[PS]Drainage Systems in Rift Basins: Implications for Reservoir Quality*

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Abstract

Ancient and modern rift basins can be found on every continent of the world and account for 31% of giant fields discovered (Mann et al., 2003) with over 620,000 (MMBOE) of estimated recoverable hydrocarbons worldwide. New rift plays are just being discovered as we explore beneath salt deposits and penetrate deeper continental margin strata. The biggest challenge in these basins is understanding reservoir location, quality, and extent. Axial- and marginal-sourced rivers provide very different sediments to the system and have significant geomorphologic differences. The architecture of rift systems varies dramatically from those located within continental versus coastal/marine environments (Gawthorpe and Leeder, 2000). A three phase study of rift drainages was undertaken to document these differences and quantify the various morphologies of drainage that characterize rifts.

A literature and imagery review of ancient and modern rift drainage systems was undertaken with the focus on ancient systems being issues and challenges to producing discovered, developed, and undeveloped hydrocarbon in rift system reservoirs. In the second phase of this work, a study of the morphology of a modern rift setting in East Africa using ArcGIS and satellite imagery allowed mapping and quantification of rift drainage morphologic characteristics, such as: drainage architecture, rift size, channel size and flow characteristics and the overall drainage nature versus catchment area. Phase 3 of this study focuses on applying the criteria and knowledge built in Phases 1 and 2 to improve prediction of drainage nature and subsequent reservoir distribution and development in a high resolution 3D seismic survey in the Dampier Sub-basin off the northwest coast of Australia. Quantitative seismic geomorphological techniques have been employed to assess the morphology, flow character and drainage size of this paleo-rift system toward a better understanding of reservoir distribution and risk.

DRAINAGE SYSTEMS IN RIFT BASINS: IMPLICATIONS FOR RESERVOIR QUALITY

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Sedimentary Analogs Database Research Program

Acknowledgments

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Problem and Key Questions

Problem

- Rift basins account for nearly **31% of discovered giant oil and gas fields and around 620,000 MMBOE of estimated recoverable resources** worldwide (Mann et al., 2003, 2007).
- Continuing **exploration into deeper areas**, below formerly explored passive margin sediments, demands **new ways to de-risk these basins** (Ex. Tupi discovery offshore Brazil)
- **Seismic usually is readily available**, with **few well penetrations** to gather reservoir data from
- The challenge is to understand the **location, quality, and extent of reservoirs within rift basins**

Key Questions

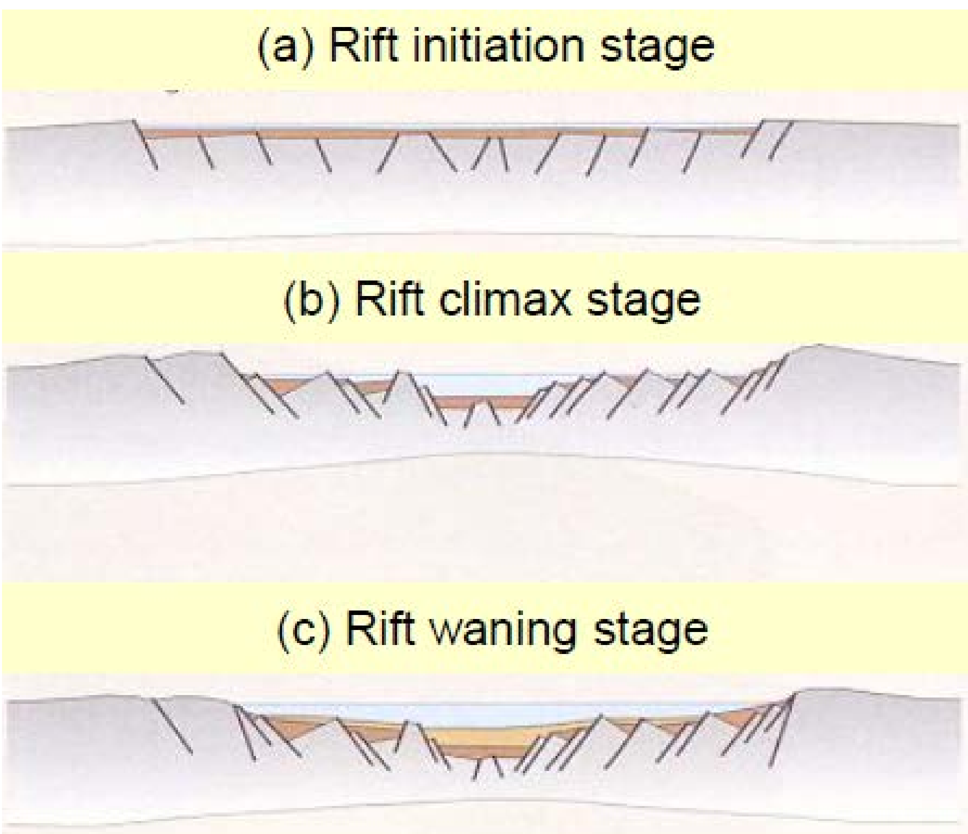
- What is the nature of the reservoir and seal elements within the syn-rift portions of rift basins and can we use seismic geomorphology to aid in understanding these petroleum system components?
- What is the nature of the axial versus transverse inputs into a rift basin? Does the confinement of the sediment sink affect the size of the drainage systems? Can we use modern rifts to assist in our understanding of ancient rift sediment routing systems?

What is a Rift Basin?

A **rift basin** is a sedimentary basin that has undergone **crustal extension** and passed through **three sedimentary evolution cycles**:

- **Pre-rift:** everything deposited before active fault movement
- **Syn-rift:** everything deposited during active faulting, which itself is comprised of three sub-phases:
  - **Rift Initiation**
  - **Rift Climax**
  - **Rift Waning** (sometimes includes sag phase)
- **Post-rift:** everything deposited after faulting has ceased

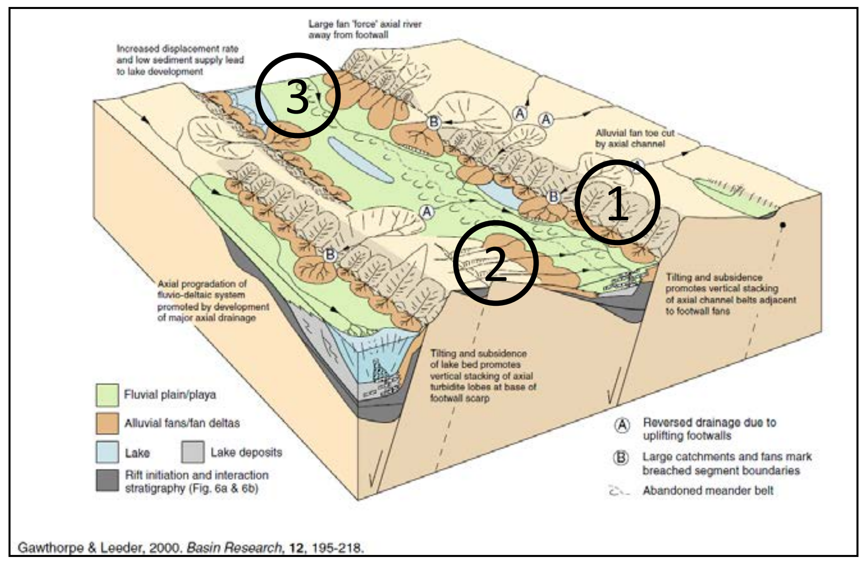
(FYI: This definition separates rift basins from spreading centers, which do not have sedimentary deposition at their basin center, and from areas of extension, which do not always have a crustal component (ex. halokinesis).)

