Prospectivity insights from automated pre-interpretation processing of open-file 3D seismic data: characterising the Late Triassic Mungaroo Formation of the Carnarvon Basin, North West Shelf of Australia

Lead author
Cliff C. Ford

C.C. Ford[1], J.K. Dirstein[2] and A.J. Stanley[2]

[1]Bio Energy Resources Pty Ltd
213 Broome Street
Cottesloe, WA 6011

[2]Total Depth Pty Ltd
21 Churchill Avenue
Subiaco, WA 6008
cliff.ford@iinet.net.au

ABSTRACT

Waveform data from pre-interpretation processing is used in nine Late Triassic interpretation case studies from an area extending more than 30,000 km² across the Exmouth Plateau, Kangaroo Trough and Rankin Trend on the North West Shelf of Australia. Events selected from a database of automatically generated surfaces extracted from six large open-file 3D marine surveys (~16,000 km²) are used to analyse reservoirs, seals, and pore fluid within the Brigadier and Mungaroo formations in this peer-reviewed paper.

Today, geoscience teams are challenged with vast data sets such as the archived versions of more than 125 Carnarvon Basin 3D seismic surveys. Pre-interpretation processing delivers a database of numerous seismic events that cannot be effectively managed using traditional interpretation workstations. With, however, a 3D viewer to query, edit and merge the results, geoscience teams are able to review many large surveys and the surfaces in their interpretation workflows.

At the 2013 WABS Conference in Perth, WA, two papers offered models for the Late Triassic gas reservoirs. These models represent many years of synthesis and integration of data by teams of geoscientists from two of the major operators on the North West Shelf. Validation and corroboration of the proposed models was gained by using selected pre-interpretation surfaces. Stacking patterns, waveform fitness, amplitude and two-way time surfaces from these spatial databases revealed geological insights about the formations, such as their complexity of structure, extent of reservoirs, and continuity of seals, along with a better understanding about the trapping and charge systems of the fields.

KEYWORDS

Pre-interpretation, GeoPopulation, 3D seismic, Mungaroo, Brigadier, Chandon 3D, Wheatstone 3D, Glencoe 3D, Draeck 3D, Duyfken 3D, Bonaventure 3D, Exmouth Plateau.

INTRODUCTION

The Late Triassic Mungaroo and Brigadier formations are proven hydrocarbon reservoirs of economic significance on the North West Shelf of Australia, and its gas underpins LNG projects that are presently producing or are under construction. The formations are known only in the subsurface of the North-ern Carnarvon Basin and their type sections are described by Hocking et al (1987). The seismic events and surfaces generated by pre-interpretation processing for these formations from six large North West Shelf 3Ds define the area of this study (Fig. 1).

In this peer-reviewed paper the processing concepts of the pre-interpretation method are outlined. Nine case studies are presented to illustrate how these automatically extracted databases of peak and trough seismic events and surfaces generated can be used to characterise reservoirs, seals, traps and direct hydrocarbon indicators (DHIs) in the formations.

Figure 2a shows how pre-interpretation processing is performed on SEG-Y volumes prior to any interpretation being commenced. The intersection of more than 300 Brigadier and Mungaroo GeoPopulations or peak and trough seismic events generated from the pre-interpretation processing of the Chandon 3D are displayed by colour in Figure 2b. This demonstrates how pre-interpretation processing provides a large database of seismic events at the beginning of the interpretation phase to assist the interpretation team.

The scope of this study is limited to pre-interpretation seismic events and surfaces generated from full-stack open-file SEG-Y volumes and the analysis of their attributes such as isochrons, amplitude and waveform fitness. This study does not include velocity or depth models, amplitude versus offset (AVO) and inversion analyses, or rigorous well ties. Instead, minimal well tie data has been augmented by public domain information. Open-file reports and published papers were relied on to constrain surfaces in chronostratigraphic and depositional models presented in recent publications (Marshall and Lang, 2013; Grain et al, 2013; Adamson et al, 2013; Payenberg et al, 2013) and to indicate their environment of deposition.

The case studies are based on pre-interpretation processing databases from six open-file 3D seismic surveys (Bonaventure, Wheatstone, Draeck, Duyfken, Chandon and Glencoe). These surveys were selected from 70 open-file 3Ds presently available on the North West Shelf (Fig. 1), based on their size, data quality and economic significance. The six seismic surveys, acquired initially by Chevron and Hess for exploration and development purposes, are now open-file data and provide seismic coverage of more than 16,000 km² in the study area. Gas fields covered include Geryon, Orthrus, Maenad, Clio, Satyr, Achilles, Nimblefoot, Glencoe, Wheatstone, Iago, Eendracht, Kentish Knock, Brederode and Thebe. These fields are economically significant and presently under consideration for development in LNG projects such as Scarborough, Wheatstone, Gorgon and Equus.

Geological setting

The Carnarvon Basin extends along the coastline of WA, between Geraldton and Karratha for more than 1,000 km and offshore for 500 km to the continental/oceanic crust boundary (Hocking et al, 1987). The Northern Carnarvon Basin lies predominantly offshore, covers about 500,000 km² and contains up to 15 km of Phanerozoic sedimentary rocks (Baillie et al, 1994; Stagg and Colwell, 1994). The study area extends from the Rankin Trend—across the Kangaroo Syncline—to the central Exmouth Plateau and covers 30,000 km².

