PS Structural Trap Modification Associated with Foreland Lithospheric Flexure*

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Abstract

Late Jurassic horst blocks represent the typical exploration target in the Bonaparte Basin (Australian North West Shelf). Following the Tertiary early development of a foreland basin in this region and a concomitant phase of fault activity, these potential traps are classically overlain by grabens and form so-called hourglass structures. The impact of such structures on the top seal is difficult to ascertain from seismic data due to signal degradation and varies locally following the heterogeneous accommodation of Tertiary strain; this classically affects the hydrocarbon column height, resulting in underfilled or totally reached traps.

We investigate the impact of the lithosphere flexure associated with the foreland basin initiation in order to constrain the 4D (time and 3D space) distribution of deformation and stress and their impact on reservoir faults and top seal. The flexural deformation is simulated by 2D elastic models and integrated to the basin evolution framework. The related stress distribution is quantified using multi-scale geomechanically-based forward deformation models. At basin scale, models outcomes support that the distribution of a flexural extension front triggers the Tertiary structural activity. At reservoir-scale, it appears that the flexural extension results in the reactivation of the reservoirs faults (Jurassic horsts) and the dissociated nucleation of the shallower faults. This evolution scenario of hourglass structures is supported by observed 3D vertical displacement patterns which suggest a connection predominantly established by the downward growth of the shallow faults (graben faults) and the minor upward reactivation of reservoir faults (horst faults). The spatial relationship between the reservoir faults and Tertiary stress tensor and the distribution of mechanical anisotropy in the stratigraphic column represent the key factors impacting on such fault propagation and connectivity. It is noted that the downward propagation of the shallow faults towards the hydrocarbon traps stresses the top seal integrity due to fault tip deformation front and the likely development of sub-seismic fractures, therefore even though the connection between reservoir and upper faults is not established thoroughly (i.e. hard-linkage), the time-transgressive evolution of hourglass structure has potential to threaten the top seal integrity.

Structural trap modification associated with foreland lithospheric flexure.

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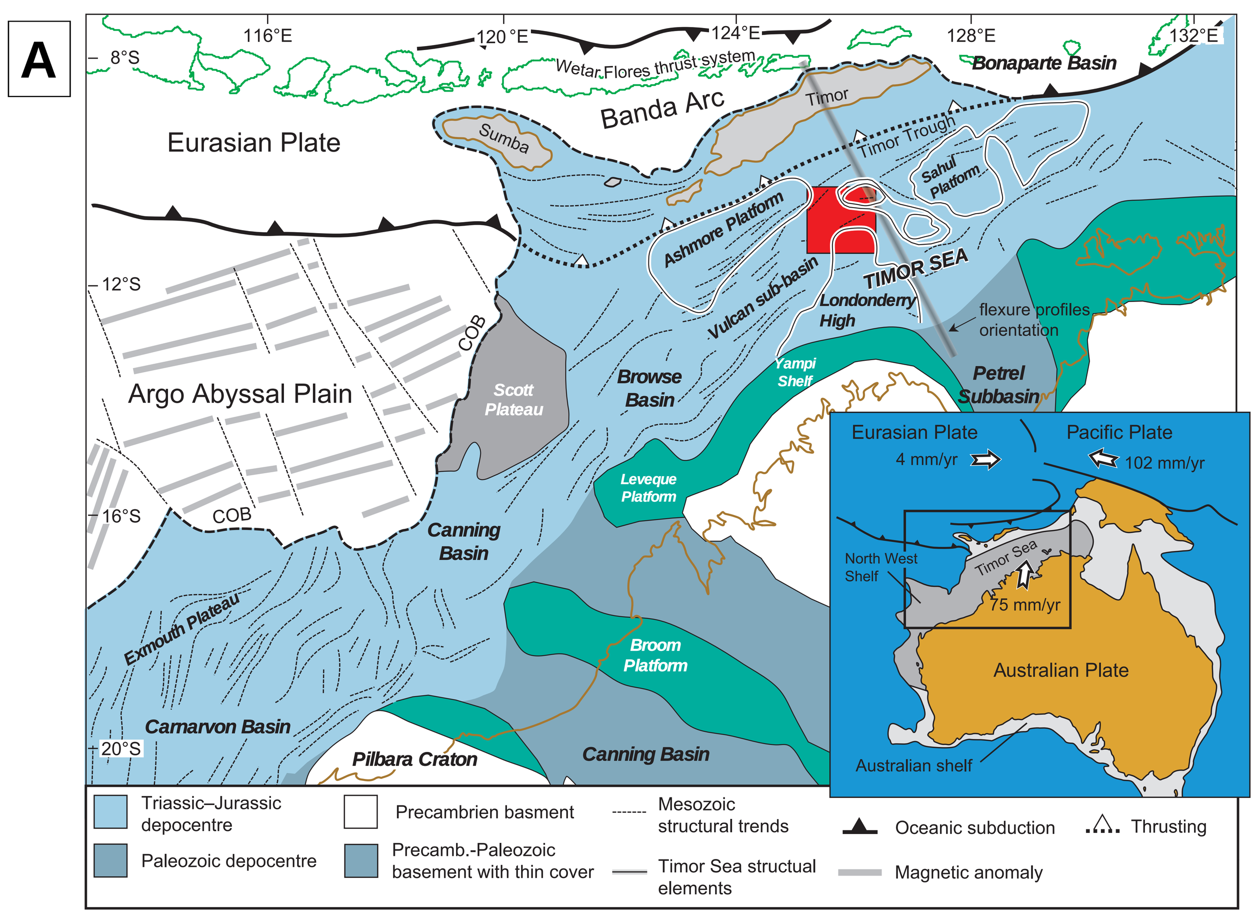
Tertiary fault development and reactivation is considered to be the primary cause of the high incidence of breached Jurassic hydrocarbon traps in the Timor Sea. The impact of structural modification on top seal integrity has been overlooked at the field scale due to the use of a structural model that does not capture the time-transgressive evolution of the trap-bounding structures. We have investigated trap evolution in detail to reveal the key issues controlling trap integrity.

- **3D structural analysis reveals Tertiary slip history and fault growth and linkage processes for various underfilled and breached traps in the Timor Sea. This is used to assess the risk(s) for top seal failure.**
- **The modeling of lithospheric deformation in the Timor Sea foreland system is used to evaluate the distribution and evolution of Tertiary flexural stress and FEM-based forward deformation models simulate the impact of regional flexure on structures and top seal integrity.**
- **Comparison between the field-scale fault growth history and the large scale lithospheric deformation is used to constrain the mechanism behind traps failure in the region and refine our regional predictions.**

Hourglass structures

In the Timor Sea (Fig. 1), conjugate sets of intersecting normal faults forming "hourglass" structures are part of the deformation pattern [1] (Fig. 2). They attracted attention because hydrocarbons are commonly trapped at their lower horst block [1, 2]. However there are frequent evidences for trap breaching with partial or complete loss of hydrocarbon columns from the reservoirs [2, 3]. It is critical to understand composite nature and temporal evolution of these structures to accurately assess the associated permeability enhancement, particularly across the top seal.