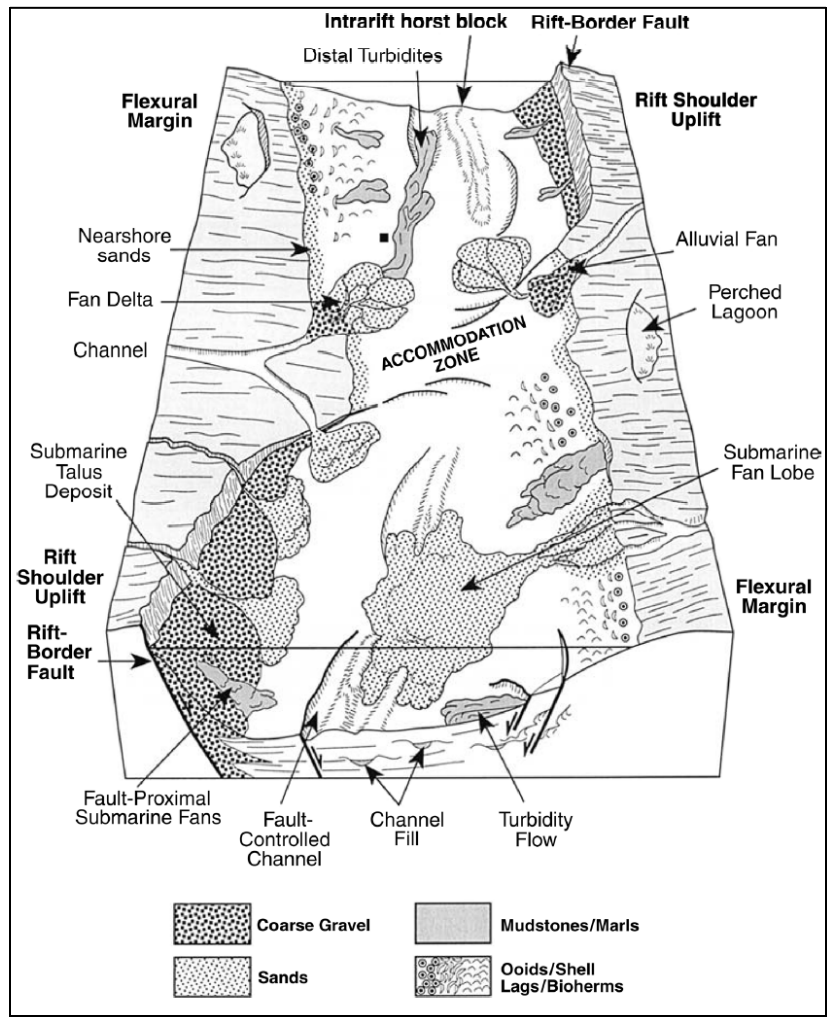


(Doust, 2015)

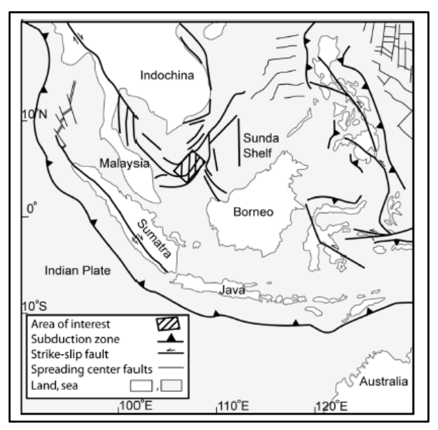
Previous Rift Basin Sedimentation Research

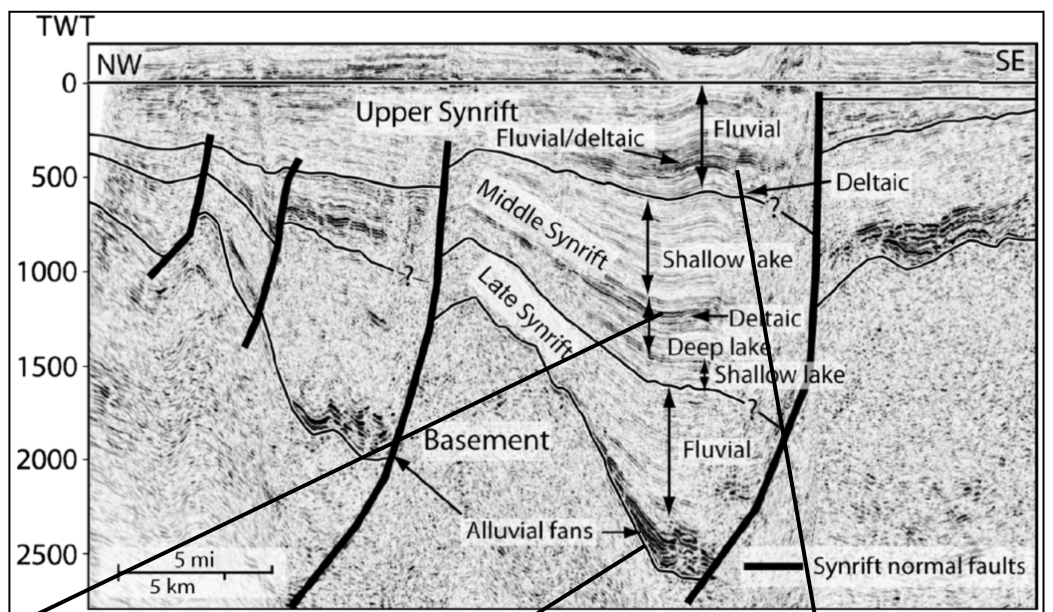
Previous research by Gawthorpe and Leeder (2000) set out to model the different ways continental- and marine-rift systems evolve through fault linkages. They identified three main sediment depositional locations within a half graben system: 1) transverse sourced from the footwall highland, 2) transverse sourced from the hanging wall highland, and 3) axial being sourced from pre-established drainages and from input of the transverse systems.

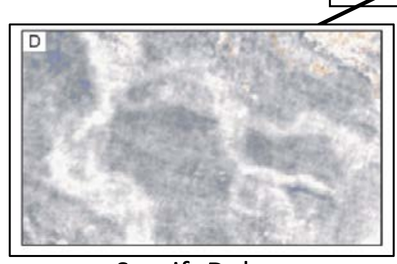




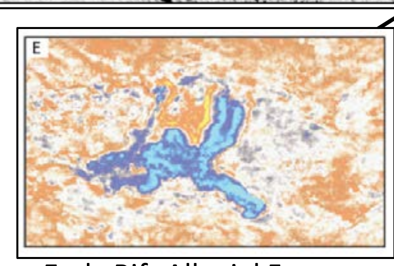
Younes and McClay (2002) studied the effects of accommodation zones within the Red Sea Rift Basin and provided a model as to the multiple types of syn-rift reservoirs that can develop in a marine to near-marine rift zone; from alluvial fans, fluvial channels, and deltas, to shoreface clastic and carbonate deposits, to deepwater channels, turbidites, and fans. Their study focused on how structure influenced the location of accommodation, while our study focuses on the interactions of the different sedimentary systems to form the best reservoirs to target for exploration.



