# Analysis of gravity-driven normal faults using a 3D seismic reflection dataset from the present-day shelf-edge break of the Otway Basin, Australia.

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## SUMMARY

The growth, interaction and controls of gravity-driven normal faults is somewhat understudied. Using three-dimensional (3D) and two-dimensional (2D) seismic reflection data, located at the present-day shelf-edge break and into the deepwater province of the Otway Basin, southern Australia, we aim to temporally and spatially constrain the development of a normal fault system and determine the controls on growth. The Otway Basin is a Late Jurassic to Cenozoic age, rift-to-passive margin basin. The seismic reflection data images a gravity-driven fault array, consisting of ten fault segments, striking NW-SE (128-308), located within Upper Cretaceous clastic sedimentary rock. We analyse the growth of a gravity-driven hard-linked fault assemblage interacting with basement normal faults. Our analysis shows that the fault assemblage is linked to major basement faults and displays Turonian-Santonian nucleation, continued growth until the latest-Maastrichtian and a maximum throw of 1.74 km. High variability of throw along-strike and down-dip of the fault assemblage indicates growth via lateral and vertical segment linkage. We interpret that the spatial and temporal evolution of the fault assemblage is the result of rifting basement fault control during Upper Cretaceous resumed crustal extension in the Otway Basin. The control of the rifting basement faults on these gravity-driven normal faults has implications towards the growth and petroleum prospectivity of gravity-driven normal faults on passive margins such as the Niger Delta and Gulf of Mexico, but also towards gravity-driven normal faults developed in supra-salt sedimentary rock in rift basins, such as the North Sea and Suez Rift.

**Key words:** normal fault growth, segment linkage, gravity-driven, Otway Basin, 3D seismic.

## INTRODUCTION

The spatial and temporal constraint and controls over gravity-driven normal fault growth are reasonably understudied in comparison with normal faults developed as a result of mechanical extension (Walsh and Watterson, 1988; Childs et al. 1995; 2003; Walsh et al. 2002; 2003). The development of gravity-driven normal faults is somewhat more complex when attempting to understand the geometric and kinematic relationship they have with underlying rifting basement faults (e.g. Jackson and Rotevatn, 2013; Lewis et al. 2013; Tvedt et al. 2013). Studies have documented that tilting, flexure and gravity gliding increases in sedimentary rock located directly above basement normal faults and this may invoke the growth of sub-parallel striking, cover restricted normal faults (Vendeville et al. 1995; Withjack and Callaway, 2000). We aim to temporally and spatially constrain the growth of a gravity-driven normal fault assemblage, imaged by 3D seismic data and located within Upper Cretaceous sedimentary rock at the present-day shelf-edge break of the Otway Basin Australia (Figure 1). The Otway Basin is a Late Jurassic to Cenozoic age, rift-to-passive margin basin, which has undergone two stages of crustal extension during the Tithonian-Barremian and Turonian-Maastrichtian, after which it developed into a passive margin basin following the breakup of Australia and Antarctica (Moore et al. 2000; Krassay et al. 2004; Stacey et al. 2013; Holford et al. 2014). The Otway Basin extends from SE South Australia to NW offshore Tasmanian and contains a latest Jurassic to Maastrichtian siliciclastic sedimentary succession, followed by Cenozoic mixed carbonate and siliciclastic rocks (Moore et al. 2000; Krassay et al. 2004). Five major depocentres comprise the Otway Basin and these include the Eastern Torquay Sub-Basin, the mostly onshore Inner Otway Basin and the deepwater Hunter, Nelson and Morum Sub-Basins (Figure 1a, Moore et al. 2000). Separating the Inner Otway Basin from the deepwater and frontier Nelson Sub-Basin is the present-day shelf-edge break, where this study is located (Amrit 3D, Figure 1).