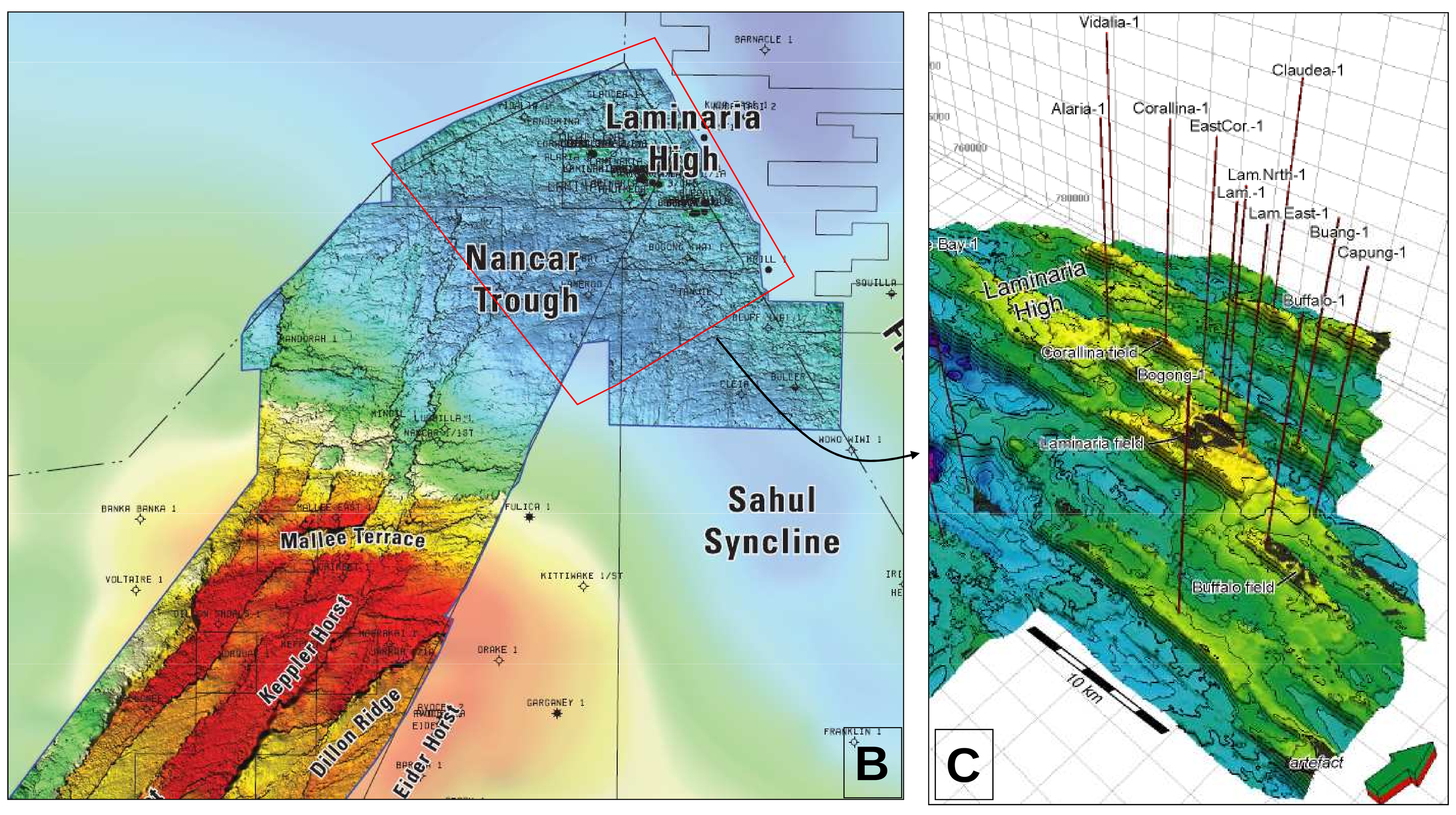


Figure 1: Location of the study area. (A) Structural elements of the Australian NW Shelf and Timor Sea foreland system; (B) Permian structure map of the central Timor Sea; (C) Close up view of the Laminaria High area showing the location of Laminaria, Corallina and Vidalia "hourglass" structures.

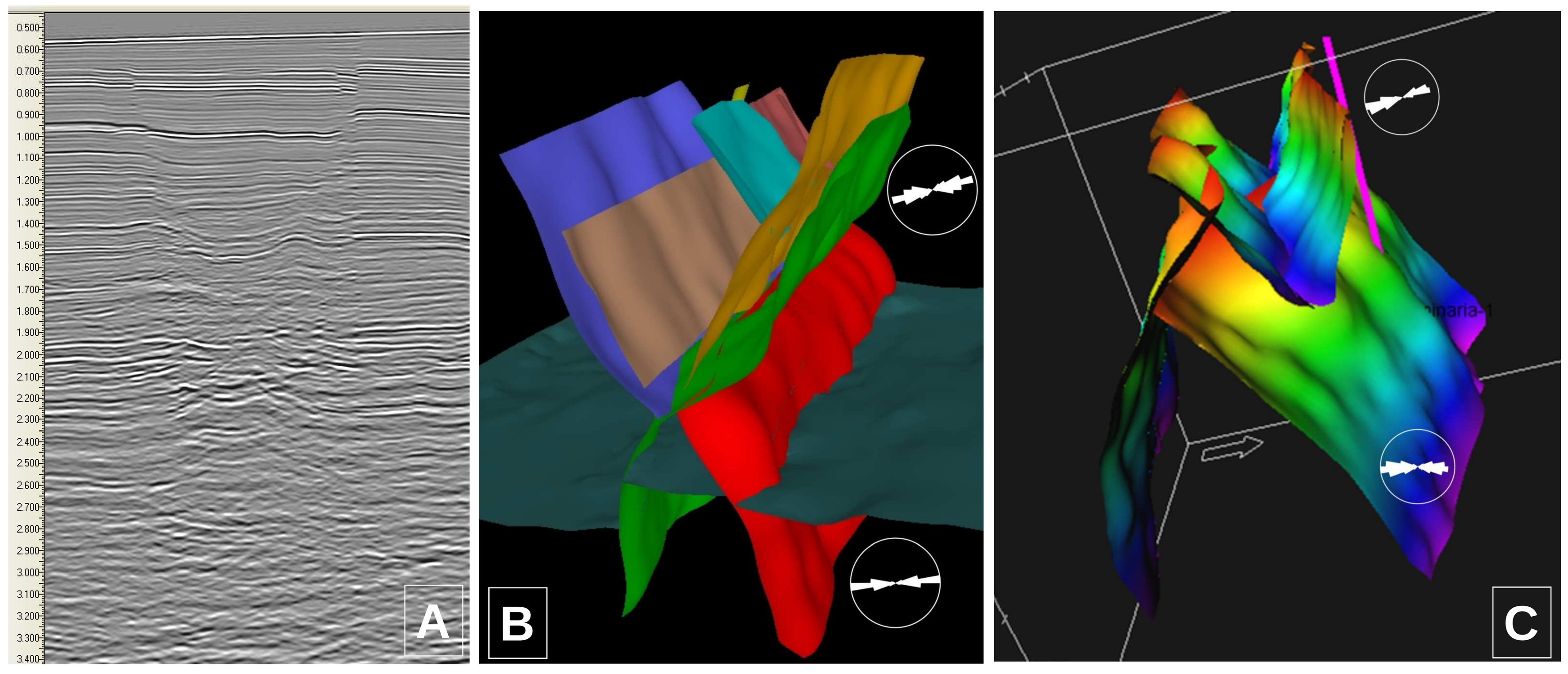


Figure 2: Geometry of the "hourglass" structures. (A) Uninterpreted seismic profile illustrating an hourglass structure. 3D fault model of the structure in the (B) Corallina Field (top reservoir in green); and (C) Laminaria Field.