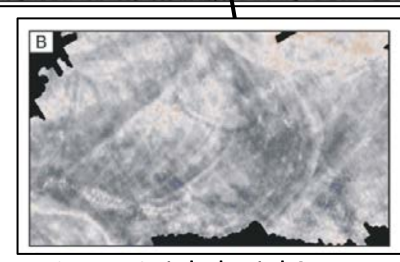




Synrift Deltas



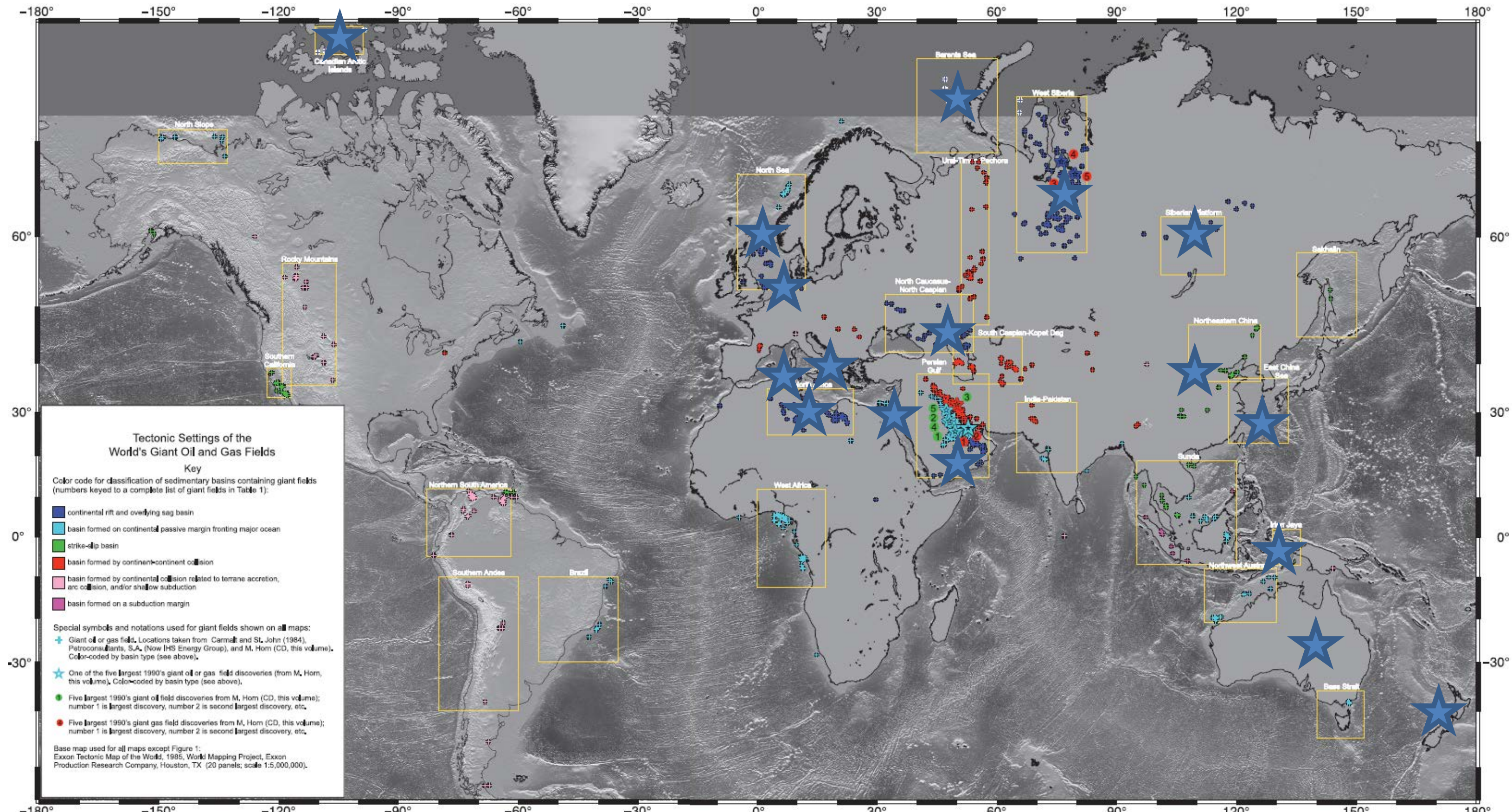
Early Rift Alluvial Fans



Large Axial Fluvial Systems

Seismic geomorphology has been effectively used in the past to explore rift systems in Indonesia, New Zealand, India and other areas to identify different geomorphic facies within the stratigraphy of the basin. These images are from work on the Sunda Shelf of Indonesia (Burton and Wood, 2011).

Survey of Rift Basins Hosting Giant Oil and Gas Fields



(Modified from Mann et al., 2003)

Mann et al. (2003) studied giant fields by tectonic setting (giant fields contain >500 MMBOE recoverable) and provides a great overview of thirty of the most petroliferous rift basins in the world. By researching the rift basins that host these fields, some interesting patterns related to reservoir and seal facies become apparent:

Rift Basins by Reservoir Type

Reservoir Rock Type	Number of Basins	Percent of Total
Carbonate	8	26.67%
Clastic	22	73.33%
Total	30	

The majority of rift basins contain giant fields hosted in clastic as opposed to carbonate reservoirs.

Rift Basins by Clastic Reservoir Type

Main Clastic Reservoir Type	Number of Basins	Percent of Total (%)
Alluvial-Fluvial	5	22.73%
Alluvial-Fluvial-Eolian	3	13.64%
Fluvial-Deltaic	3	13.64%
Deltaic-Shoreface	8	36.36%
Submarine Fans-Turbidites	3	13.64%
Total	22	

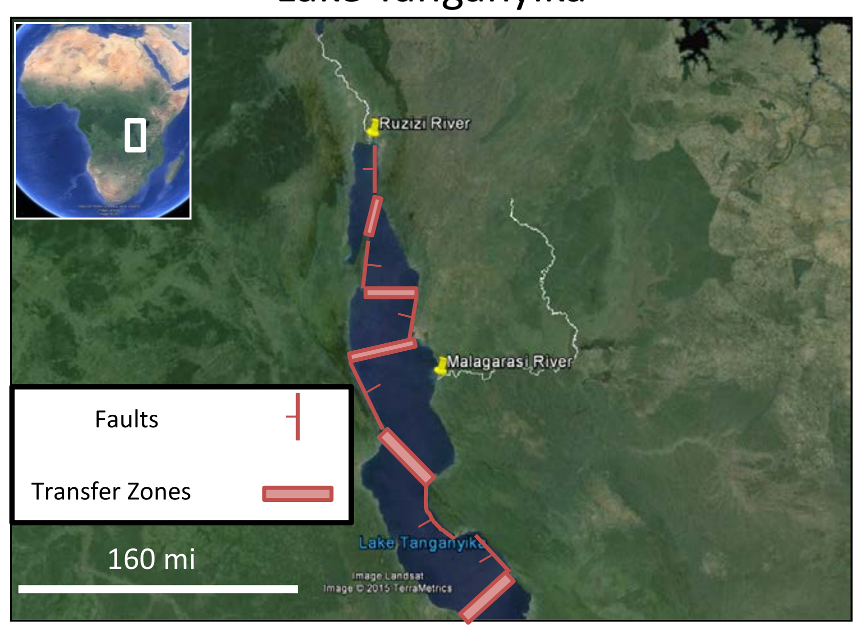
Rift Basins by Seal Type

Seal Type	Number of Basins	Percent of Total (%)
Anhydrite/Evaporites/Salt	12	40.00%
Carbonate/Dolomite/Marl	7	23.33%
Marine Shale (basin wide seal)	4	13.33%
Shale (intraformational)	4	13.33%
Lacustrine/Fluvial Mudstone	2	6.67%
Faults and Shale	1	3.33%
Total	30	

Reservoirs that dominate Clastic rift settings (22 basins) are primarily fluvial and deltaic in nature and the seals dominantly marine in nature. We hypothesize that documenting a seismic geomorphologic history in the basin will be most effective done within a framework of key sequence stratigraphic surfaces.

Lessons from a Modern Rift

Lake Tanganyika



Modern rifts provide a "window" into the nature and morphology of evolving rift reservoir systems. Lake Tanganyika is a rift of multiple inter connected half grabens creating a series of "mini-rift basins".