We use two methods to analyse the growth of the fault assemblage: [1] throw-distance *(T-x)* graphs and [2] throw-depth *(T-z)* graphs. Throw-distance graphs enable the examination of along-strike throw variance, which allows us to highlight individual fault segments, which have linked during their growth history (Walsh and Watterson, 1988; Peacock and Sanderson, 1991; Childs et al. 1995; Walsh et al. 2003). Throw-depth graphs highlight anomalous down-dip throw deficits, which may indicate the down-dip linkage of fault segments, known as dip-linkage (Mansfield and Cartwright, 1996). In addition, we also provide cross-sections of our seismic interpretation to highlight the cross-section geometry of the faults analysed and the presence or absence of basement fault interaction. Our analysis shows that the fault assemblage is linked to major basement normal faults, has accumulated up to 1.74 km of throw, nucleated during the Turonian-Santonian and continued growth until the latest Maastrichtian. Based on our interpretation, we have constrained the development of this fault assemblage into four stages: [1] Turonian-Santonian basement rifting during crustal extension between Australia and Antarctica. This, along with sediment loading, invoked an increase in tilting, flexure and gravity gliding in Upper Cretaceous sedimentary rock and instigated the nucleation of the fault assemblage as an isolated and cover restricted fault assemblage; [2] persistent sediment loading with deltaic Campanian-Maastrichtian influx, in addition with further crustal extension, caused flexure above major basement faults and the gravity-driven growth of the fault assemblage continued [3] hard-linkage along-strike of fault segments eventually occurred forming a NW-SE striking fault assemblages, and; [4] latest Maastrichtian termination of fault growth. We show that the rifting basement faults controlled the nucleation and growth of the fault assemblage and eventually formed geometric linkage. This may imply a kinematic linkage between the Upper Cretaceous fault assemblage analysed and the underlying basement normal faults, highlighting that Upper Cretaceous rifting in the Otway Basin had a large control over the temporal and spatial evolution of gravity-driven fault assemblages near the present-day shelf-edge break. Given that faults may act as conduits for vertical and cross-fault migration of hydrocarbons, and they may also be sealing allowing for hydrocarbon entrapment, the spatial evolution of the faults analysed in this study has implication towards the hydrocarbon prospectivity of the Otway Basin.

## DATASET AND METHODS

We use a 3D seismic reflection survey (Amrit 3D), which covers an area of ~1,120 km$^2$ (~ 43 km along strike and ~ 26 km down dip) and images to a depth of 6.5 seconds TWT. The survey is located approximately 55 km south of the town Portland, at the present-day shelf-edge break of the Otway Basin (Fig. 1a). The survey has a 12.5 m inline and crossline spacing, with the inlines oriented NW-SE and crosslines oriented NE-SW. The water depth within the survey ranges between 130 m and 1,750 m and all depths discussed herein use sea level as a datum. The vertical resolution of this survey ranges from 19 m to 38 m, between 2-6 seconds TWT, which is the depth range of interest to this study. This was calculated using the dominant frequency at the upper and lower limits of the TWT interval. Three 2D seismic lines (ds01-108, ds01-109 and ds01-110), transecting the 3D survey, were used in this study to interpret major basement faults, located deeper than the 3D survey. Well data from Amrit-1 and Hill-1 and 2D seismic lines that tie to wells outside the study area (e.g. Bridgewater Bay-1 and Triton-1, Fig. 1a) were used to establish chrono-stratigraphically constrained horizon ties.