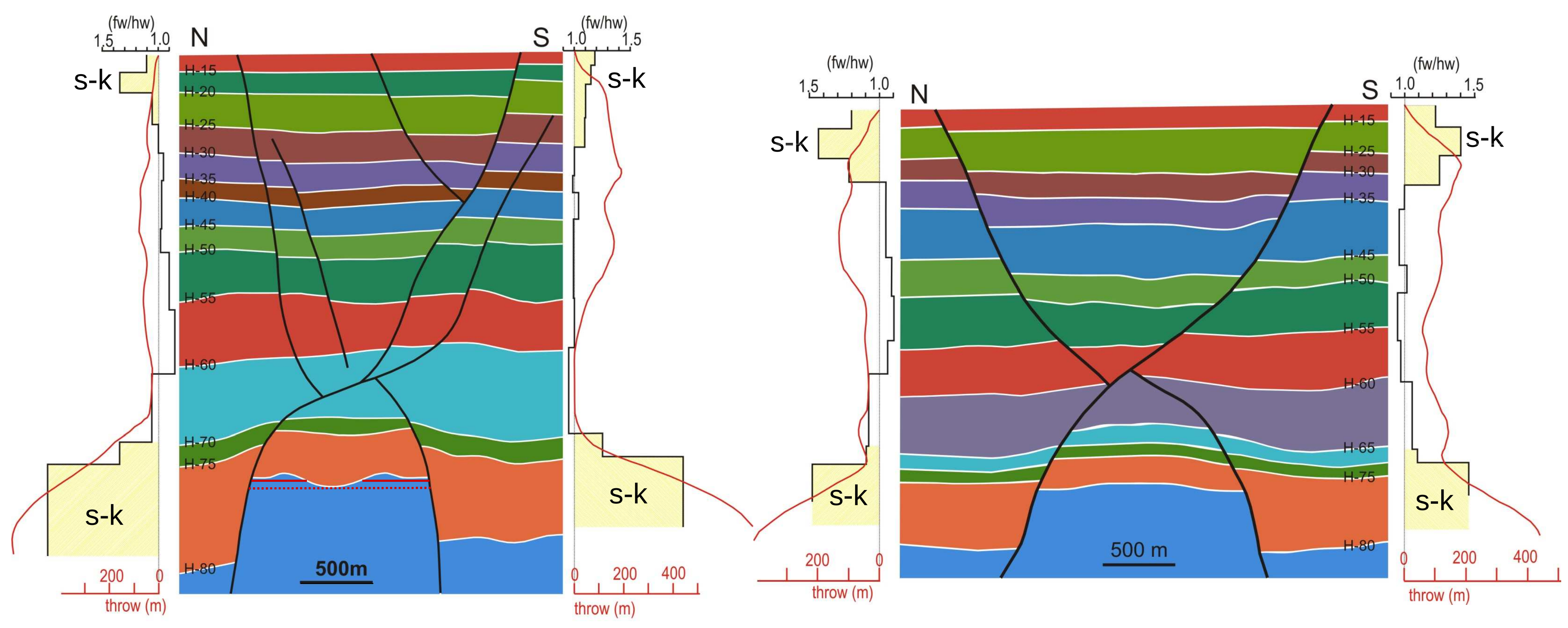


Figure 3: Throw and thickness analysis of an "hourglass" structure from Corallina (A) and Vidalia (B) structures. Red line on the throw profiles show the cumulative throw for the north dipping (right hand side) and south dipping (left hand side) faults. Hanging-wall to footwall thickness ratio (hw/fw) depicts the syn-kinematic strata (s-k) correlating with the 1st and 2nd phases of deformation.

Hourglass structures incorporates two distinct fault systems developed by separate phases of deformation (Fig. 3):

- 1st-phase fault system comprises older, horst bounding normal faults which formed during the Late Jurassic;
- 2nd-phase fault system comprises younger, graben forming normal faults which formed during the Tertiary.

The two fault systems interact around the intervening Cretaceous shale (top seal) and can be detached (Laminaria Field), poorly connected (Corallina Field) or well connected (Vidalia dry structure).
Connection of the two systems forms composite, time-transgressive fault planes with along-dip variation of displacement. This variation is controlled by location of fault nucleation, fault tips and syn-kinematic deposition (Fig. 3).

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Structural trap modification associated with foreland lithospheric flexure (2).

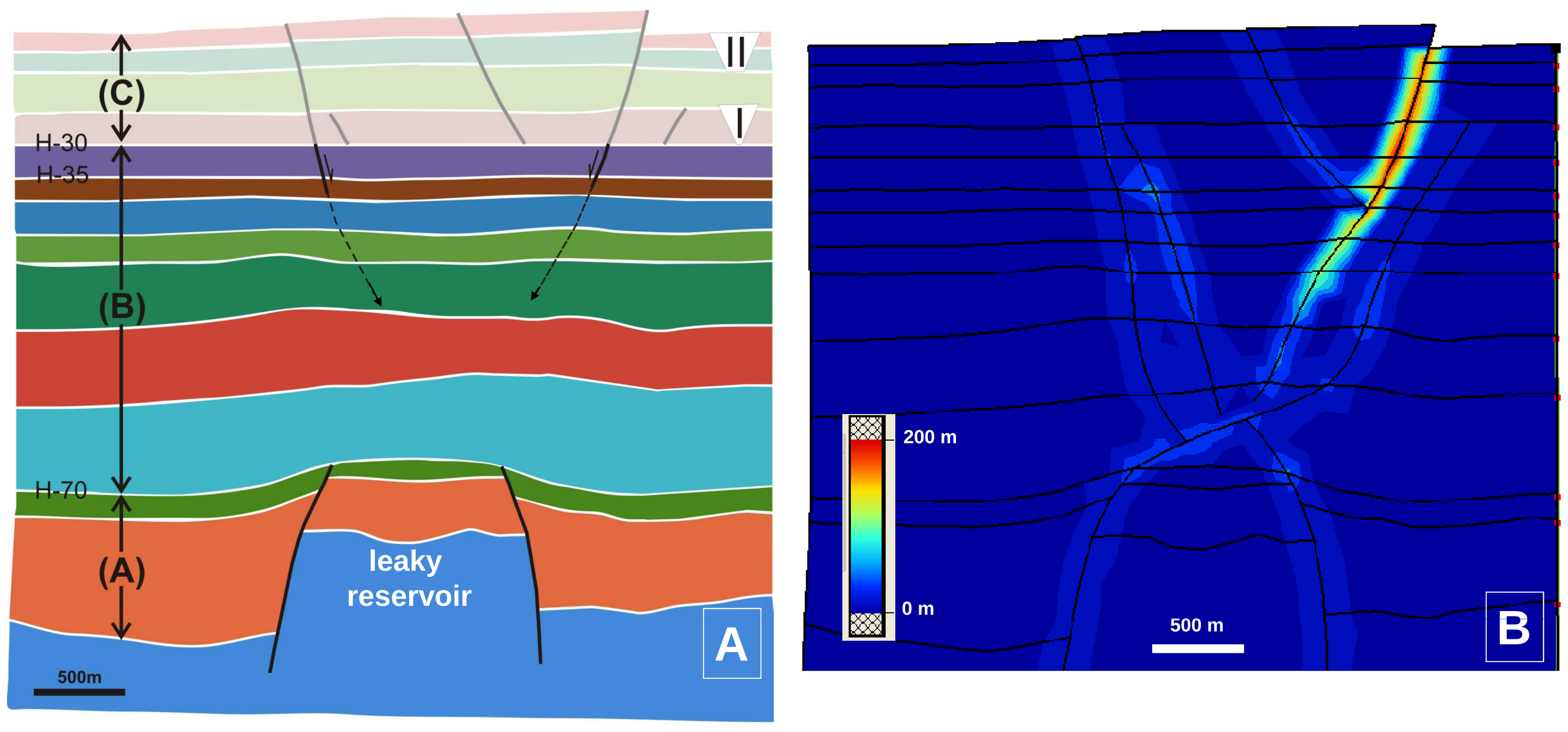

Figure 4: (A) Section restored back to the beginning of the Tertiary (H30) deformation phase. (I) Onset of Tertiary extension, (II) first palaeo-seafloor evidence for leakage (I). **(B)** The restoration offsets of the Tertiary deformation phase suggest that the initial Tertiary strain was mostly accommodated by the downward propagation of 2nd-phase faults while reactivation of deeper 1st-phase faults is minor.