- **Footwall Uplift**: Footwall uplift along the outer faults cause river systems to drain away from the rift, which can lead to sediment starved rift basins.
- **Historical River Systems**: In the case of Lake Tanganyika, the largest single drainage into the lake is the Malagorasi River, which predates the initiation of rifting and flowed further west to connect with the Congo River. Though smaller, less developed river systems may be diverted after rifting, the Malagorasi River is a prime example that established river systems can serve an outsized role in rift basin drainage.
- **Sediment Source**: The river systems within the Lake Tanganyika catchment cut through erosion resistant, crystalline basement rock, allowing little clastic input to the basin and leading to the lake fill being primarily silts and clays. In the northern Lake Turkana, where the river systems cut through weaker volcanic rocks, there is significantly more clastic input.

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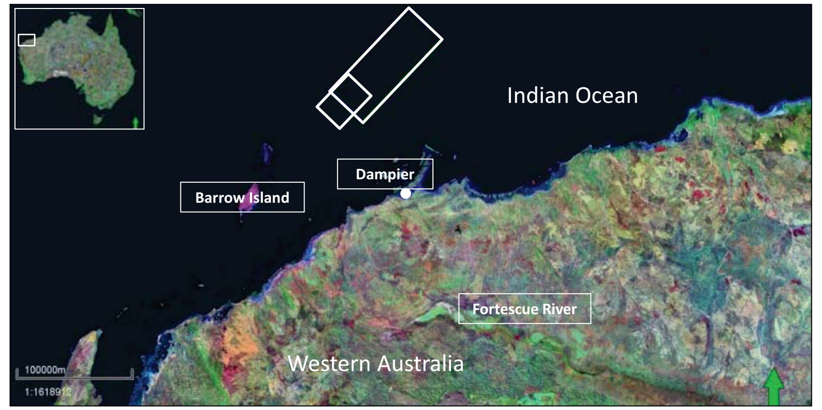
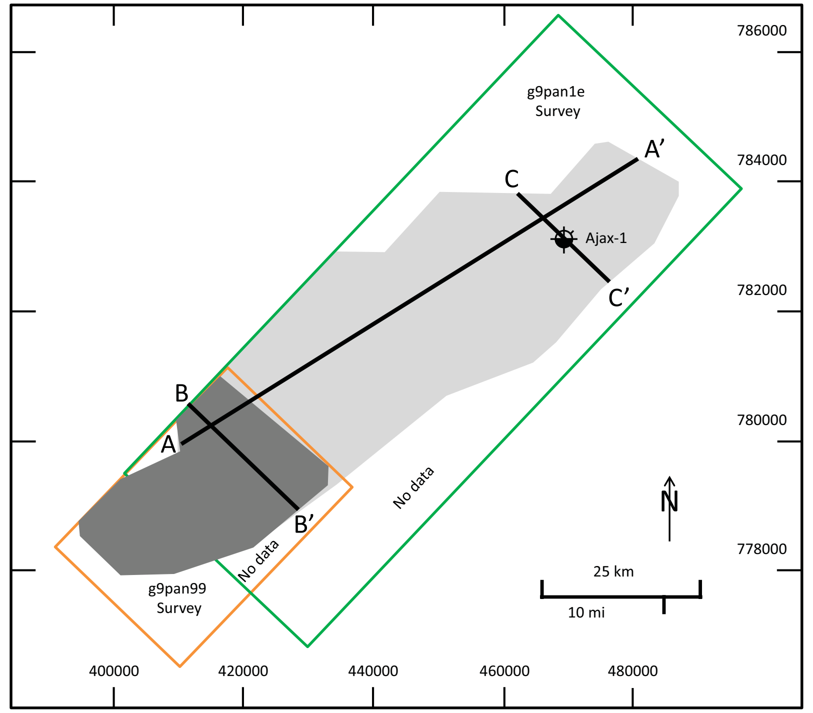
Study Location



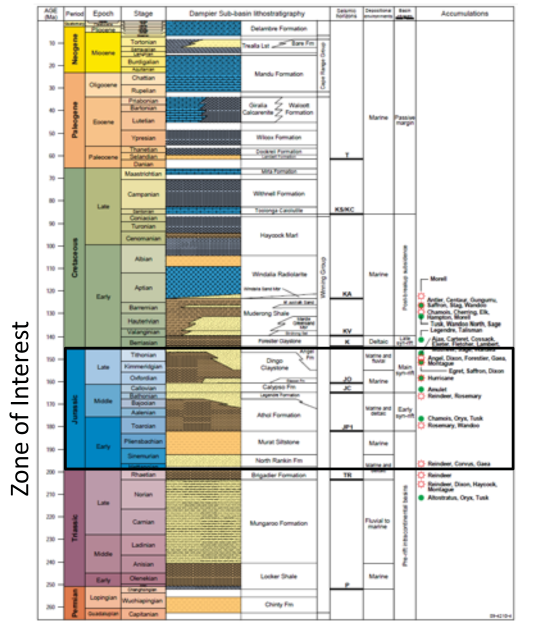
This map shows the location of the 3D seismic surveys displayed with 15 m Landsat imagery of Australia.

Seismic Survey Locations and Data Coverage



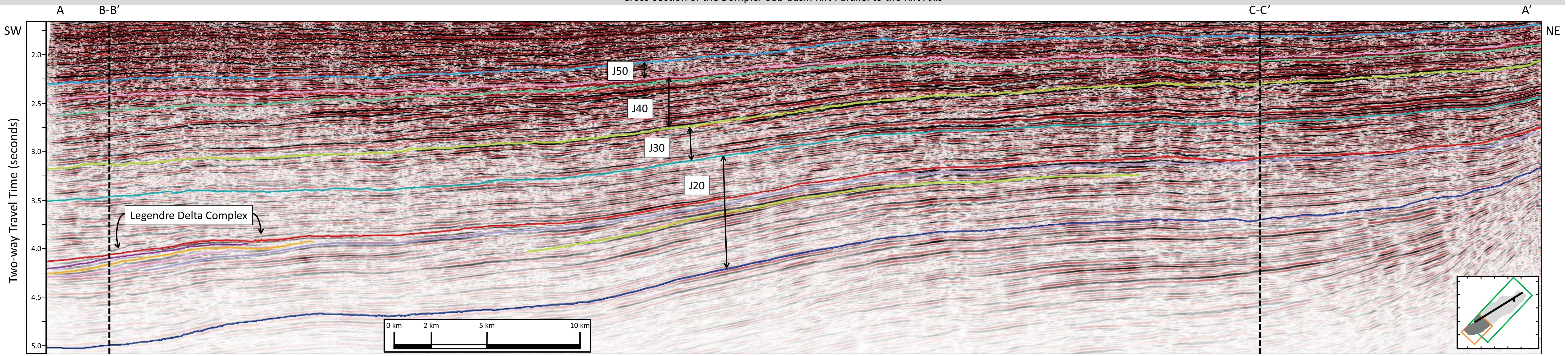
Index map of the g9pan1e and g9pan99 surveys and the location of the Ajax-1 well used in this study. Datum AUS-50 (UTM Zone 50 S on Australian Datum 1984) units are eastings and northings. The shaded areas indicate the extent of seismic data the encompasses the main rift sediments within each survey. Additionally, map indicates the locations of the main rift axis seismic line, as well as the two seismic lines orthogonal to the rift axis.