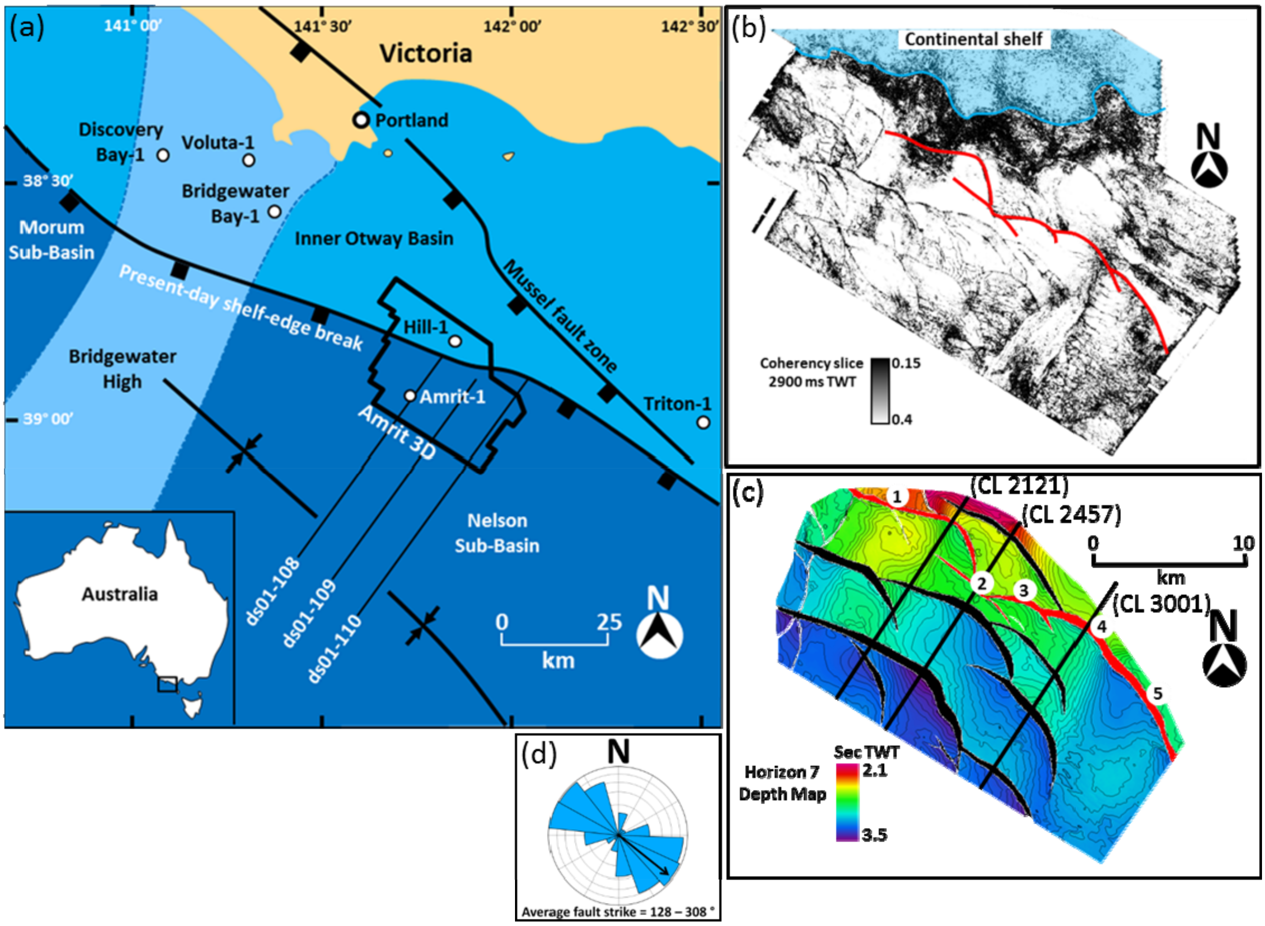


**Figure 1: (a) Location map of the 3D seismic reflection survey, 2D seismic lines ds01-108, ds01-109, ds01-110 and wells Discovery Bay-1, Voluta-1, Bridgewater Bay-1, Hill-1, Amrit-1 and Triton-1 used for this study. (b) Coherency slice (2900 ms TWT), highlighting the continental shelf (blue) and faults of interest to this study (red). These faults are also shown as fault polygons on the depth (TWT) map of horizon seven (c), with individual fault segments shown for each fault assemblage. Also highlighted on this map are the cross-sections shown in Fig. 3. The average strike of the fault array (d) is NW (128-308).**

Interpretation of the seismic dataset was conducted for horizons 1-8 and these eight horizons divided the subsurface geology into nine stratal units, which can be seen on seismic cross-sections (Figure 3). Stratal unit 1 is the Palaeozoic basement rock and stratal units 2 and 3 represent Tithonian-Albian and Turonian-Santonian aged units, respectively. Stratal units 4-8 are all Campanian-late Maastrichtian aged and stratal unit 9 represents the latest Maastrichtian and Cenozoic aged rock. Horizons 2, 3 and 8 have been tied to proximal and distal wells (Figure 1a) to create a chronostratigraphically constrained framework. Two methods were used to analyse the spatial and temporal evolution of the fault assemblage: [1] throw-distance *(T-x)* graphs and [2] throw-depth *(T-z)* graphs. Along-strike throw variance of the fault assemblage may be analysed using *T-x* graphs and highlights individual fault segments, which have linked at some stage in their growth history (Walsh and Watterson, 1988; Peacock and Sanderson, 1991; Childs et al. 1995; Walsh et al. 2003). Throw variance down a fault plane, using *T-z* graphs, allows for the analysis of vertical segmentation (Mansfield and Cartwright, 1996; Jackson and Rotevatn, 2013) and together with *T-x* graphs, this enables a three-dimensional interpretation of segmented normal fault growth. We also present cross sections of our seismic interpretation to visually show normal fault geometry, interaction and syn-depositional growth packages in the hanging wall of normal faults.