Temporal evolution of the hourglass structures

1. 1st-phase faulting and deposition of Late Jurassic to Early Cretaceous syn-kinematic strata (Section A, Fig. 4A).
2. Deposition without any faulting during the Late Cretaceous to Late Miocene (Section B, Fig. 4A).
3. Initiation of the 2nd-phase of deformation with faults nucleating around H-35 (Late Miocene) (Fig. 4A).
4. Deposition of 2nd-phase syn-kinematic strata during the (Late Miocene) (Section C, Fig. 4A). 2nd-phase faults were active and have grown downward while the reactivation of 1st-phase faults remained minor (Fig. 4B).
5. Connection of 1st and 2nd phase faults. There is a time lapse between the onset of 2nd-phase and the connection of the two fault systems. This is supported by the delay between palaeo-seafloor evidences of hydrocarbon leakage (H-20) and the onset of 2nd-phase extension (H-30) (Fig. 5).

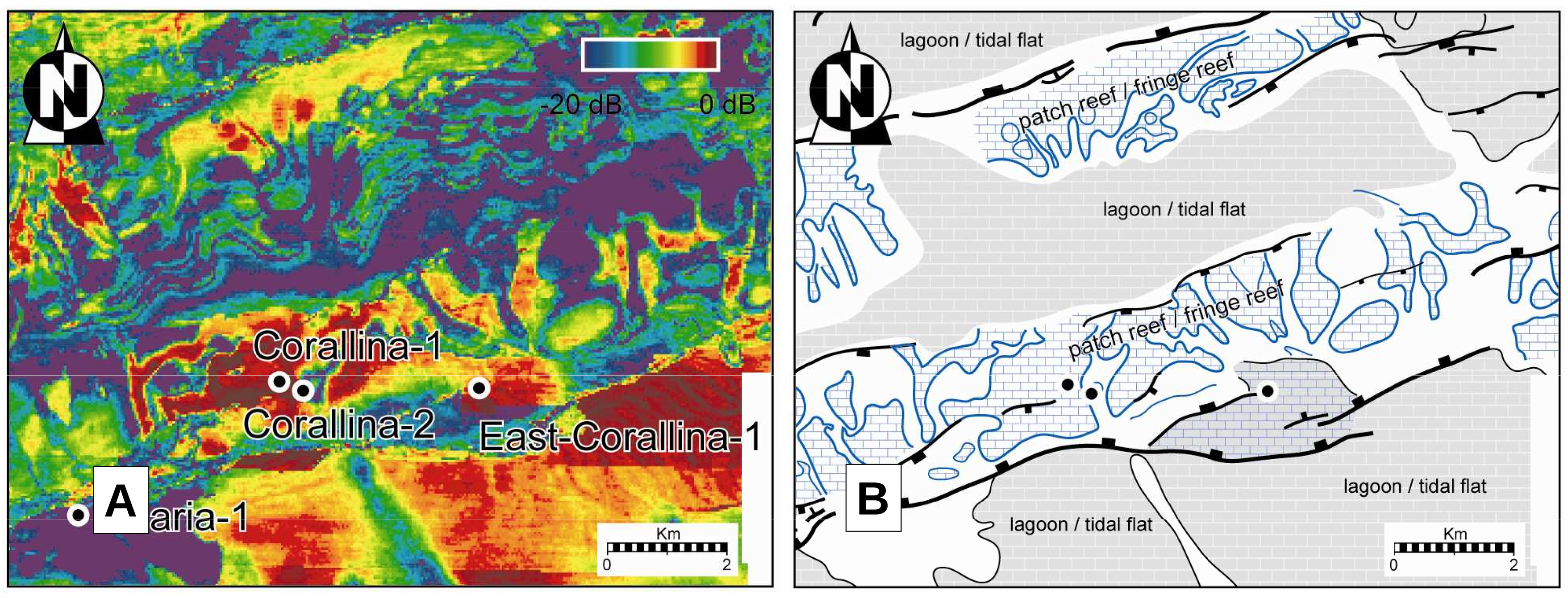

Figure 5: (A) Reflection strength extraction of the horizon H-20 at the Corallina structure. **(B)** The reflection strength anomalies are interpreted as the carbonate build-ups related to hydrocarbon leakage from the 1st-phase horst block. Note that there is a time gap between the initiation of 2nd-phase faults and the first sea-floor evidence of hydrocarbon leakage. This time gap probably accounted for the downward propagation of the 2nd-phase faults and the linkage of the two systems.

Mechanism of fault development and reactivation

The Tertiary continent-arc collision north of the Timor Sea induced the flexure of the underthrusting plate; the development and reactivation of normal faults are expected in areas of high curvature (hinge and slope) where greater tensional stresses are located.

The evolution of the plate flexure in the Timor Sea is evaluated using simple 2D elastic half-beam models simulating the deflection of the elastic lithosphere (elastic and homogeneous plate) under an end load (Fig. 6) and reconstruction of the Timor foreland system from the Late Miocene (Fig.7).