Dampier Sub-basin Stratigraphy



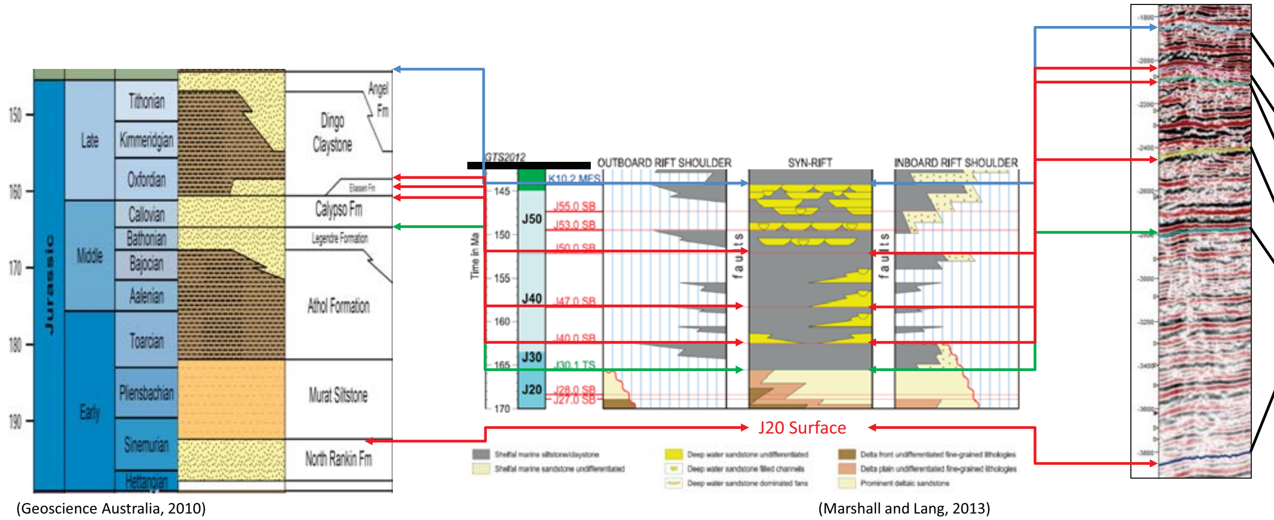
Generalized stratigraphic column for the Dampier Sub-basin, highlighting the lithostratigraphy, stages of basin evolution, and reservoirs for major accumulations of oil and gas (Australian Government, 2010).

Cross-section of the Dampier Sub-basin Rift Parallel to the Rift Axis



Seismic line shows the depositional changes parallel along the rift axis through the Dampier Sub-basin. Highlighted are the four main Jurassic regional play intervals (RPI) defined by Marshall and Lang (2013). Additionally, the main clinoforms within the Legendre Delta Complex have been highlighted to show the structure and size of the system. Orthogonal cross-lines are denoted with dashed lines and displayed below.

Seismic Mapped Horizons and their Relation to Dampier Sub-basin Lithosotratigraphy and Sequence Stratigraphy



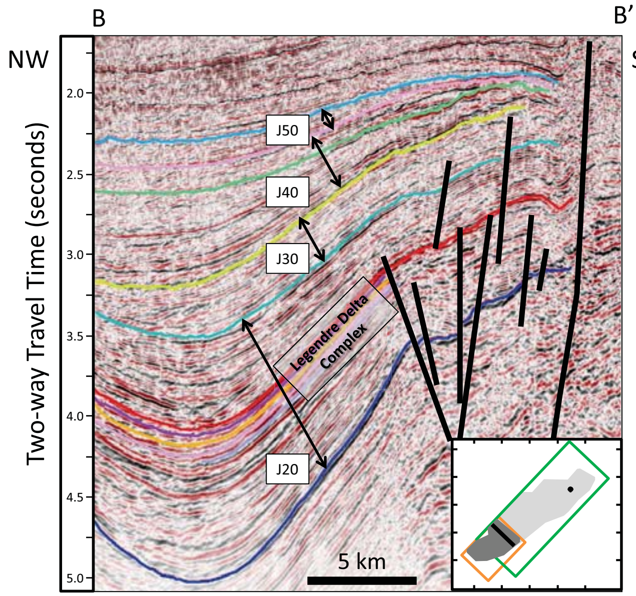
(Geoscience Australia, 2010)

(Marshall and Lang, 2013)

Horizon Name	Relative Age (Marshall and Lang, 2013)	Formation Top (Marshall and Lang, 2013)	Phase	Surface Type (Marshall and Lang, 2013)
K10	Top Jurassic	Dingo Claystone/ Angel Formation	Peak	Maximum Flooding Surface
J50	Late Jurassic (Tithonian)	Eliassen Formation	Peak	Sequence Boundary
J47	Late Jurassic (Oxfordian)	Oxfordian Sequence Boundary	Peak	Sequence Boundary
J40	Late Jurassic (Oxfordian)	Calypso Formation	Trough	Sequence Boundary
J30	Middle Jurassic (Callovian)	Athol Formation/ Legendre Formation	Peak	Transgressive Flooding Surface
J20	Early Jurassic (Sinemurian)	North Rankin Formation	Peak	Sequence Boundary

Seismic mapped horizons were named according to the regional play interval (RPI) stratigraphic naming convention described by Marshall and Lang (2013). This naming convention was originally defined by Longley et al. (2002), where the authors used regional seismic picks to define the base of different play intervals or inter-play seismic horizons. This work built upon that of Jablonski (1997) who had originally identified several regional horizons that were identifiable in seismic, well logs and from biostratigraphy, that span multiple sub-basins of the northwest shelf. He defined these horizons as "having sequence stratigraphic significance" and used them as time markers across the area. Marshall and Lang (2013) further refined and published this play interval naming convention for use in a sequence stratigraphic understanding of the whole of the Northern Carnarvon Basin and other basins in the North West Australian off-shore area (Westralian Super-basin).

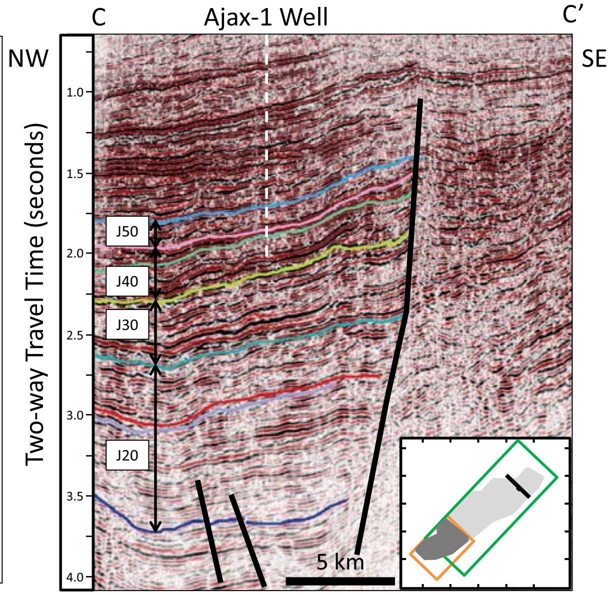
Cross-sections of the Dampier Sub-basin Rift Orthogonal to the Rift Axis



X-line 17324 (survey g9pan99)

Cross-line B-B' shows the depositional fill in the center of the Dampier Sub-basin.

- **Structural Observations**: the eastern flank of the rift center is bounded by the large border fault and shows significant normal faulting (black lines) that offset the J20 and J30 surfaces, but do not continue up into the J40 and younger surfaces, indicating that significant faulting did not occur until Middle Jurassic time and was not coincident with movement on the large border fault.
- **Sedimentary Observations**: only subtle thickness variations are observed in the J20 and J30 RPI's, while there is significant thickening into the basin from east to west in the J40 and J50 RPI's, indicating these were the times of maximum subsidence.
- **Seismic Geomorphologic Observations**: within the Legendre Delta Complex clinoforms, there is evidence of fan lobes being confined to the basin center with subtle lobe migration; just above the red-clinoform reflection there is a feature that scours into underlying strata; the J47 surface is irregular in the eastern side of the seismic line following a bright scoured reflection that possibly indicates the scar from a large mass transport deposit.