## MEASUREMENT OF SYN-KINEMATIC STRATA

Throw-depth analysis (Figure 2a) reveals a steady increase in throw with depth at fault 1 (location 1), throw minima at horizon 6 (intra Campanian-Maastrichtian) from the SE potion of fault 1 and faults 2 and 3 (locations 2-5) and throw minima at horizons 3 (top Santonian, locations 5 and 6, faults 3 and 4) and 4 (intra Campanian-Maastrichtian, locations 7 and 8, fault 5). Throw-distance analysis (Figure 2b) of the fault assemblage indicates highly variable throw along strike, with several minor throw maxima separated by local throw minima and major throw maxima on horizon 2 (top Albian) at locations 1 (~1.62 km) and 7 (~1.74 km), separated by a major throw deficit between locations 3 and 4. Dip-linkage to major basement faults has been interpreted on regional 2D seismic lines, where this fault assemblage penetrates below the 3D survey at locations 1, 2, 4, 5 and 6 (Figures 3d, e and f). Basement normal faults are generally spaced 1-3 km apart, dip basinward (SW) and typically display throw upwards of 200 ms TWT, offsetting landward (NE) tilted half-graben fault blocks, which also have minor intra-fault block normal faulting in some places (Figures 3d, e and f).

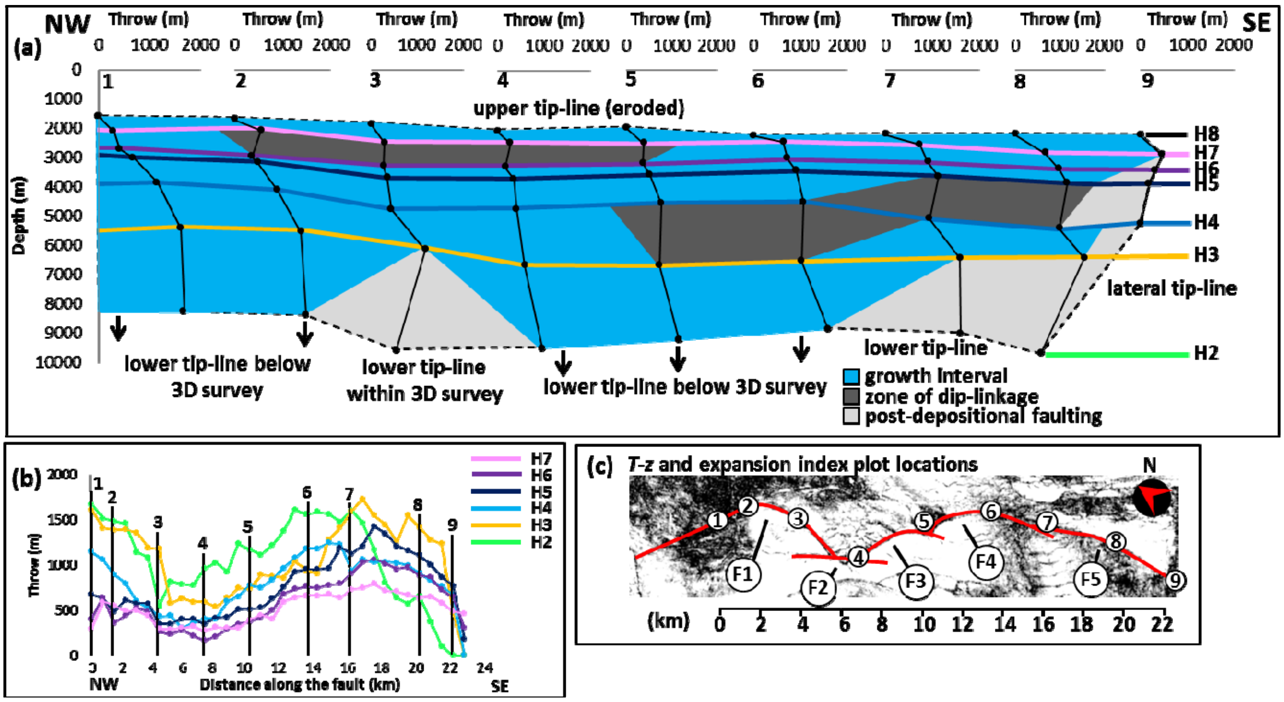


**Figure 2: (a) Throw-depth (*T-z*) analysis from NW (left) to SE (right) of the fault assemblage, comprised of faults 1-5. Note the upper zone of dip-linkage (dark grey) at locations 2-5 and the lower zone of dip-linkage at locations 5-8. (b) Maximum throw-distance graph showing the variability of throw along strike of the fault for horizons 2-7. The location of *T-z* plots 1-9 are displayed (c).