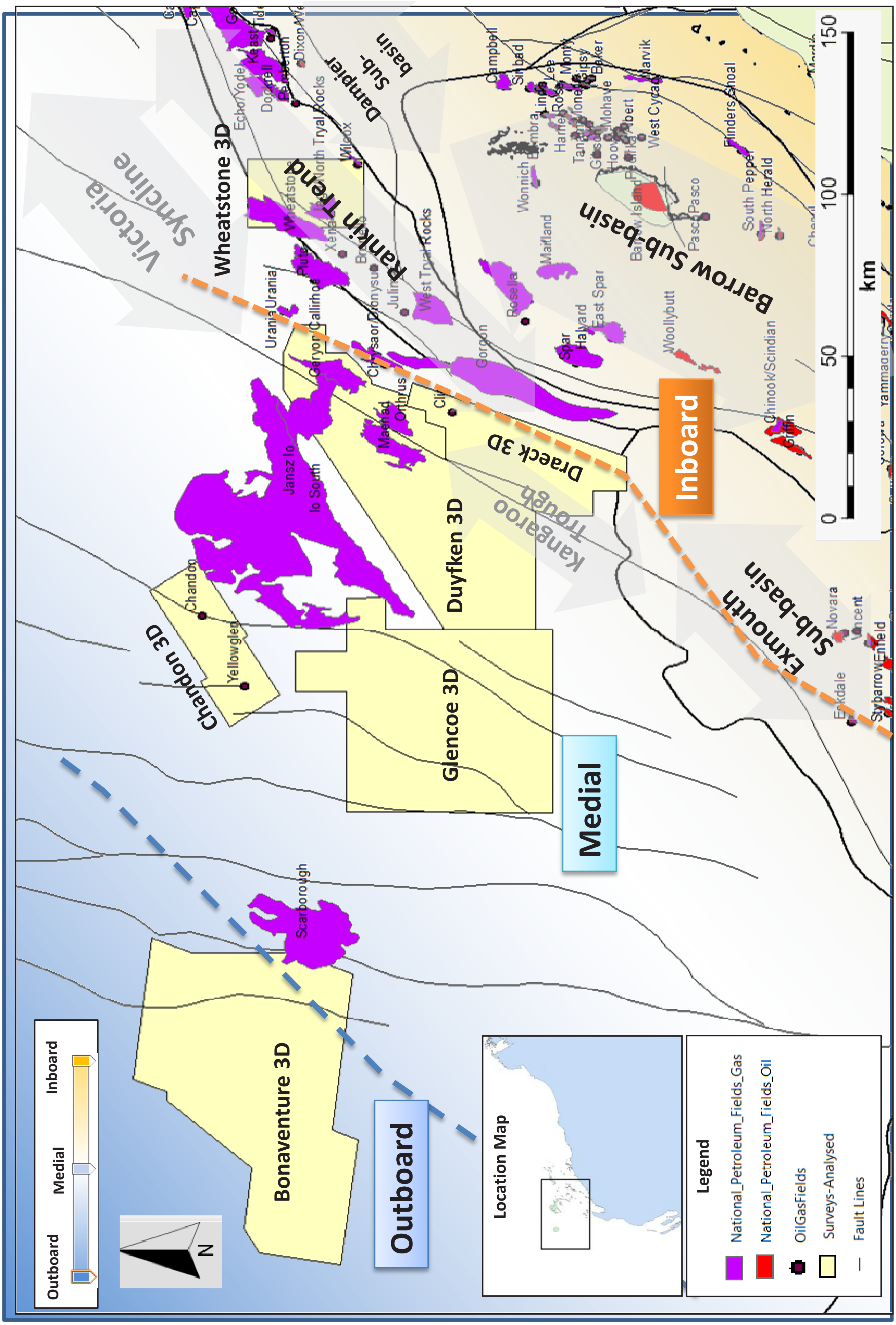

Figure 1. Northern Carnarvon Basin location map showing gas fields, structural elements, open-file 3D marine seismic surveys pre-interpretation data sets, and Late Triassic facies regions (inboard, medial and outboard; after Adamson et al, 2013).