X-line 8220 (survey g9pan1e)

Cross-line C-C' shows the depositional fill in the shallowest, up-dip area of the Dampier Sub-basin and includes the Ajax prospect.

- **Structural Observations**: the eastern border fault is the main structural component within the up-dip portion of the Dampier Sub-basin, with minor faulting observed offsetting the J20 surface.
- **Sedimentary Observations**: fewer of the Legendre Delta Complex's clinoform surfaces can be mapped as far up-dip as compared to the basin center; there are not the same dramatic thickness changes within the RPI's as were observed in the basin center likely due to the lack of accommodation up-dip from the basin center; the RPI's seem to thin from east to west in contrast to their profiles in line B-B'.
- **Seismic Geomorphologic Observations**: there is thickening into the eastern border fault, indicating significant fan deposition onto the footwall of the fault; this is seen significantly within the J40 RPI, where this over steepening of fan deposition during rift climax fault movement caused submarine debrite deposits to form, such as the Ajax prospect in the center of the seismic line.

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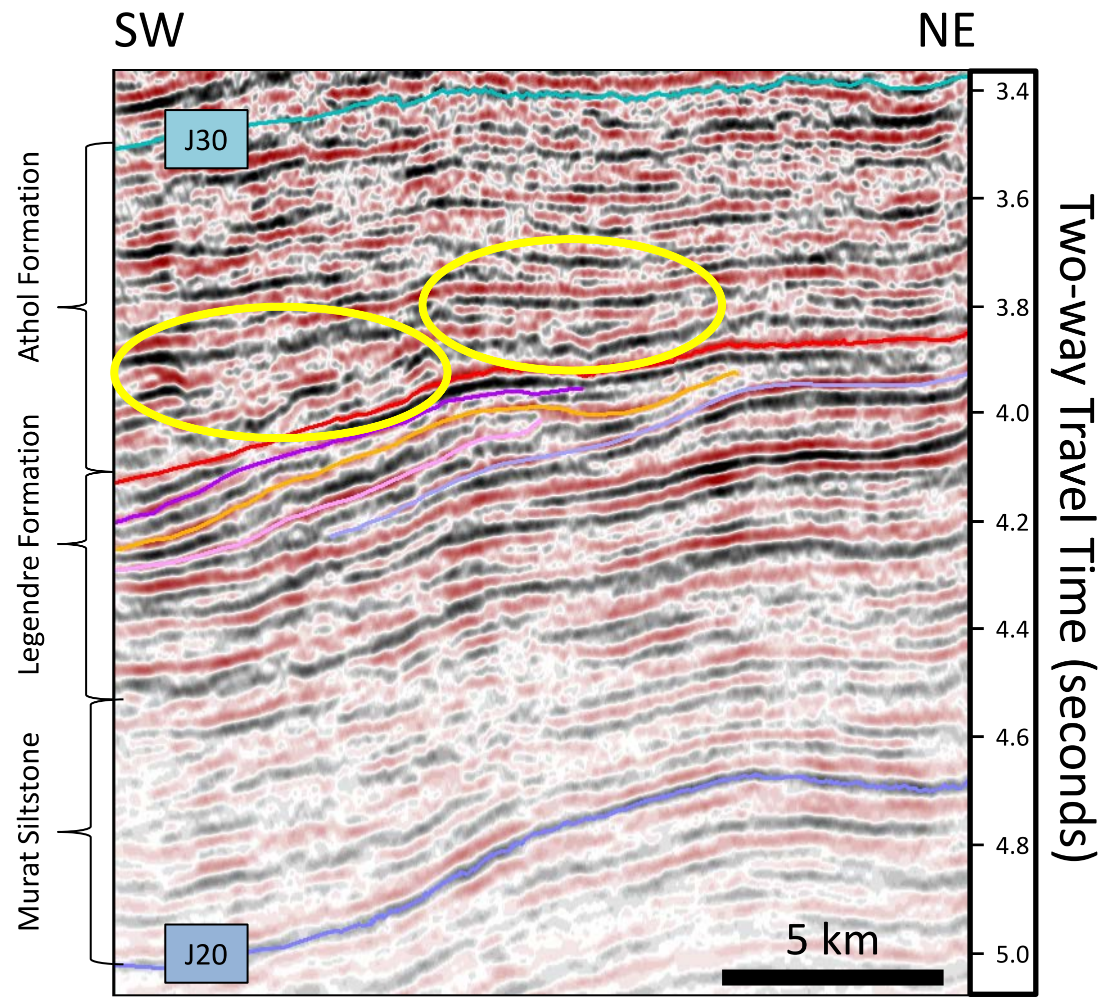
Preliminary Observations of the Jurassic Regional Play Intervals (RPI) of the Dampier Sub-basin

J20

The J20 RPI is bounded at its base by the J20 surface and at its top by the J30 surface.

Morphology Analysis: The J20 RPI contains the Murat Siltstone at its base, which are the low amplitude, discontinuous reflections. The Legendre Delta clinoforms (interpreted at right) are high amplitude, continuous reflections with a thickness of around 250 ms, or a thickness of 525 to 750 m. This clinoform height can be used to calculate paleo water depth during Legendre Fm time (Patruno et al., 2015) to be between 535 and 780 m deep. The Athol Fm on-laps the clinoforms of the Legendre Delta here in the basin center. Additionally, significant channels have scoured down into the underlying strata just above the interpreted clinoforms (circled in yellow). These channels are 110 to 180 ms thick and indicate a change at the end of Legendre Fm deposition to the basin being dominated by the axial progradation of the delta to transverse channels reworking the prodelta and delta front sediments. Because of the loss of seismic frequency with depth, horizon slices through the J20 RPI do not image distinct features.

Depositional Environment Evolution: During rift initiation there was an initial subsidence allowing for the deposition of the Murat Siltstone, followed by the progradation of the Legendre Delta and the eventual shoreline transgression through the end of the J20 RPI.