**

## SPATIAL AND TEMPORAL DEVELOPMENT OF THE FAULT ASSEMBLAGE

Given that this fault assemblage penetrates below the 3D survey, the exact timing of nucleation cannot be determined through *T-z* analysis (Figure 2a). However Aptian-Albian aged sediment deposition is widely considered to be controlled by thermal subsidence, with fault dormancy preceding the first stage of rifting in the Otway Basin (Hill et al. 1995; Krassay et al. 2004). The oldest growth strata measured in this study is the Turonian-Santonian Shipwreck Supersequence (stratal unit 3, between horizons 2 and 3), unconformably overlying the Eumeralla Supersequence (Aptian-Albian). Therefore, if the Aptian-Albian was indeed a period of fault dormancy, we interpret that the Turonian-Santonian growth strata represents the nucleation of the gravity-driven fault assemblage, which have subsequently dip-linked to underlying basement normal faults.

We interpret this fault assemblage to have grown from the nucleation of faults 1, 2, 3 and 4 during the Turonian-Santonian, evident by T-z graphs (Figure 2a) showing downward increasing throw at locations 1, 2, 4, 5, and 6, between horizons 3 (top Santonian) and 2 (top Albian). Location 3 (fault 1) shows a maximum throw on horizon 3 (top Santonian; Figure 2a). Therefore, only the NW half of fault 1 (locations 1 and 2) nucleated at this stage. The SE portion of fault 1 (location 3) and fault 5 (locations 7 and 8) nucleated during the deposition of the earliest measured Campanian-Maastrichtian strata (stratal unit 3, between horizons 3 and 4), evident by maximum throw occurring on horizon 3 (top Santonian; Figure 2a). The fault assemblage continued growth until the latest Maastrichtian, with growth via vertical and lateral segment linkage, evident by anomalous throw deficits down the fault plane, shown as zones of dip linkage (Figure 2a) and highly variable along-strike throw (Figure 2b). The upper fault tips have been eroded and unconformably overlain by post-Maastrichtian mixed carbonate and siliciclastic sedimentary rock, leaving the latest Maastrichtian growth unmeasurable (Figure 3).

