoic, and thus appear to have drifted westward from the Bird's Head region by motion on strands of the Sorong fault system (Pigram and Panggabean, 1984; Milsom et al., 2000). Reassembly of those motions and some eastward restoration of the Bird's Head appear to us to be reasonable in light of the structural elements involved. Regardless of its exact paleo-location, then, the ArafuraSPAN data indicate that prior to involvement in the triple junction Seram and the Bird's Head were unified in a single continental fragment.

To the west of Seram, the Pacific/Asian boundary is located along the western side of Halmahera, but to connect to its current position along the Seram Trough, the boundary must work its way across the splay faults of the Sorong system (separating the fragments of the 'Sula Spur'), nearly perpendicular to the left-lateral displacement field (Figure 2).

South of Seram. The boundary between the Asian (Banda microplate) and Australian plates is usually traced southward from Seram along the Tanimbar trough toward Timor. The Tanimbar accretionary prism lies in the middle, along the east rim of the Banda Sea where it is well imaged in several of the ArafuraSPAN lines (Figure 7) . Even though it is often regarded in the literature as a continuation of the Seram wedge, none of the Paleozoic and Mesozoic stratigraphy recognized in Seram can be recognized in the Tanimbar prism south of and more or less opposite Kai Besar. Presumably, the Tanimbar prism has a plate-scale tectonic significance in that it relates to the convergence between the Asian plate (specifically the Banda microplate) and Australian continental crust, in contrast to the intra-plate thrust relationship between the Seram wedge and the Bird's Head.

The frontal part of the prism is reasonably well imaged and shows thin imbricate fault slices lying within the tip of the thrust wedge, which itself lies over Neogene stratigraphy in the foredeep. Imaging is less clear within the prism itself, but there are hints of mud diapirism and possibly some intact crustal slabs but no hard volcanic core or basement of any kind. Piggyback basins are common on top of the wedge, and a bottom simulating reflector covers much of the prism, indicating the presence of gas hydrates.

Figure 7 also shows the extreme contrast in water depths from over 7 km above oceanic crust in the Weber Deep of the Banda Sea to less than 200 meters in the shallow Arafura Sea on continental crust of the Australian craton. The west side of the accretionary prism, as far as we know, has never been deeply imaged before. The top of the prism is dropped down below its regional depositional level on the east edge of the Weber Deep in a stepwise fashion, with rotation of features inside each of the fault slices toward the east. This indicates that normal faults have been superimposed on the prism separating the outer forearc portion of the prism from any volcanic core that it may have had. Volcanism is now located west of the Weber Deep between it and the south basin of Banda oceanic crust. To the south that volcanic string swings in closer to the frontal parts of the prism behind Timor. We presume these normal faults relate to the opening of the Weber Deep, which gravity modeling indicates is developed over thin, oceanic-like crust.

The Weber Deep, then, looks like young oceanic crust in the ArafuraSPAN data: the deep basin suggests that extension in the Weber Deep nucleated in the forearc of the Tanimbar sector of the accretionary prism and severed the volcanic arc from its forearc, probably more or less contemporaneously with the defection of the Bird's Head from the Australian plate to the Pacific plate. We would suggest that remains of the old arc may lie in the central

Banda Sea overlapped by the contemporary volcanism there.

Hence the SPAN data suggest that the Banda microplate is separated from Australia through the center of the Weber Deep rather than at the leading edge of the Tanimbar prism. The forearc of the accretionary prism is literally stranded on the rim of the Arafura shelf by extension to its west.

Intraplate effects. The Aru Trough (Figures 13 & 14) is a young extensional basin filled with a very complicated Plio-Pleistocene stratigraphy. ArafuraSPAN lines show that it is not connected to the Tanimbar Trough as is commonly shown in the literature and hence lies in an intraplate setting on the Arafura shelf. Other than seismic imaging, the stratigraphy in the Aru Trough is poorly controlled. Dredge samples near the eastern side of Kai Besar Island have established that a fairly complete Carboniferous-Permian and younger Australian Northwest Shelf section is involved in the western wall of the Trough (Cornee et al., 1997). Geological mapping on Kai Besar itself and the neighboring islands shows that the Paleogene and Neogene are involved in the deformation and are overlain unconformably by Pliocene and Quaternary deposits (Burollet and Salle, 1985); this dates the development of the western fault system to the last few million years, not as precisely as one might want.