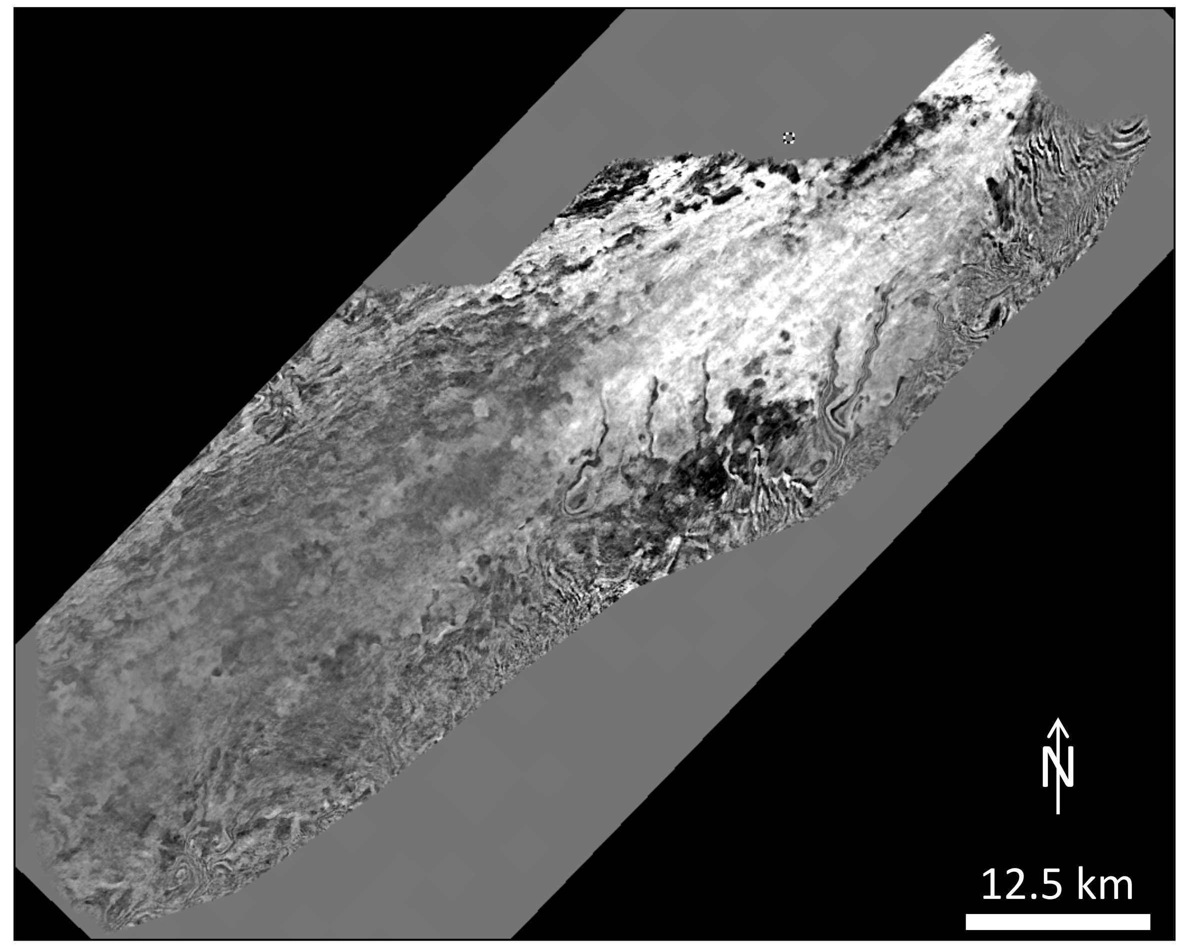
J30

The J30 RPI is bounded at its base by the J30 surface and at its top by the J40 surface.

Morphology Analysis: The J30 PRI contains the Calypso formation which does not display significant seismic-scale morphologic features in plane view, however there is an interesting change in seismic character of the interval across the basin. In the updip (NE) section of the rift basin, the interval is high amplitude and very continuous. As you follow the reflections to the deeper basin center (SW) the seismic character becomes lower amplitude and more discontinuous (see right). This could be due to the Calypso Formation becoming more homogenous towards the basin center where there likely would have been more submarine deposition and less influence of any shallow marine processes.

Depositional Environment Evolution: The shallow marine claystone of the Calypso Formation was deposited on top of the Callovian Unconformity. The claystone was deposited homogenously in the basin center, but likely was reworked closer to the NE margin of the basin by shallow-marine to shoreface processes such as wave or tidal influence.

Horizon Slice 74 ms above J30 Surface (g9pan1e survey)



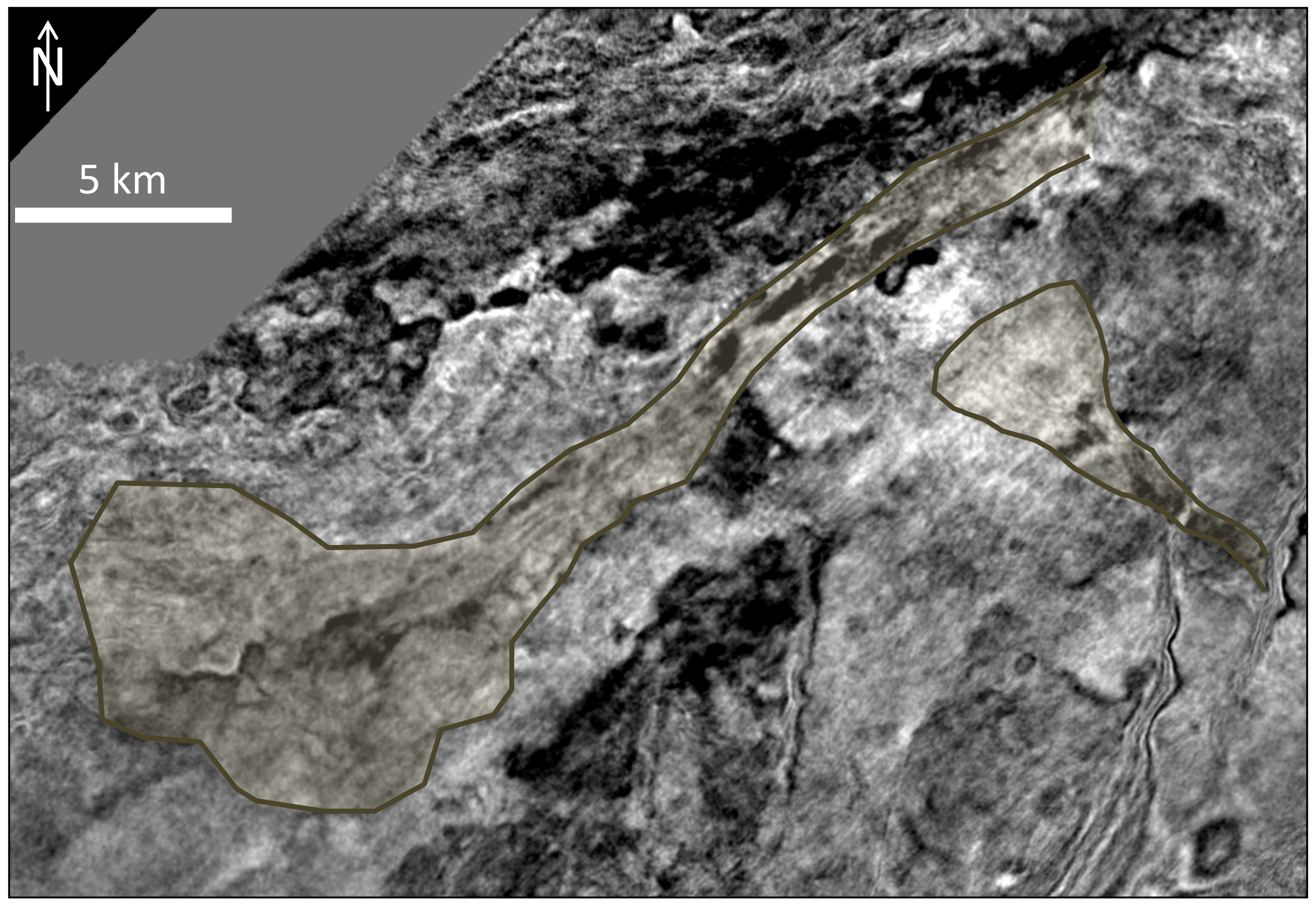
J40

The J40 RPI is bounded at its base by the J40 surface and at its top by the J50 surface and contains the J47 surface.

Morphology Analysis: The J40 interval contains many features such as debrite deposits (see Ajax prospect on C-C' seismic line), massive scour surfaces (see J47 surface on B-B' seismic line), and interpreted channel and fan deposits (see right). In the horizon slice at right, the smaller fan in the eastern portion seems to cut across or predate one fault, yet be clearly influenced by the eastern most fault. The overall seismic character is of similar amplitude and continuous reflections across the basin, with the exception of areas that are scoured.