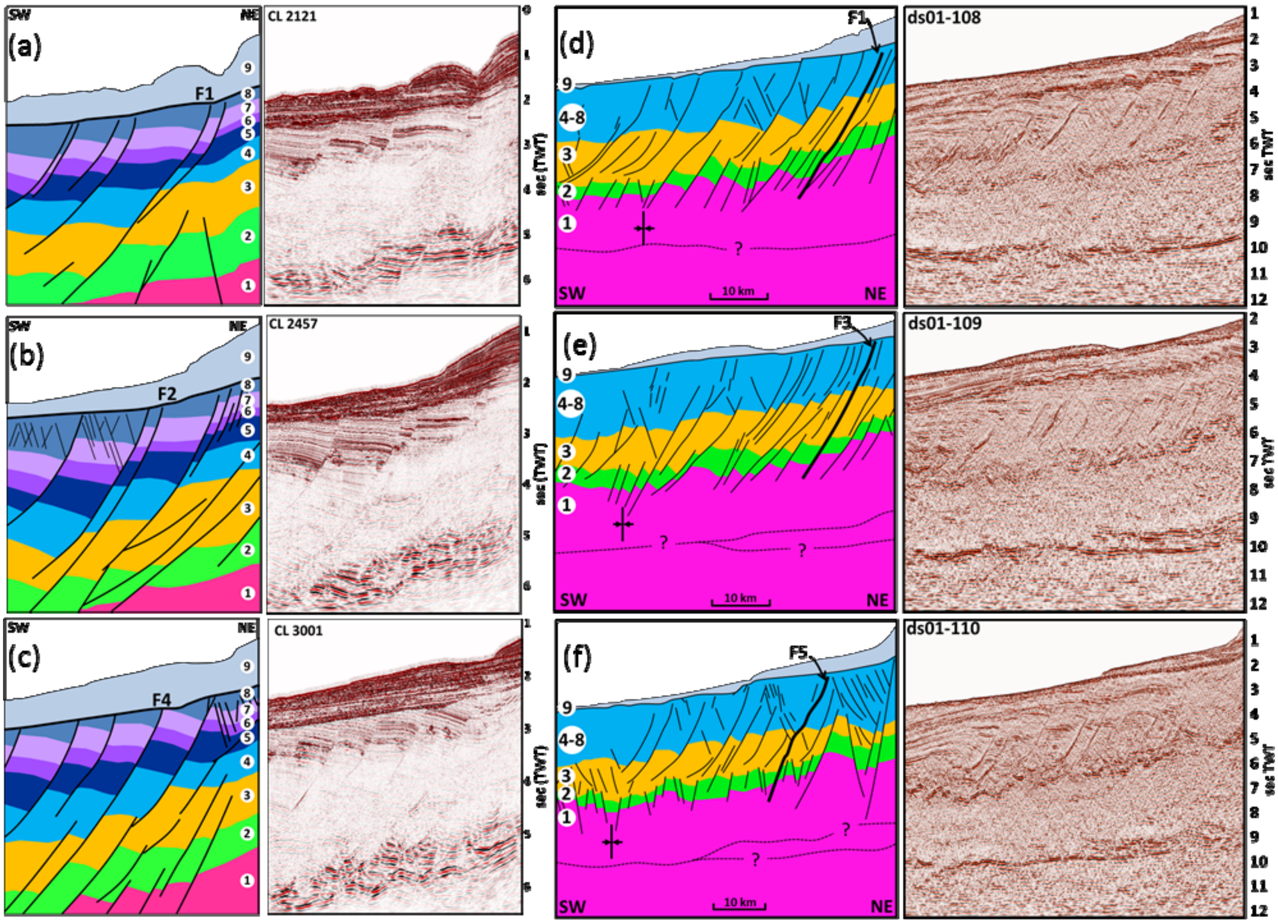


**Figure 3: Crosslines 2121 (a), 2457 (b) and 3001 (c) of Amrit 3D with interpretation on the left hand side (See Figure 1 for location of crosslines). Regional 2D seismic lines ds01-108, ds01-109 and ds01-110 used to show the linkage of the fault assemblage to major basement faults. The numbers on the right hand side of all interpreted cross-sections represent stratal units we used for this study (see methods).**