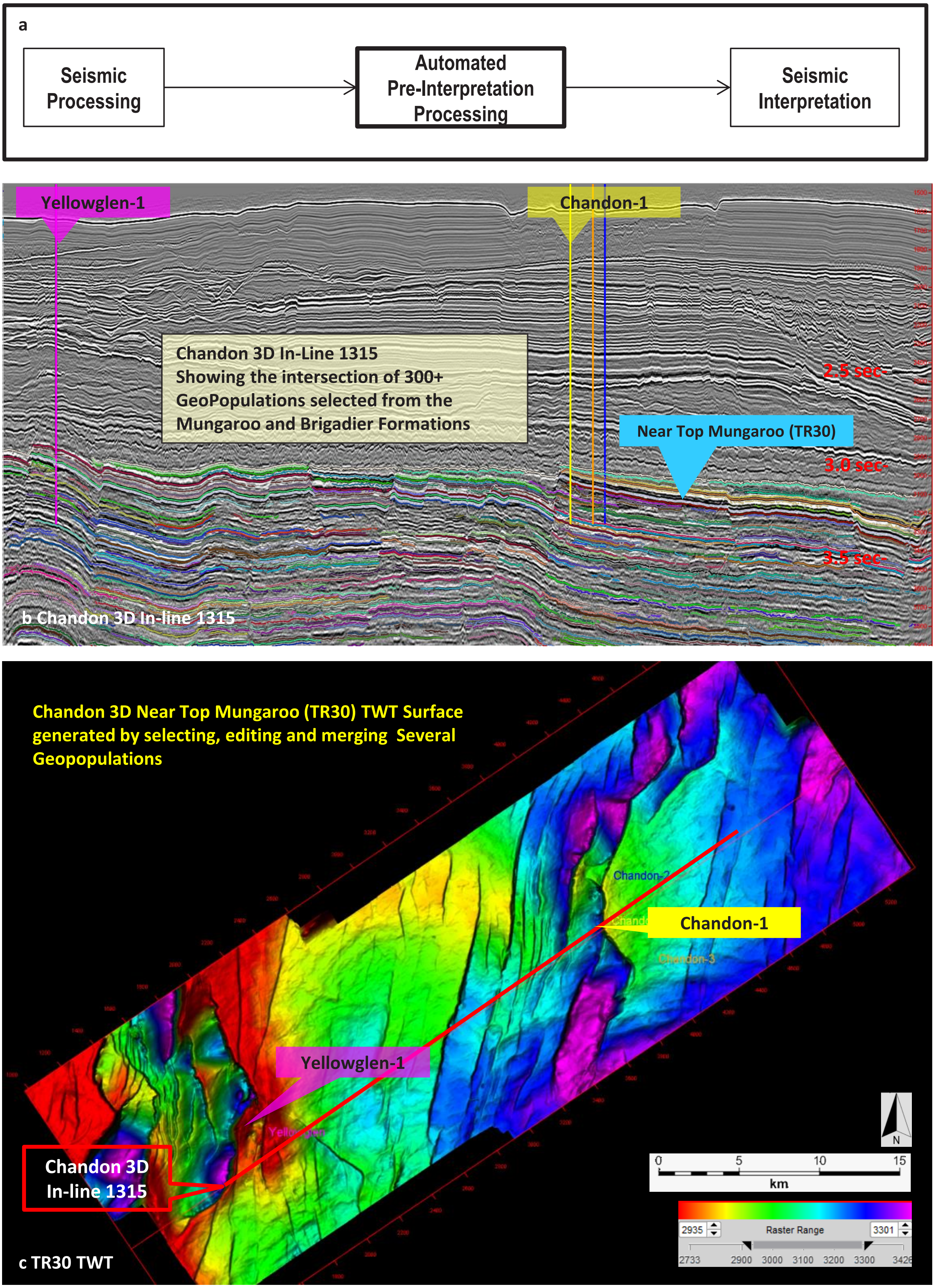

Figure 2. The diagram in 2a shows how pre-interpretation processing is performed on SEG-Y seismic volumes without any prior interpretation. Intersections of more than 300 Mungaroo and Brigadier formation GeoPopulations generated by pre-interpretation processing are displayed on an arbitrary seismic line (Chandon 3D) in 2b, and in 2c the Top Mungaroo (TR30) two-way time (TWT) surface, generated by selecting and merging several GeoPopulations, is shown.

Water depths range from 200–2,000 m. The Exmouth Plateau is a submerged continental platform extending approximately 150–500 km off the northwest coast of WA (Barber, 1988). It is bound on three sides by oceanic crust at depths of 4,000 m. To the southeast of the plateau the Rankin Trend forms the margin to several inboard Jurassic rift basins that are the Exmouth, Barrow and Dampier sub-basins (Woodside Offshore Petroleum, 1988; Parry and Smith, 1988; Newman, 1994; Stein, 1994).

The structural architecture and evolution of the study area is similar to that described by McCormack and McClay (2013) for the Gorgon Platform, which is the southern part of the Rankin Trend. In stage 1 after a period of thermal sag, the Mungaroo and Brigadier formations were deposited and were assigned to the TR20 and TR30 Play Intervals (Marshall and Lang, 2013). In stage 2, from Latest Triassic to Upper Jurassic, rifting and extension proceeded, which resulted in a prominent north-northeast to south-southwest fault trend. Stage 3, from the Upper Jurassic to Lower Cretaceous, was a period of oblique extension. Finally, in stage 4, from the Lower Cretaceous to the present-day, the platform has been a passive margin and is subsided.

The Brigadier and Mungaroo formations extend across the entire Northern Carnarvon Basin and contain pre-rift, Late Triassic marine, deltaic and fluvial sequences formed in a large depositional system that drained broadly from east to west. Jupiter–1 in the central Exmouth Plateau penetrated 39 m of the Brigadier Formation and 3,050 m of the Mungaroo Formation, while the total Permo-Triassic interval may be more than 8.5 km thick (Barber, 1988). The majority of the traps are fault traps, however, combined structural stratigraphic traps are also common, such as unconformity traps and Intra Mungaroo channels.

Depositional model

The Mungaroo environments of deposition vary from marine pro-delta in the western outboard area to deltaic and coastal plain in the medial area, and fluvial in the eastern inboard region on the Rankin Trend (Adamson et al, 2013). The Brigadier environments of deposition vary from offshore carbonate and reefal in the outboard and medial regions to fluvio-deltaic and fluvial inboard (Adamson et al, 2013; Grain et al, 2013).

The Mungaroo Formation is assigned to the TR20 regional play interval and the Brigadier Formation to the TR30 regional play interval (Adamson et al, 2013; Payenberg et al, 2013). Woodside's chronostratigraphy (Marshall and Lang, 2013) and sub-play nomenclature are adopted here. Four surfaces have regional significance:

1. TR22.1 is a transgressive surface that separates drier facies below (dominated by broad channel belts) from wetter facies above (dominated by narrow channel belts);
2. TR 26.5 *H. balmei* maximum flooding surface (MFS), a marine incursion with dinoflagellate abundance;
3. TR30 is a transgressive surface separating the Mungaroo below from the Brigadier above; and,
4. J10.0 SB is the top of the Brigadier and is a transgressive surface that separates nearshore marine deposits below from open marine deposits above.

Chevron's regional stratigraphic framework is similar but also integrates chemostratigraphy (Payenberg et al, 2013).

The key surfaces discussed in this paper are the TR26.5 MFS (*H. balmei*) and TR30.1 TS (TRR). The most common lithofacies associations interpreted for the TR20 and TR30 plays are fluvial channel, crevasse splay, soil, swamp/bog and coal, lake, distributary channel, mouthbar, interdistributary bay, pro-delta, and tidal inlet/barrier. In Figure 3 (modified from Adamson et al, 2013), the case study locations are shown with respect to sequence stratigraphic surfaces in Figure 3a and facies regions (medial, inboard and outboard) and selected 3Ds in Figures 3a and 3b. It is a schematic that demonstrates how the environments of deposition vary from fluvial dominated in the east to marine dominated in the west of the study area. It also demonstrates the cyclicity of the Mungaroo facies and how some major transgressive and regressive units extend across the study area.