Depositional Environment Evolution: The straight nature of the channels terminating in fans can suggest that these are submarine deposits. During Late Jurassic, fault movement increased into the rift climax stage causing significant mass wasting events in the form of debrites and a possible massive mass transport deposit, whose scar is interpreted to be the J47 surface on seismic line B-B'.

Horizon Slice 29 ms above J40 Surface (g9pan1e survey)



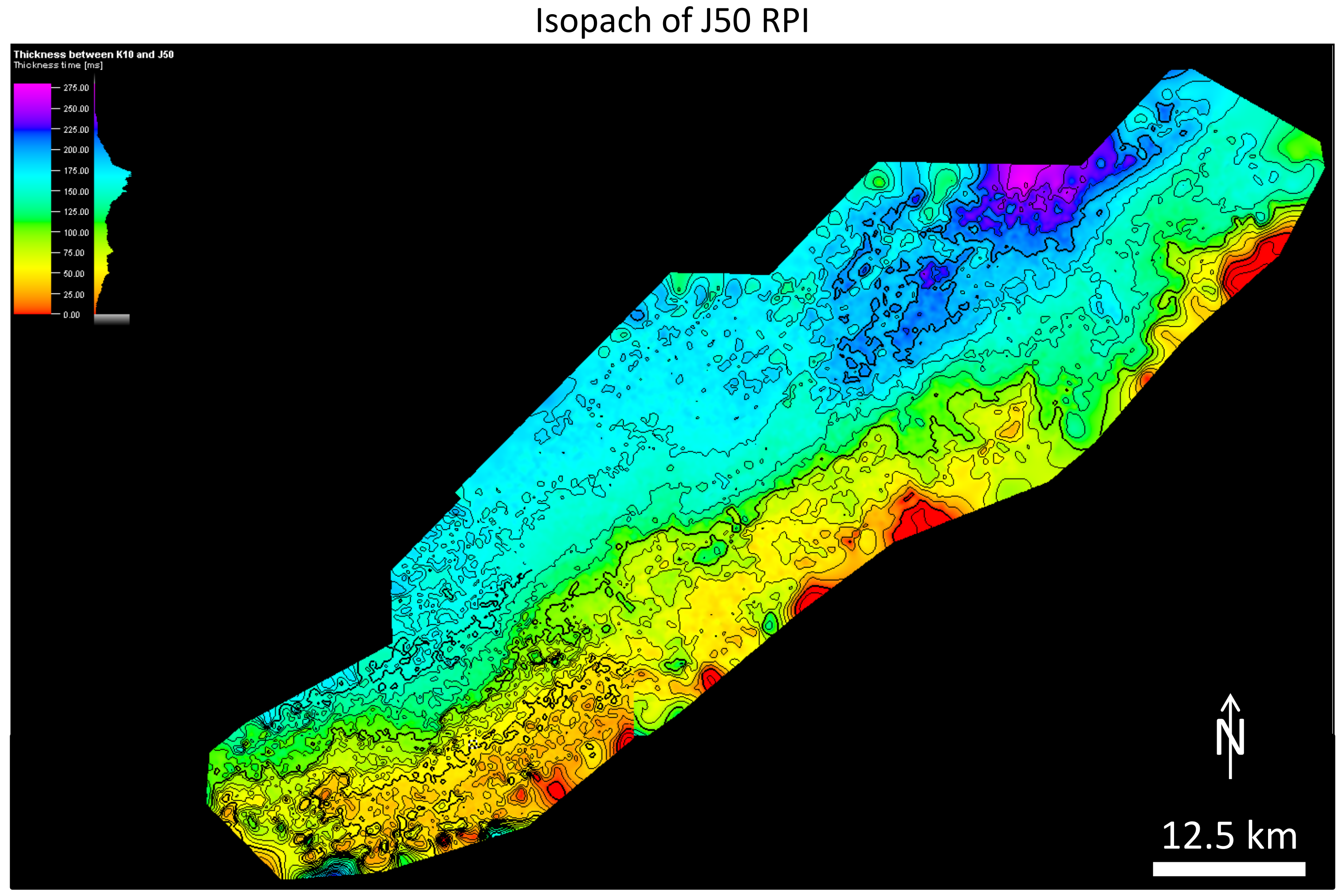
J50

The J50 RPI is bounded at its base by the J20 surface and at its top by the K10 surface.

Morphology Analysis: The J50 interval contains the rift waning stage, consisting of the Dingo Claystone and Angel Formation. The time-thickness map to the right (warm colors=thin; cool colors=thick) show that this interval is relatively thin, only obtaining a maximum thickness of about 270 ms near the NE corner of the study area.. This could be due to the lack of accommodation during the end of rifting.

Depositional Environment Evolution: The lack of adequate sediment supply to prograde a Legendre sized delta into the basin during the rift waning stage leaves little fluvio-deltaic deposition at the very NE part of the study area. The rest of the basin was passively filled with the marine Dingo Claystone, which is one of the main source rocks for the basin.

Isopach of J50 RPI



Preliminary Conclusions

- Rift basin petroleum systems are primarily composed of clastic reservoirs, usually of fluvial-shoreface-deltaic facies, and marine seals, either carbonate, shale, or evaporite; therefore a geomorphologic understanding of a rift basin was undertaken within the framework of key sequence stratigraphic surfaces (e.g. RPI's used in this study).
- By studying modern rifts, such as Lake Tanganyika in the East African Rift, we can learn about unique aspects of rift sediment routing systems, such as the limited catchment area and confinement of rift systems. This characteristic was also observed in the Dampier Sub-basin by the restricted area of the Legendre and Angel deltas within the basin.
- Seismic geomorphologic techniques allow for a suite of information (seismic, horizon slices, isopachs) to be used together to inform when, where, and why different reservoirs were deposited within a rift setting.
- The confined nature of the Dampier-Sub basin restricted the areal distribution of the axial inputs into the basin (Legendre and Angel deltas) to the basin center where subsidence was highest. Transverse inputs were significant only when fault movement was greatest, during the J40 interval, when the Eliassen fans and debrites were deposited and accommodation was greater than sedimentation to allow for significant sediments to build up on rift margins.

References

Burton, D., and L. J. Wood, 2010, Seismic geomorphology and tectonostratigraphic fill of half grabens, West Natuna Basin, Indonesia: AAPG Bulletin, v. 94, no. 11, p. 1695–1712, doi:10.1306/06301010003.

Doust, H., 2015, Rift Basin Evolution and Petroleum System Development, *in* 34th Annual Gulf Coast Section SEPM FoundationPerkins-Rosen Research Conference: p. 14.

Gawthorpe, R. L., and M. R. Leeder, 2000, Tectono-sedimentary evolution of active extensional basins: Basin Research, v. 12, no. 3-4, p. 195–218, doi:10.1111/j.1365-2117.2000.00121.x.

Geoscience Australia, 2010, Offshore Petroleum Exploration Acreage Release.

Mann, P., L. Gahagan, and M. B. Gordon, 2003, Tectonic Setting of the World ' s Giant Oil and Gas Fields: no. JANUARY 2001, p. 15–28.

Mann, P., M. Horn, and I. Cross, 2007, Emerging Trends from 69 Giant Oil and Gas Fields Discovered from 2000-2006: Search and Discovery, v. 110045.

Marshall, N. G., and S. C. Lang, 2013, A New Sequence Stratigraphic Framework for the North West Shelf , Australia: no. August, p. 18–21.

Patruno, S., G. J. Hampson, and C. A. Jackson, 2015, Quantitative characterisation of deltaic and subaqueous clinoforms: Earth-Science Reviews, v. 142, p. 79–119.

Younes, A. I., and K. Mcclay, 2002, Development of accommodation zones in the Gulf of Suez–Red Sea rift, Egypt: v. 6, no. 6, p. 1003–1026.