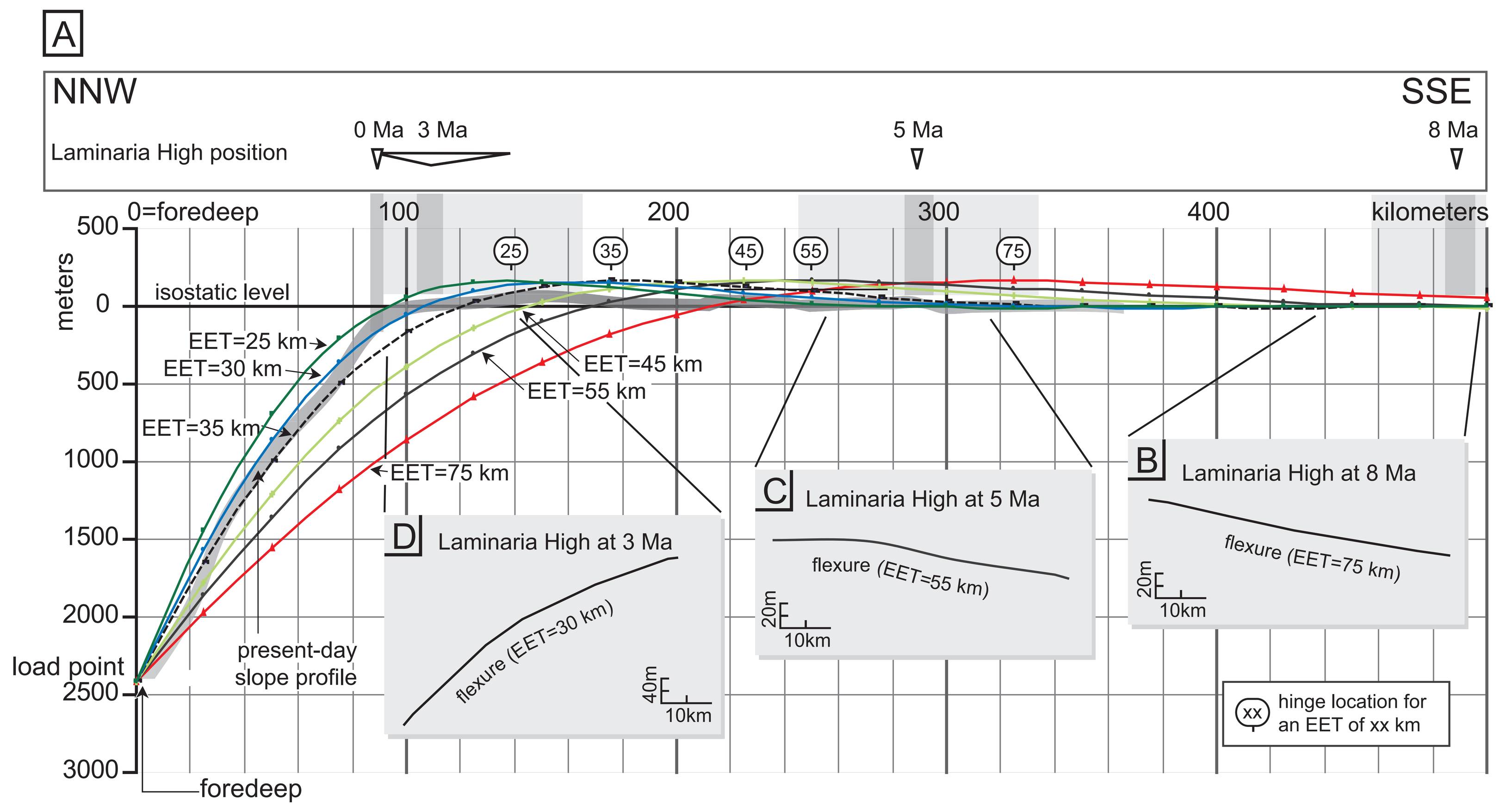

Figure 6: 2D models of the lithosphere flexure with Effective Elastic Thickness (EET) varying through time. The EET is the thickness of a perfectly elastic plate which has the same elastic flexural proprieties as lithosphere whose strength has been reduced by brittle and plastic behaviour [4]. **(A)** 2D models for EET between 75km (late Miocene) and 25km (Pleistocene). **(B) (C) (D)** Flexure at the location of the Laminaria High for the Late Miocene, Early Pliocene and Late Pliocene respectively (see Fig. 7 below).

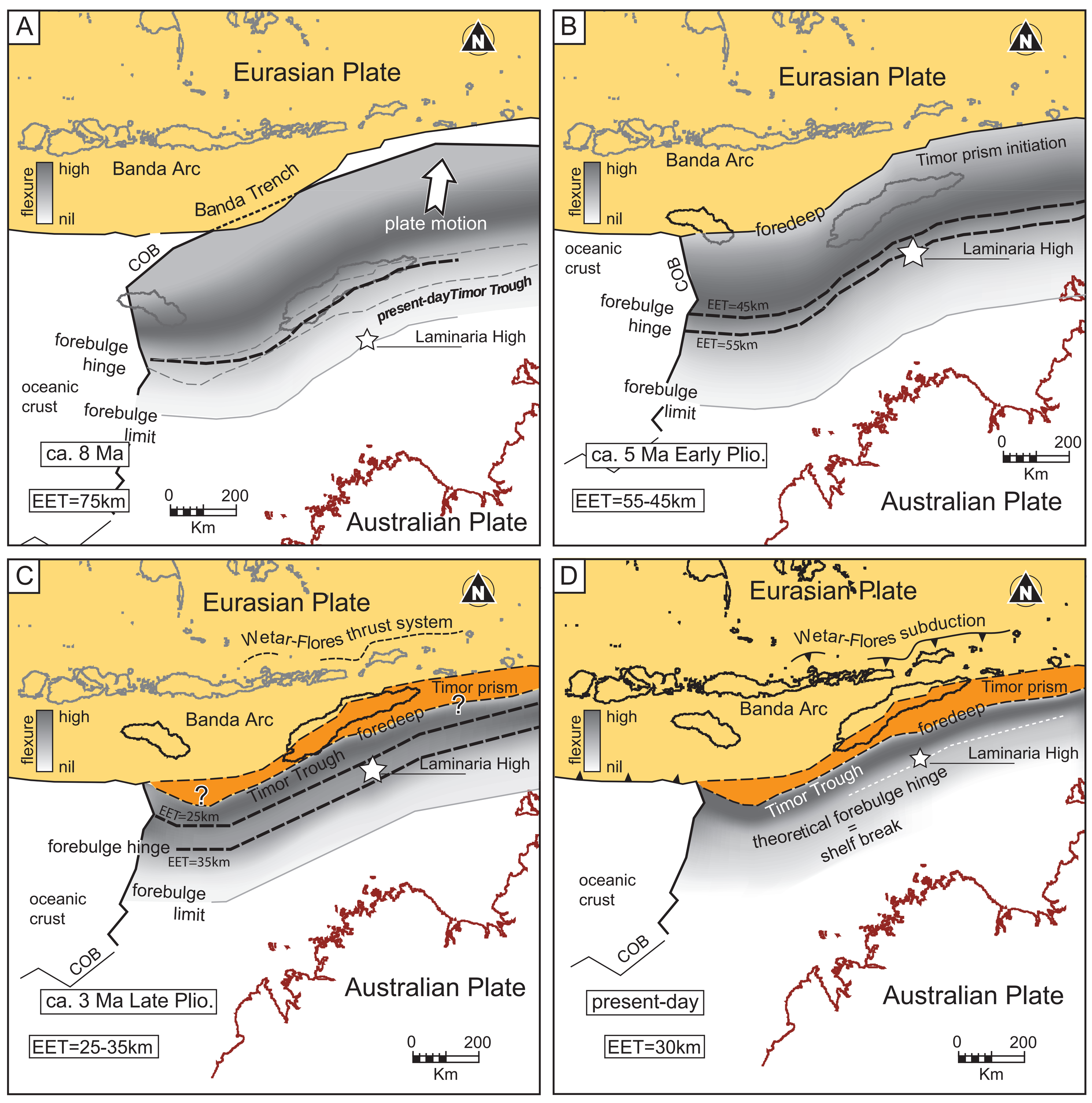

Figure 7: Reconstruction of the Timor foreland basin and distribution of the flexural front. **(A)** Late Miocene initiation of the continent-arc collision. The Laminaria High is located north of the forebulge structure calculated with EET=75km. **(B)** Early Pliocene. The Laminaria High is located on the theoretical forebulge hinge (with EET=55 km to 45 km). The Timor accretionary prism is initiating. **(C)** Late Pliocene. The Laminaria High is located on the slope, north of the theoretical forebulge hinge (with EET=25 km to 35km). **(D)** Present-day configuration and theoretical forebulge structure calculated with EET=30 km. The forebulge hinge correlates with the shelf break. A southward subduction initiated north of the Timor prism.

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Structural trap modification associated with foreland lithospheric flexure (3).

Effect of flexure on Tertiary fault activity

FEM-based forward deformation models are used to test the geomechanical impact of the modeled flexure. The margin-scale model (Fig. 8A) attests that the hinge and the slope of flexed plate are zones of extension. The local model (Fig. 8B, C) shows that the highest fault density is expected on the upper part of the Tertiary limestone where 2nd-phase fault nucleated (Fig. 3, 4). Newly developed faults cluster above reactivated Jurassic faults as expected [3].