Pre-interpretation processing concepts

With the number, size and density of 3D seismic data coverage increasing dramatically in the past two decades, traditional methods of extracting surfaces can only examine relatively small portions of the available data. Consequently, there is a need to develop more automated analysis methods that can quickly and consistently process entire volumes to help ensure geological models are developed based on a review of all the data instead of only a small portion.

The pre-interpretation processing method applied in this study was inspired by mathematical techniques developed in the Human Genome Project (Dirstein and Fallon, 2011). Genetic algorithms are mathematical processes that use the principles of natural selection and biological evolution to determine the variability and size of a surface in a seismic 3D volume.

Instead of chromosomes, the processing algorithm initially segments every trace in the seismic volume into waveforms (Figs 4a and 4b). From here, a waveform will only join with another waveform population if there is sufficient spatial genetic compatibility. As each population evolves, genetic information from each generation is passed on to the following generation so that the common waveform (genotype) for each population also evolves (Fig. 4c). The evolutionary process continues simultaneously throughout the volumes (Figs 4c and 4d) until virtually all populations of the trough and peak surfaces have been identified and catalogued into a 3D visual database of uniquely named GeoPopulations™ (Fig. 4e). Open-file final full-stack SEG-Y volumes were processed to produce pre-interpreted databases of GeoPopulations for each of the six 3D seismic surveys included in the study using a standard interpretation workstation with eight cores and 192 Gb of memory.

Pre-interpretation databases, GeoPopulation selection and 3D viewing

The pre-interpreted 3D visual databases of GeoPopulations were then reviewed using a range of query criteria in the 3D viewer provided. Each GeoPopulation has associated attributes including two-way time (TWT), amplitude and fitness. The fitness attribute provides a measurement of the genetic relationship between any individual trace waveform to the common waveform (genotype) for the entire population (Fig. 4a). Variability observed on the fitness map draws the interpreter's attention to areas of changing reflector geometry. Review of these fitness changes and their morphology often reveals insights about changes in lithology, depositional facies, pore fluid, reflector geometry and the stability of boundary conditions. While many of the open-file 3D seismic data volumes have been processed in this manner, six surveys were selected for more detailed examination.

Triassic and Mungaroo Formation GeoPopulations were displayed, sorted, selected and edited using various functions available in the 3D viewer. GeoPopulation selections were guided by well ties and information from open-file reports and publications. On several 3D regional surfaces, a number of key seismic events were produced by selecting and merging several GeoPopulations.