The ArafuraSPAN data set is, as far as we know, the deepest seismic imaging of the Aru Trough to date. Figure 12 shows the position of the Aru Trough along line 700. It is a profile across the Trough north of Kai Besar and the Aru Islands with the Arafura Platform section in detail on the right. In form, the Trough is a graben in 3000+ m of water. It is composed of a number of narrower troughs containing thick sections between multiple steeply-dipping faults with normal separation (they are not necessarily purely dip-slip faults so this separation is not the net offset). Some of the sections between the faults are remarkably planar-bedded, with sections up to 5 km thick in 15 km-wide subbasins. Thick sections such as these are characteristic of narrow, pull-apart basins in which sediment accumulates on ramps between fault strands.

The ramps drop the surrounding shoulders of the rift down into the floor of the basin early in its development, and are later cut and isolated as separate subbasins as faults lengthen and intersect (Figure 7). The accumulating sediment is shingled above the rotated surface of the underlying ramp so that in reality the stratigraphic section in any single place may not as thick as indicated in seismic lines. Some of the subbasins in the Aru Trough contain sediments that are severely deformed--older, pre-rift rocks and/or syn-rift sediments. They are deformed because they are caught between converging strands of the fault system within the larger graben, or between diverging strands if extension is involved.

The western boundary of the Aru Trough strikes SSW from line 700 toward the eastern side of Kai Besar (Figure 14), and the eastern boundary is located at the edge of the Arafura Shelf. Both sides are marked by sharp, apparently active faults that drop the section down into the larger structure and control bathymetry. Those two sides are arranged in a right-stepping en echelon pattern, thus implying the Aru as a whole has a right-lateral pull-apart geometry. Furthermore, the fracture and fold patterns as mapped on Kai Besar by Burollet and Salle (1985) are compatible with the ENE-WSW shortening direction implied by such a system, which corresponds in a general way to the Pacific-Australia convergence vector for the recent past (DeMets et al., 1990, 1994).

Timing of extension in the Aru Trough is indicated by the thin to nonexistent sedimentary drape over the structures. It is restricted to the later Pliocene and Quaternary by outcrop on Kai Besar (Burollet and Salle, 1985), implying that the sediment supply to this part of the shelf in recent time has been minimal (a starved basin). The Trough is restricted to the shelf, and at its southern extreme it shoals and is overlain by but is not connected to the accretionary prism. This relationship indicates that the Aru Trough is older than the emplacement of the accretionary prism, i.e. older than the collision of the Banda-Tanimbar prism with the Australian continental margin.

The Aru Trough has received scant attention in the literature over the years except in the context of other tectonic elements, but there is a sense in the literature that strike-slip motion is involved. Hamilton (1979) simply places the trough along the northeastern end of the Banda accretionary prism, as do Katili & Asikin (1985), although they assign a right-lateral component to its sense of offset. Hobson et al. (1997) drew a comparison to the Waipona Basin on the east coast of Cenderwasih Bay, and interpreted the two basins as pull-apart basins along strands of a right-lateral system. If a physical connection between the two basins is real, however, it has been broken since by younger, cryptic tectonic activity in the "Bird's Neck" of New Guinea.

Conclusions

Deep crustal reflection profiling offers a valuable tool in tectonic studies as well as petroleum exploration to transcend the scale of conventional exploration data sets, to enhance understanding of the regional picture, and to allow meaningful comparisons between more focused studies, such as individual conventional seismic surveys.

In the Arafura Sea, the ArafuraSPAN data and interpretation have specifically:

- Imaged the stratigraphic connections across the Arafura Sea between Australia and New Guinea within a single survey, so that jump ties between different surveys need not be made,
- Clarified the Precambrian underpinnings of the New Guinea foreland region by making a sound connection to the Precambrian of northern Australia, and in particular has for the first time illustrated some remarkable features of and the relationships between the

Arafura Basin Wessel Group, the underlying McArthur Basin, and true crystalline basement,
- provided a better link between geotectonic studies of the SE Asian/Australian collisional zone in the Banda Sea area and the crustal scale aspects of the structural geology, e.g. better imaging of the frontal part of the Seram fold and thrust belt, and in particular its subthrust relationships, the internal geometry of the Aru Trough and thus its kinematics, and the role of the Weber Deep in the Tanimbar sector of the accretionary prism.

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