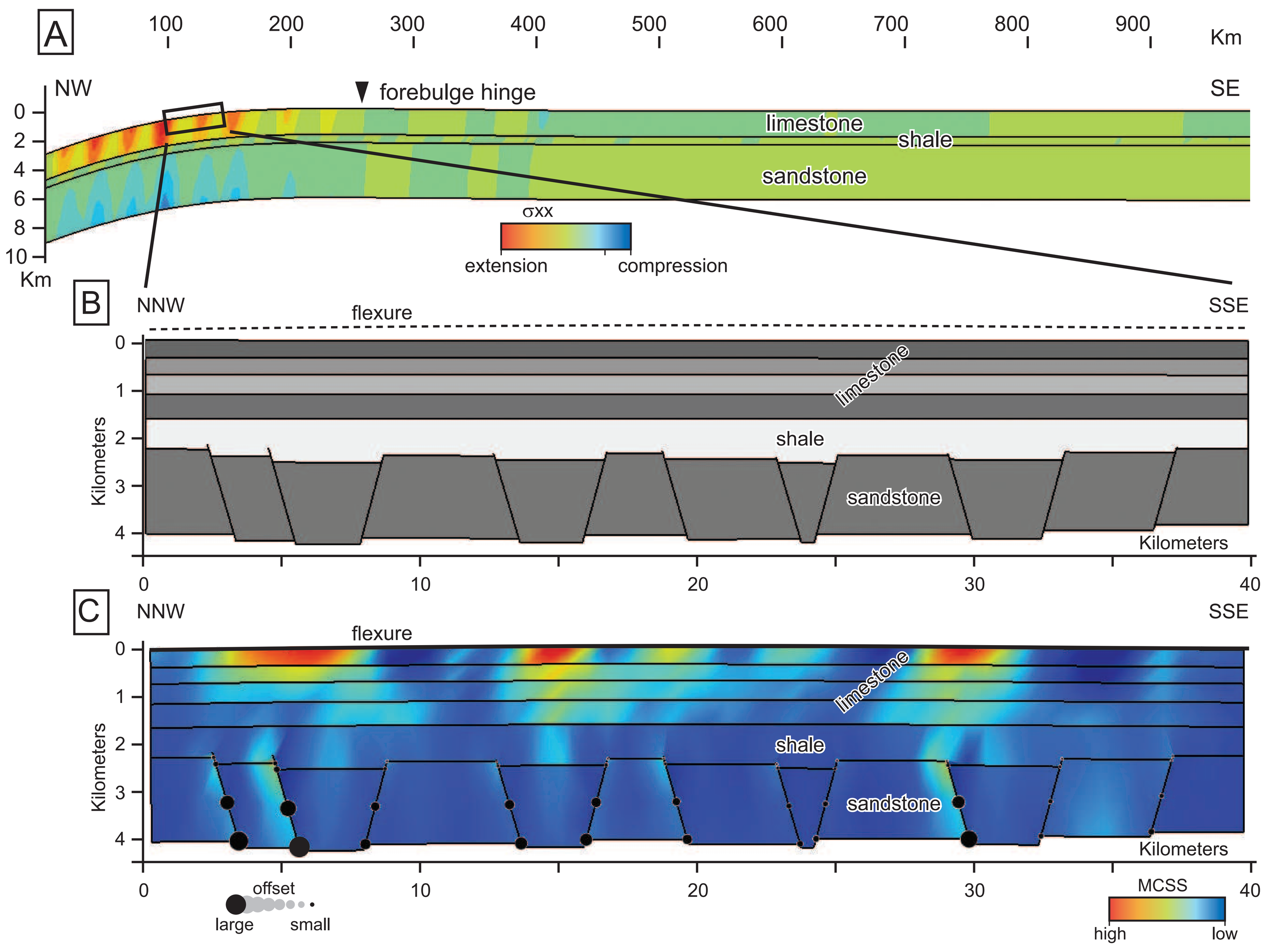

Figure 8: Forward deformation modeling based on the calculated Early Pliocene flexure. **(A)** Normal stress along the x axis for the margin-scale model. The original horizontal beam is deformed to match the target deformed Miocene-Pliocene topography on a NW-SE profile through the Laminaria High. **(B)** Six-layer model for the Laminaria High and target flexure profile. **(C)** Maximum Coulomb shear stress (MCSS) used as a proxy for fault location and density.

The impact of the lithospheric flexure on the Tertiary fault activity is demonstrated by the correlation between fault slip history and evolution of flexural extension inferred from the reconstruction (Fig. 9).

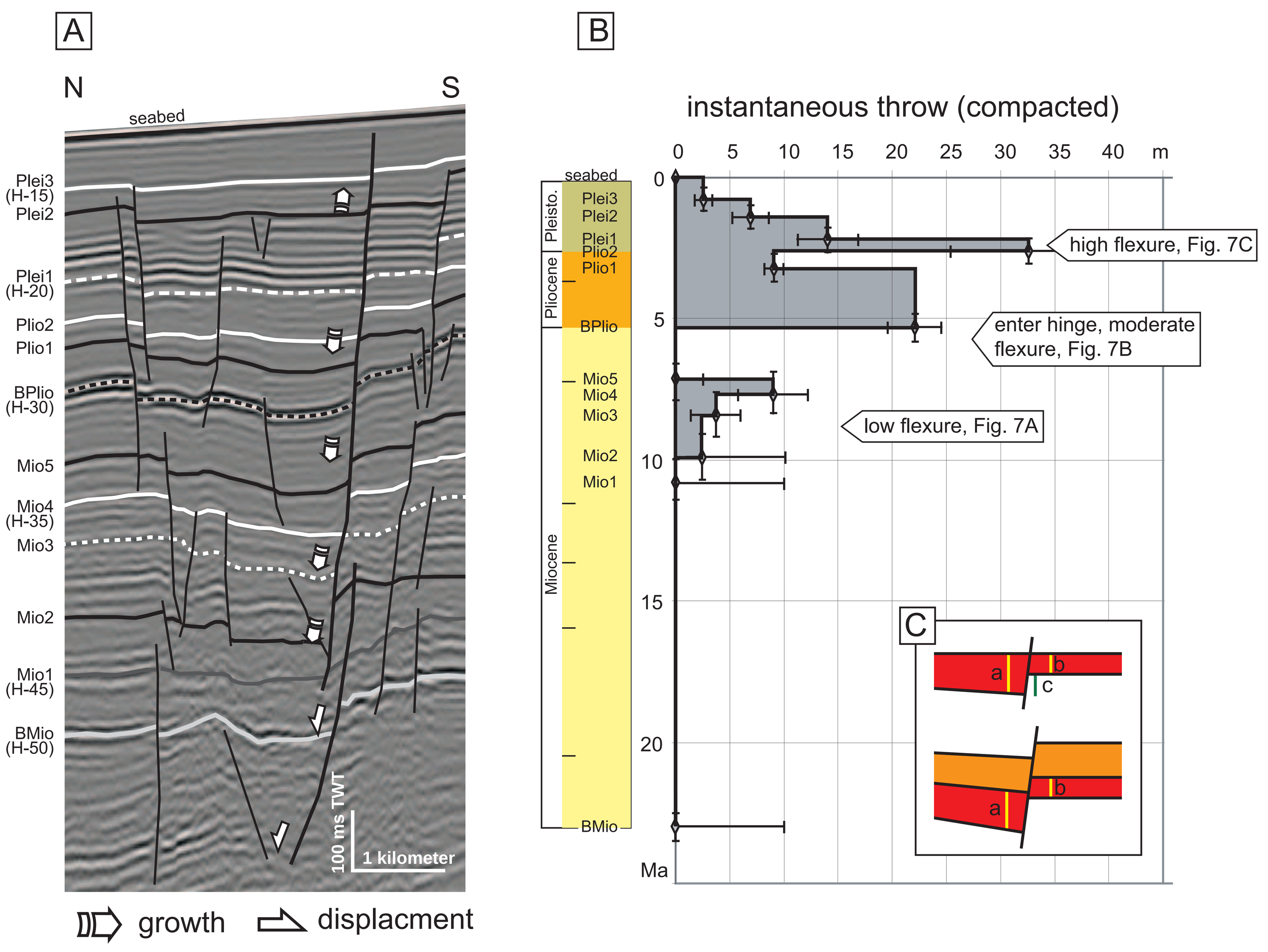

Figure 9:. Miocene to present-day fault slip history on the Laminaria High **(A)** Corallina Field north-dipping fault. **(B)** Instantaneous throw (compacted thicknesses) showing the slip history of the fault plane and the correlation with the evolution of flexural stress affecting the Laminaria High. **(C)** The instantaneous throw (c) is the difference between the hanging wall (a) and footwall (b) thicknesses.