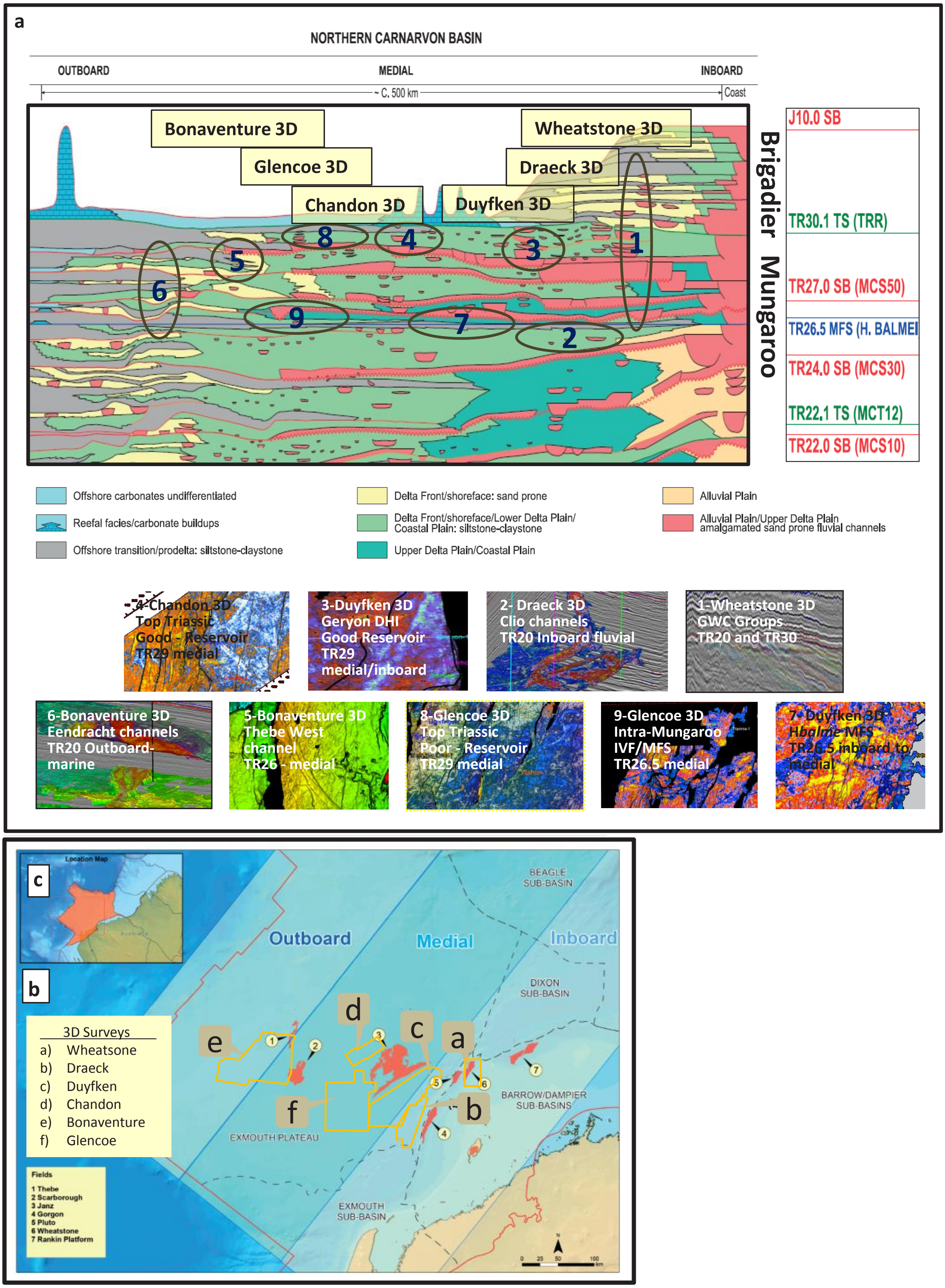

Figure 3. Schematic stratigraphic cross section across the Northern Carnarvon Basin modified after Adamson et al (2013) to show the location of the case studies relative to the location of the 3D seismic surveys, sequence stratigraphic surfaces and facies regions. Colour-shaded background denotes generalised Late Triassic facies regions (inboard, medial and outboard).

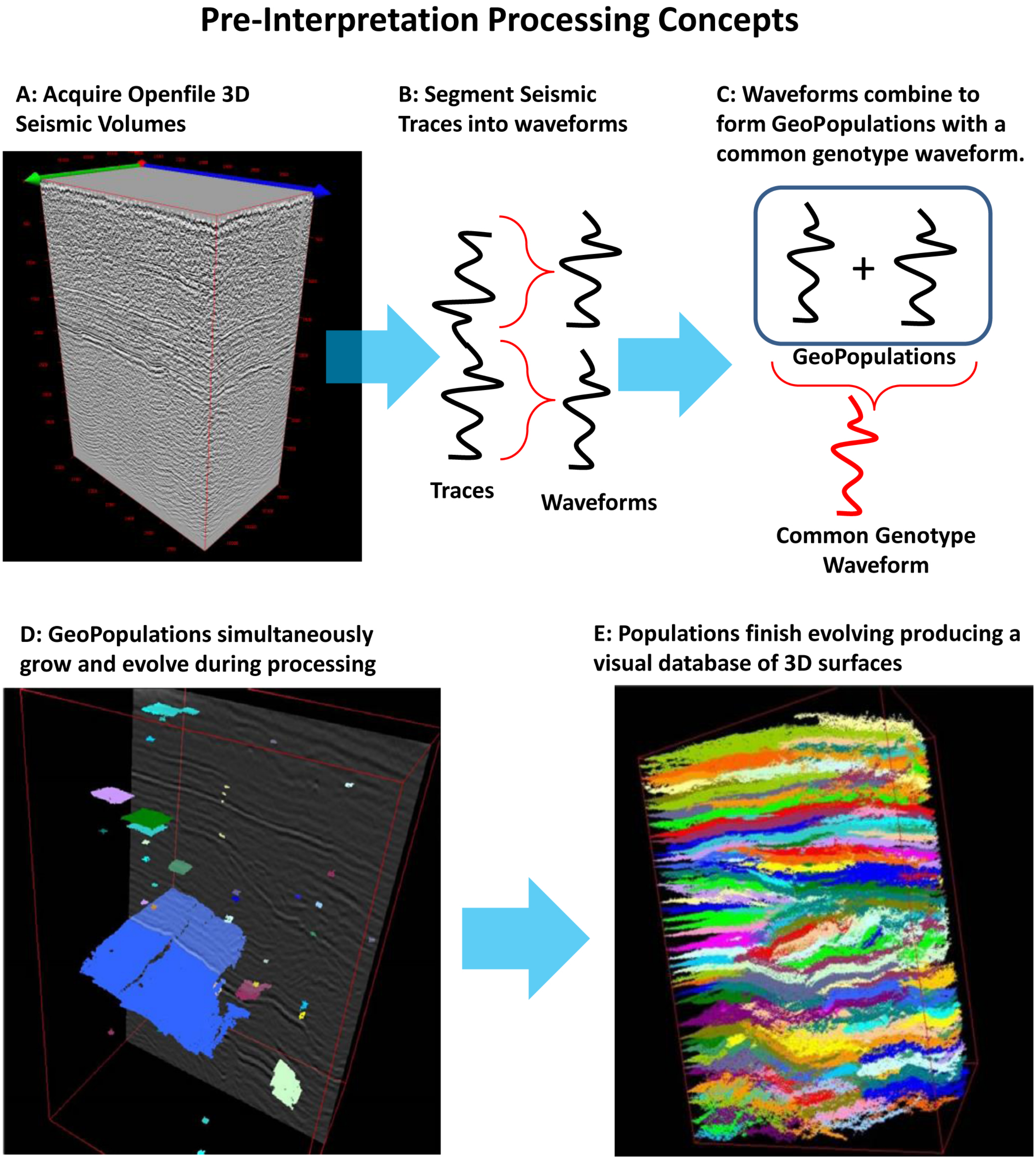

Figure 4. Seismic traces from 3D SEG-Y seismic volumes (4a) are segmented into waveforms (4b) before being combined as GeoPopulations of a common waveform (4c). The populations grow and evolve simultaneously during the process (4d), and generate a database of 3D GeoPopulations or seismic events within the seismic volume (4e).

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Since a seismic waveform represents an interval often containing different geological units (e.g. above and below an unconformity), examination of portions of the waveform targets smaller geological intervals. This sub-waveform analysis (e.g. gene sequencing) was applied to selected GeoPopulations to reveal additional detail and perspective into specific zones of interest; for example, sedimentary depositional sequences (Dirstein et al, 2013b) the extent of shale units, reservoir characterisation, gas water contacts (GWCs), subtle channelisation, and differential compaction at the Triassic reservoir level as well as potential new prospects in these formations.

Once the database of pre-interpreted projects was built, the process of analysing and reviewing such a large area could be achieved in real time. Moreover, this workflow is more observation-led compared to a traditional workflow, and could easily be extended and applied to a variety of objectives such as fluid flow studies (Dirstein et al, 2013a) and geohazards analysis (Dirstein et al, 2011).