## IMPLICATIONS FOR NORMAL FAULT GROWTH AND HYDROCARBON PROSPECTIVITY

The aim of this study was to temporally and spatially constrain the growth of a gravity-driven normal fault assemblage (Figure 1b and c), imaged by 3D seismic data and located within Upper Cretaceous sedimentary rock at the present-day shelf-edge break of the Otway Basin Australia (Figure 1a). We have temporally constrained the growth of the fault assemblage between Turonian-Santonian nucleation and latest Maastrichtian termination of growth. We have spatially constrained normal fault growth by providing evidence for along-strike and down-dip segment linkage, which highlights the complexity in fault plane geometric development. Studies have shown that the development of sub-parallel striking cover-restricted normal faults can be invoked by increased tilting, flexure and gravity gliding of cover sediments above basement normal faults (Vendeville et al. 1995; Withjack and Callaway, 2000). Furthermore, analysis using 3D seismic datasets from the North Sea have shown a geometric and kinematic relationship between reactivation of sub-salt basement normal faults and the development of supra-salt normal fault systems, with extension in cover sediments instigated by basement normal fault reactivation (Jackson and Rotevatn, 2013; Lewis et al. 2013; Tvedt et al. 2013). Based on our data, we interpret a potential kinematic relationship between underlying basement normal faults and the gravity-driven normal faults developed within Upper Cretaceous sedimentary rock, which is schematically expressed (Figure 4). This is evident by dip-linkage connecting the faults which have nucleated directly above these major basement normal faults upon resumed Upper Cretaceous extension (Figures 3d, e and f; Figure 4c). This is a process of 'active' kinematic linkage, as opposed to static or coincidental 'inheritance' (Jackson and Rotevatn, 2013). However, given that we cannot establish the basement fault geometry or throw variations down to basement level with 2D seismic data, we cannot rule out the possibility of linkage through coincidental 'inheritance' (Jackson and Rotevatn, 2013). The vertical migration of hydrocarbons from deep source rocks into shallow reservoirs may be permitted through permeable fault planes and associated damage zones. Our study shows that the dip-linkage of gravity-driven normal faults to major basement normal faults (Figure 4c) may have allowed for this process to occur, as opposed to gravity-driven faults which develop in vertical and geometric isolation from basement faults (see gravity-driven faults uninfluenced by basement faults, Figure 4c).

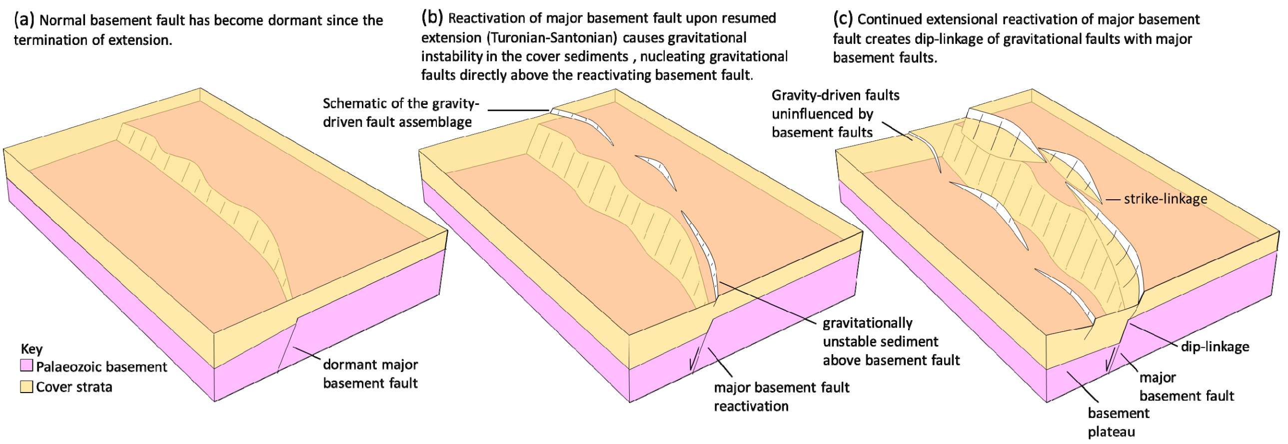


**Figure 4: Schematic diagram showing our three-stage interpretation of normal fault development. The three stages (a, b and c) are explained in the figure and text.**

## CONCLUSIONS

Using a 3D and 2D seismic dataset from the present-day shelf-edge break of the Otway Basin, Australia, we have temporally and spatially constrained the growth of a gravity-driven fault assemblage, which is dip-linked to major basement faults. We have shown that this fault assemblage displays nucleation during the Turonian-Santonian, with growth continuing until the latest Maastrichtian. We also show the geometric complexities in fault plane development by highlighting growth through lateral and vertical segment linkage. A kinematically coherent relationship has been proposed between the basement normal faults and the Upper Cretaceous aged gravity-driven faults, implying that the spatial and kinematic growth of the later is the result of basement fault reactivation, creating flexure, titling and gravity gliding in cover sediments. However, we do note that the inability to measure throw and fault plane geometry down to basement level hinders the certainty of this proposal. Our study provides new insights into the structural evolution of the underexplored and understudied present-day shelf-edge break and deepwater province of the Otway basin, Australia, and has implications towards the growth of other gravity-driven fault systems located on passive margins (e.g. Gulf of Mexico and Niger Delta) and within rifted basins (e.g. North Sea and Suez Rift) around the world.

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