Implications for hydrocarbon traps

Cretaceous shales have ductile capacity to detach 1st and 2nd-phase faults and probably acted as a horizontal barrier to fault growth during evolution of the hourglass structures (Figure 10). Therefore this interval accumulated ductile strain at the tips of evolving fault planes (Figure 11). Interference of the deformation fronts beyond the fault tips can create a zone of distributed deformation through the shale interval and risk the integrity of the top seal. Leakage through top seal is possible even without hard linkage of the two fault systems.

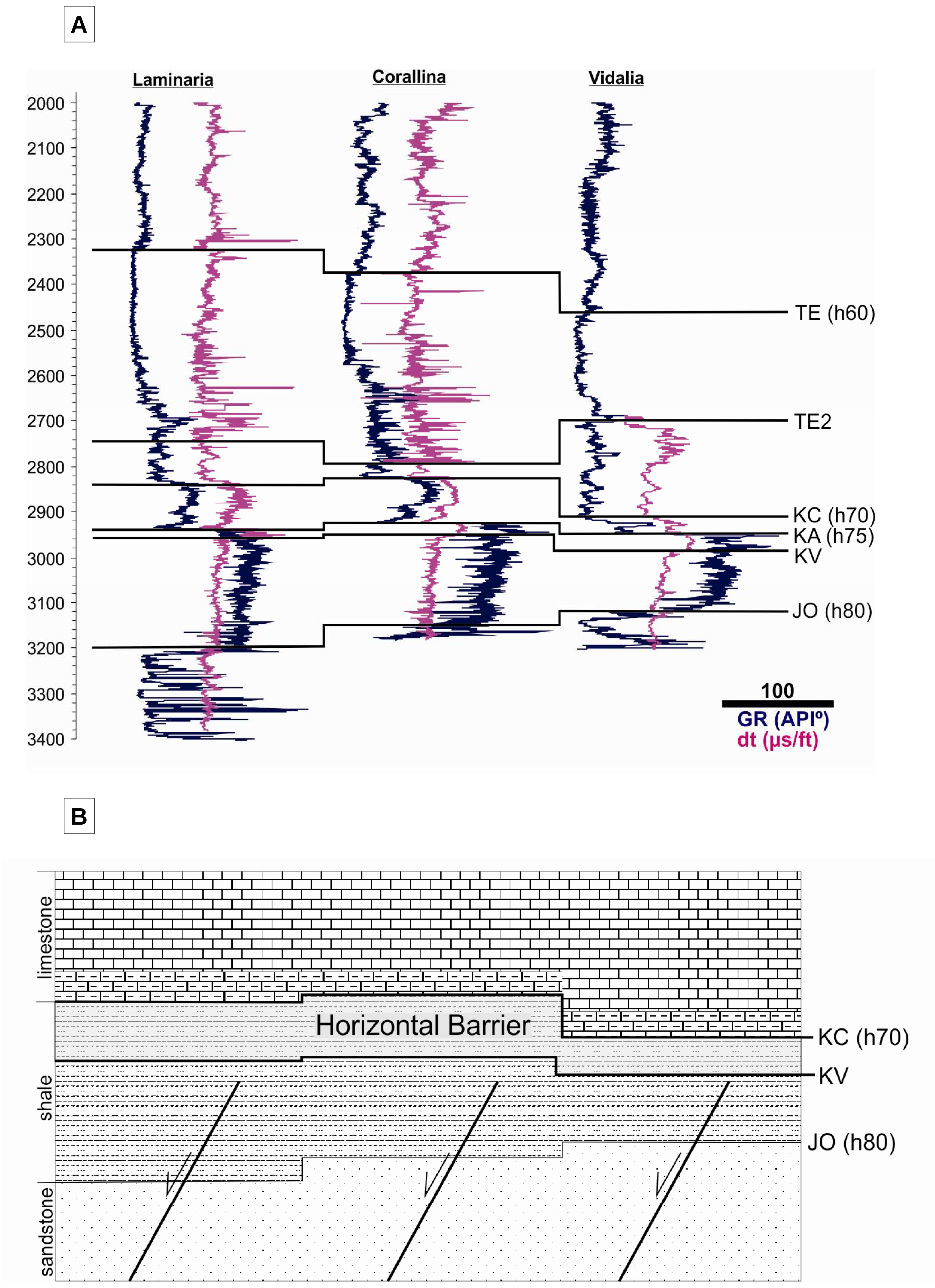

Figure 10: (A) Gamma ray (blue) and sonic curves (red) illustrating lithology through mid to deeper section of the hourglass structures. **(B)** Schematic model showing horizontal barrier to up-dip propagation of 1st-phase faults. The connection is realised between 1st- and 2nd-phase faults at the Vidalia structure (Fig. 3B) where the barrier is thinnest. The integrity of the top seal is higher above the Laminaria and Corallina oil fields.

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Structural trap modification associated with foreland lithospheric flexure (4).