GEOPOPULATION CASE STUDIES

The nine GeoPopulation case studies are presented in Figure 3. They provide insight into the seismic character of several Mungaroo reservoir and seal facies from the medial inboard and outboard regions described by Adamson et al (2013) in Figure 3.

Inboard zone

WHEATSTONE: UNCONFORMITY TRAP (TR20 AND TR30)

The Wheatstone structure is a large north–south trending horst block where late Triassic beds sub-crop the Intra Jurassic Unconformity (IJU) and dip to the north, striking east–west. The Mungaroo (TR20) and Brigadier (TR30) consist of marine and fluvial sequences with the sub-cropping reservoirs grading from fluvial in the south to marine in the north. The trap and reservoir stratigraphy of the Wheatsone Gas Field described by Palmer et al (2005) are similar to the Pluto and Xena fields described by Tilbury et al (2009). TR20 fluvial shales form the base seal and the reservoir units are fluvial deltaic sands. The Brigadier (TR30) is a conformable sequence of marine reservoir sands overlain by marine shales. In Figure 5a the GeoPopulation correlated to the IJU is displayed as a colour-shaded TWT surface. Several gaps in the surface are areas where the waveforms have changed and they are not included in the GeoPopulation. The IJU fitness displayed in Figure 5b shows broad bands of different fitness striking across the field outlined in pink. This is the same as the strike of sub-cropping Triassic events displayed in Figure 5c. The arbitrary line in Figure 5d, 5e and 5f shows how these events can be grouped to help identify hydrocarbon zones.

Interpretation of the reservoir sub-crop at Wheatstone on the open-file TWT seismic volume is challenging. Velocity variations below the shelf slope and in the overburden distort the pre-stack time migration (PSTM) seismic image. In time the structure dips to the west due to the steeply dipping water bottom, and local velocity variations in overburden channels result in a wavy to wormy and discontinuous seismic character at the reservoir level. Interpretation of sub-cropping Late Triassic seismic events and of direct hydrocarbon indicators such as flat spots and bright spots is difficult; however, GeoPopulations can be categorised with respect to the gas water contact, as either terminating above/below it or crossing the contact (Fig. 4). This suggests that the seismic waveform of reservoir events changes from gas to brine saturations. Several GeoPopulations that cross the contact may be shaley units or flooding surfaces in which hydrocarbon saturations and, therefore, waveforms remain consistent.

The Wheatstone case study suggests GeoPopulation stacking patterns in a trap could help indicate hydrocarbon zones. Geological models for reservoir facies often rely on attributes such as amplitude to indicate properties such as width and direction. At Wheatstone the strong grouping of GeoPopulations above and below the gas zone suggests the seismic-based attributes variability are likely influenced more, in this case, by pore fluid rather than geology. This needs to be considered when developing the geological model.

Medial zone

CLIO: STRUCTURAL-STRATIGRAPHIC TR25

Many of the major Late Triassic gas fields are located in the medial zone in the Northern Carnarvon Basin, and include the Clio and Acme gas fields. Clio–1 and –2 penetrated stacked fluvial channel sands, which are up to 80 m thick and are thought to be stacked multi-storey fluvial channel sands (Heldreich et al, 2013). The channels are extensive and can be mapped for many kilometres away from the Clio field. They are similar to the channelised fluvial deltaic interval (TR24 to TR25) at Goodwyn (Bennett and Bussell, 2006; Adamson et al, 2013). Lawrence (2013) observed that the Acme and Acme West gas fields, which lie to the east of Clio, penetrated a more complete section of the Mungaroo and Brigadier formations than Clio. The younger alluvial to Upper delta plain reservoirs (TR27 to TR28) encountered in the hanging wall trap at Acme West are juxtaposed to the older TR25 sands of the main reservoir unit encountered in Clio–1 (D sand).

The GeoPopulations that correlate to the main gas sands penetrated in Clio–1 and Clio–3 were selected and merged. The surface identified defines both the extent and continuity of the reservoir channel and also shows the complex architecture of the amalgamated sand channels further south. The genetic fitness and amplitude maps exhibit variability at the edges and also across the channel network. Strong amplitude and waveform variability along different portions of the channel form are likely to indicate changes in reservoir properties. These channels are easily identified using interpretation techniques such as optical stacking geobody extraction and slicing. The surface imaged in Figure 6, however, suggests mapping of properties such as thickness, net to gross and porosity in the channels and of other facies may also be possible. Figure 6 also shows how the channels are embedded in distinctive wavey to hummocky and variable amplitude seismic facies. Seismic and well facies associations described by Heldreich et al (2013) suggest a fluvial deltaic environment of deposition. The 3D viewer facilitates the building of the whole channel complex by picking and merging of further high-amplitude GeoPopulation surfaces in the facies. This facies has been identified on other 3Ds and similar channel complexes have been mapped at Satyr, Achilles and Orthrus.

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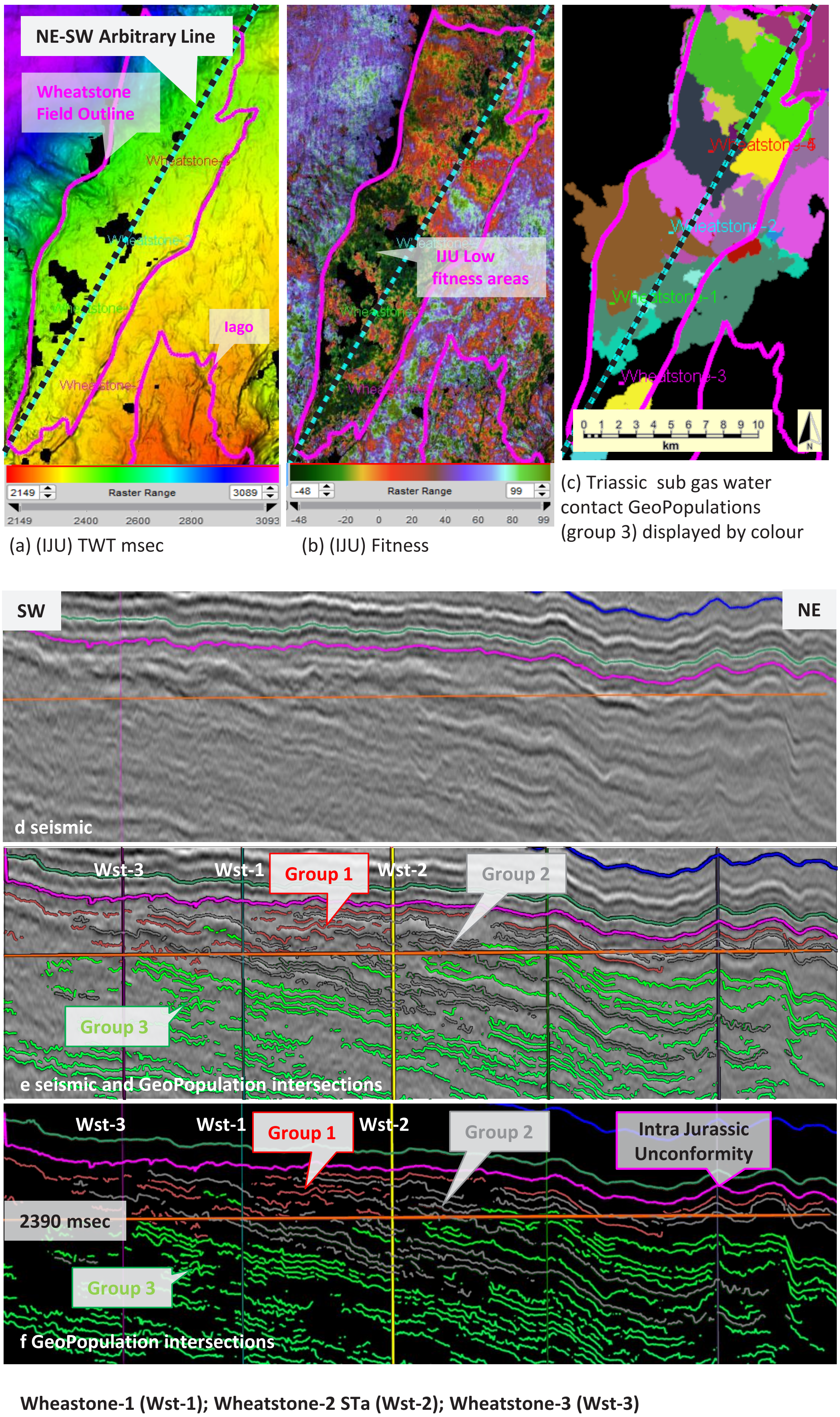

Figure 5. Wheatstone Gas Field pre-interpretation GeoPopulations and surfaces (5a) show the Intra Jurassic Unconformity (IJU) time structure. In 5b the waveform fitness of the IJU varies due to sub-cropping Mungaroo and Brigadier beds, and 5c shows GeoPopulations by colour below the gas water contact (GWC). 5d, 5e and 5f show a Wheatstone 3D north-northeast to south-southwest arbitrary seismic line with Wheatstone–1 (Wst–1), –2a (Wst–2) and –3 (Wst–3) projected. 5d is seismic only, 5e shows seismic with GeoPopulation intersections grouped by colour, and 5f shows the section with only the intersections.