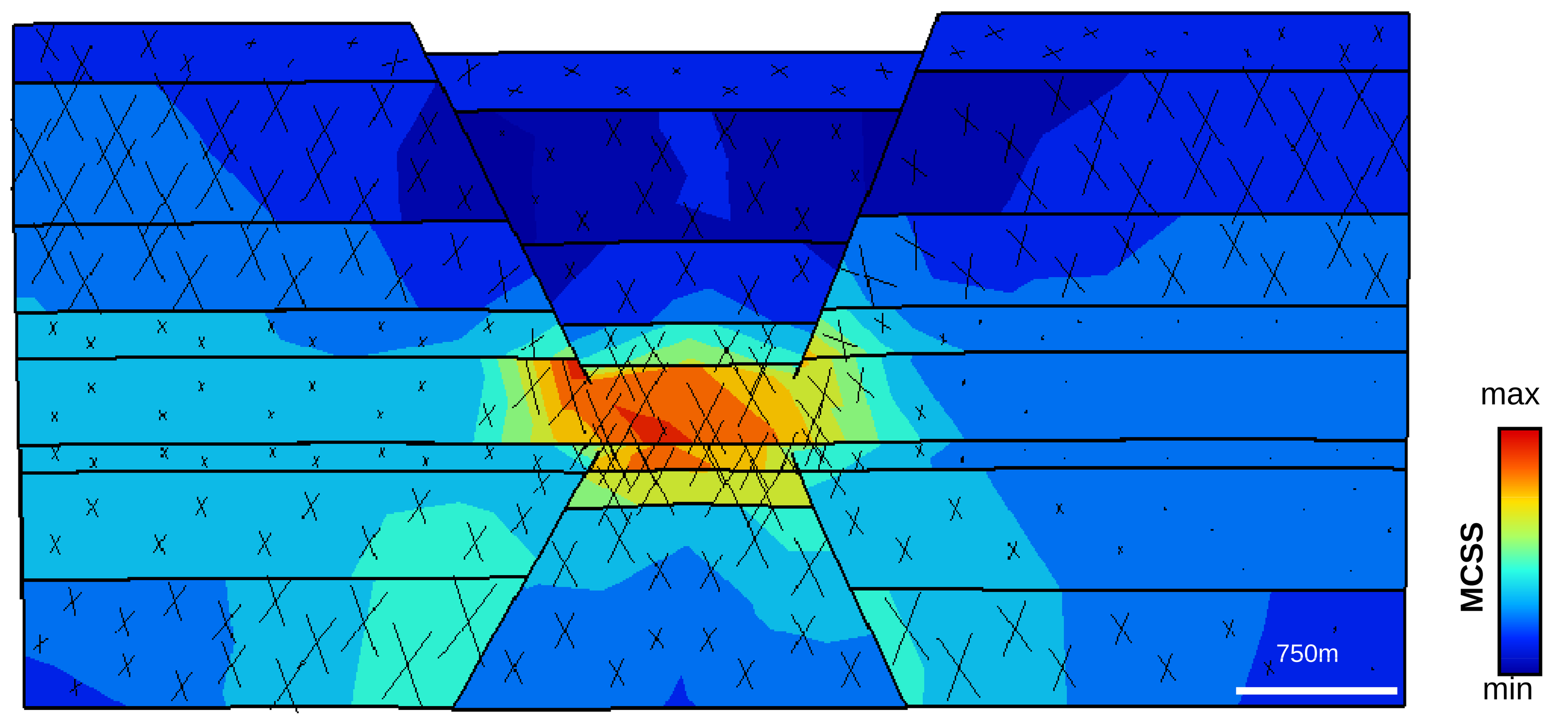

Figure 11: Forward modelling of an hypothetical fault configuration mimicking scale and deformation style of the investigated "hourglass" structures. Colour illustrates the distribution of Mohr-Coulomb Shear Stress (MCSS) and the black lines depicts the likely orientations of failure planes with size scaled to the predicted intensity. Note the concentration of deformation around the top seal interval where 1st- and 2nd-phase faults interact.

Preservation of hydrocarbon columns is more likely under following conditions:

- As a horizontal barrier to fault propagation, thickness of the shale layer is sufficient to impede the up-section growth of the 1st-phase faults (Figure 10).
- Tip deformation front of 2nd-phase faults remain distant to the reservoir/seal sequence therefore interference of the deformation fronts between 1st and 2nd-phase faults are avoided (Figure 11).
- Reactivation of 1st-phase faults are minimal. This is predominantly controlled by the orientation of 1st-phase faults relative to flexural front (Figure 13). Obliquity favors poor connection between 1st and 2nd-phase faults.

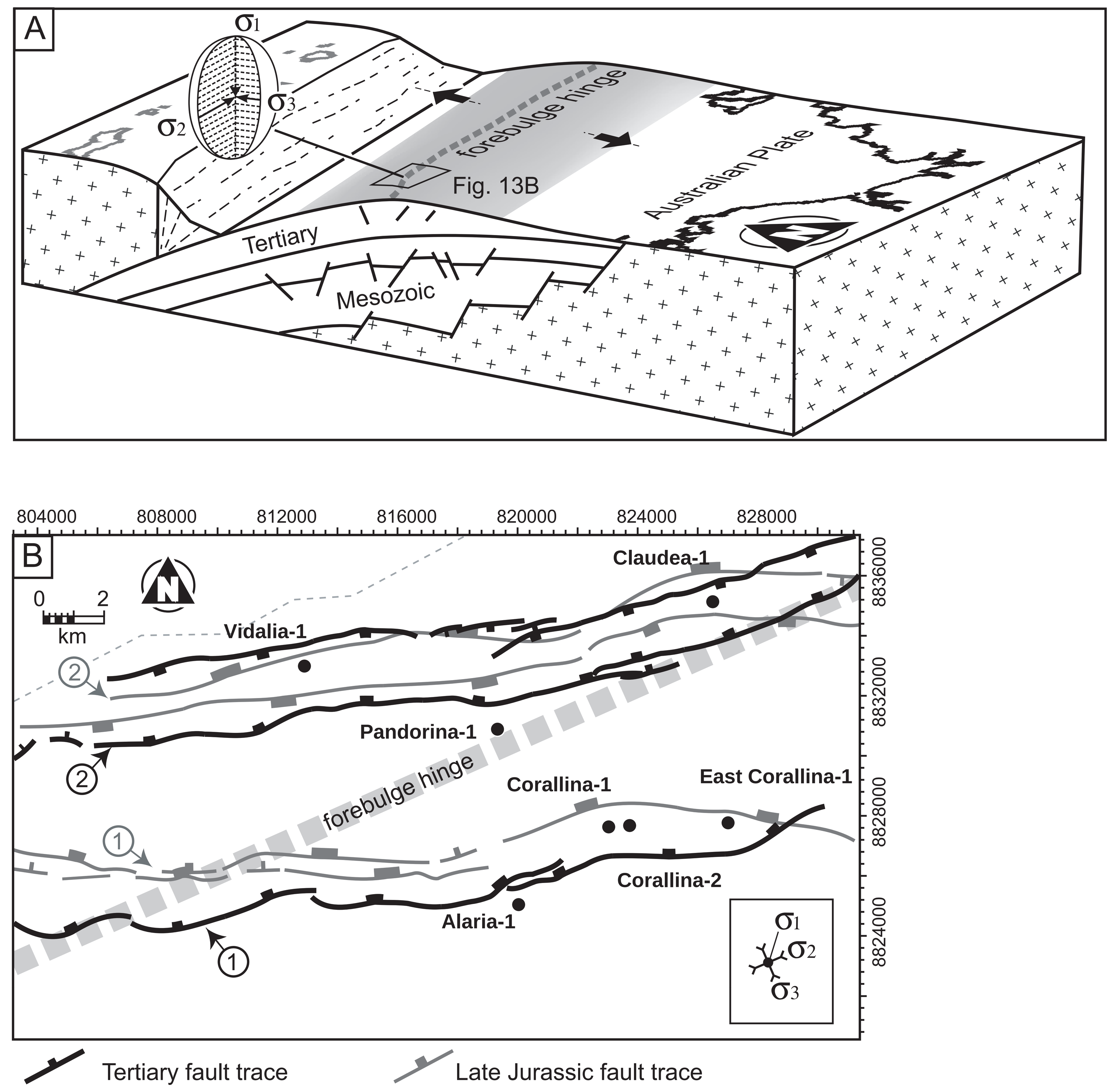

Figure 13: Stress regime and fault pattern on the Laminaria High. (A) Schematic block diagram showing the Timor foreland system near the Miocene-Pliocene boundary and the local stress regime for the Laminaria High. Not to scale. (B) Structural map on the Laminaria High showing the Late Jurassic (grey) and base Pliocene (black) fault traces for the north-dipping faults bounding the Corallina Field (1) and the Vidalia-Claudea structure (2). The local stress field is inferred from the orientation of the forebulge hinge. A transition between full connection (Vidalia) and poor connection or disconnection (Corallina) seems to occur when the angle between the Jurassic structure and the Neogene sHmax reaches ~20°.

Conclusions

- **The investigated hourglasses are composed of two different fault systems each formed through distinct episodes of deformation with a time gap in between.**
- **Connection of the two systems was mainly achieved by downward growth of 2nd-phase faults while the reactivation of 1st-phase faults may have remained relatively minor.**
- **Deformation associated with tips of 2nd-phase faults may introduce risk for top seals as they approach the vicinity of hydrocarbon traps.**
- **The flexural extensional stress related to the development of the Timor sea foreland system is likely responsible for the development of the 2nd-phase fault.**
- **The mechanical anisotropy of the sedimentary column and the spatial relationship between the flexural front and the 1st-phase faults both control the vertical propagation of faults and are key elements to evaluate top seal integrity in the region.**

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