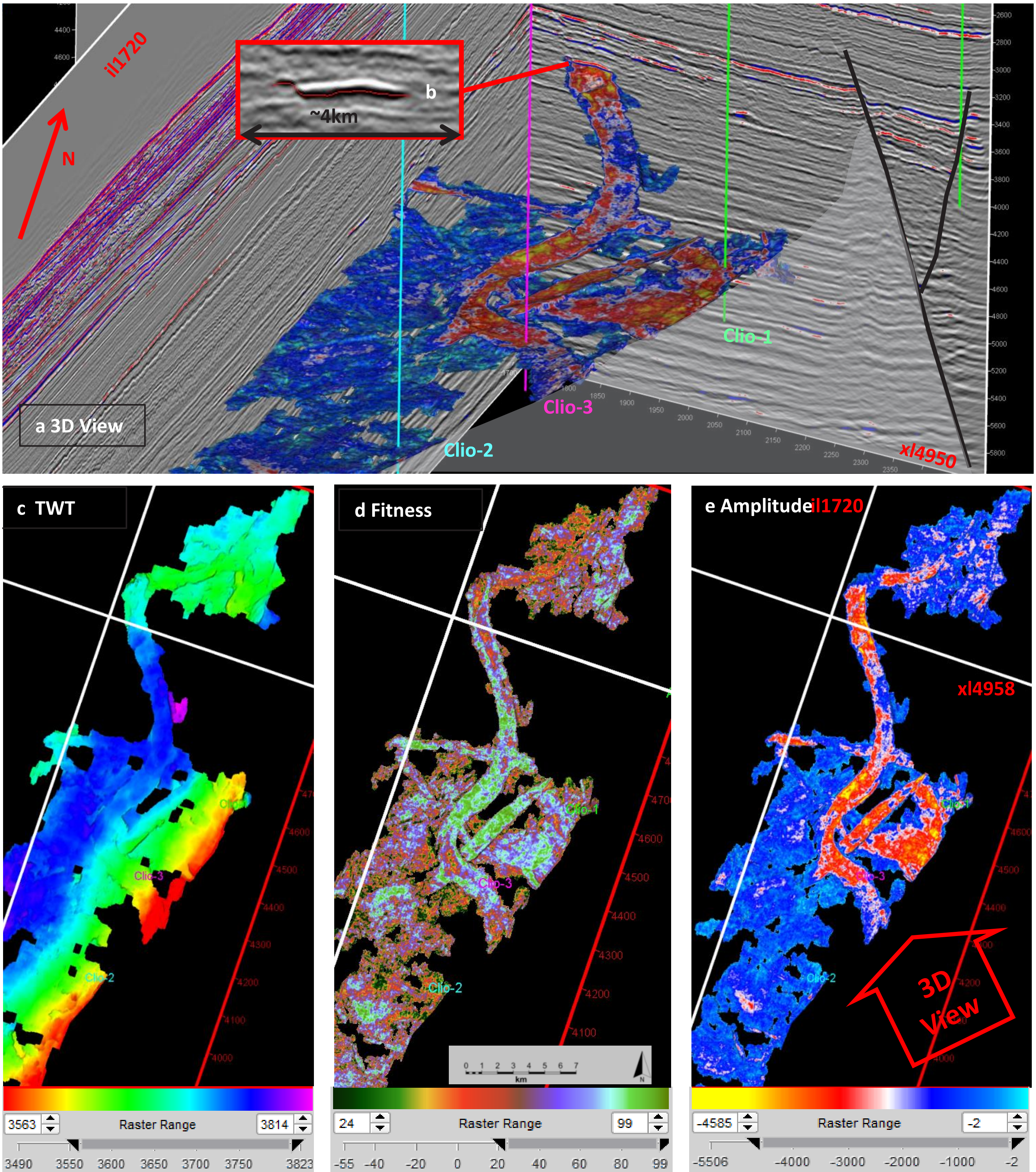

Figure 6. Pre-interpretation processing surfaces from the main gas zone encountered in Clio–1 reveal a network of multidirectional stacked meandering channel forms. Wave form fitness variation shows a distinctive internal tram-track character and an external complex of overbank sand facies. Areas of high amplitude in the channels may be due to tuning in response to thickness changes or due to variation of petrophysical parameters such as hydrocarbon saturation, net to gross and porosity.

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GERYON, ORHTRUS AND MAENAD: TRIASSIC FAULT TRAPS TR28 AND TR29

The Geryon, Orthrus and Maenad gas fields (GOM area containing 8.9 Tcf original gas in place [OGIP]) were discovered between 1999 and 2000 (Korn et al, 2003). The Geryon structure is a footwall fault trap formed by two north-trending faults and reservoir/seal pairs dipping to the west. The Maenad structure is a northeast trending combination horst/four-way closure and the Orthrus structure is a northeast trending anticline. Sibley et al (1999) correlate the main AA and A reservoirs with the E and F sands in the Rankin area. Marshall and Lang (2013) assign these to the TR27 to TR29 sub-play intervals in their sequence stratigraphic framework for the North West Shelf. Two reservoir facies are correlated by Korn et al (2003) in the Geryon–1 area, an upper delta plain sequence consisting of fluvial facies and a marginal marine sequence consisting of shoreface and deltafront facies. The Late Triassic reservoirs in Geryon–1 are sealed laterally across the faults by juxtaposed marine shales of the Brigadier Formation (Fig. 7; Korn et al, 2003). Geryon–1 encountered 100 m of net gas pay with porosities of 30% in the TR27-28 sands (AA sands). Callirhoe–1 was drilled 2.5 km southeast of Geryon–1 to appraise the TR27 sands and to test the older TR 24 to TR 25 Mungaroo reservoirs.

The near top Mungaroo GeoPopulation correlating to the TR30 seismic event was selected from the Duyfken 3D database in the GOM area and displayed with TWT, co-rendered amplitude and fitness, and sub-waveform fitness attributes (Fig 7). The TWT surface has imaged the north-northeast trending faults and relay ramps, the co-rendered amplitude and fitness define the Orhtrus and Maenad fields and at Geryon amplitude conforms to structure (Fig. 7c), and the TR29 sand GWC is a high fitness anomaly (Figs 7d and 7f). The seismic section through the well shows it is where the top TR29 sands and the base gas events begin to interfere (Fig. 7e). It is, however, sinuous and trends roughly north–south along the flank of the structure and could be mistaken for a channel. Korn et al (2003) interpreted north–south trending channels on amplitude/time slices through an inversion cube. In this case study, however, a subtle east–west trend is observed on the sub-waveform map for the amalgamated TR29 channels (Fig. 7d). At Maenad and Orthrus where high amplitude extends north of the mapped gas fields, co-rendering of the amplitude with fitness (Fig. 7c) reveals bright yellow to red anomalies that conform to the field outlines. This case study has shown how fitness, amplitude and co-rendering can be used to help define DHIs related to gas fields. It also shows how sub-waveform analysis is used to determine reservoir trends.

CHANDON AND YELLOWGLEN: TRIASSIC FAULT TRAPS TR30.1 TS

The Chandon and Yellowglen gas fields are Triassic footwall fault traps that dip to the east. The Mungaroo reservoir consists of amalgamated sands (TR27-28 fluvial and TR29 deltaic) that are sealed by the Brigadier (TR30.1 TS). This surface was selected from the database and the time and sub-waveform attribute maps displayed (Fig. 8). The complex faulting and structures in the graben are defined exceptionally well on the pre-interpretation surface (Fig. 8a). While the full wafeform fitness map of the TR30.1 GeoPopulation is featureless, the sub-waveform fitness highlights amalgamated channels in the reservoir at Chandon and the extent of the gas water contact at Yellowglen. The sub-waveform fitness and time surfaces are co-rendered in 8c and 8d and sub-waveform strips are displayed on sections through the wells in panels 8e and 8f. The gas water fitness anomalies are clear on smaller structures in the graben to the west of Chandon and Yellowgen, suggesting these are also gas accumulations. At Chandon there may be a fitness anomaly associated with the gas water contact but the feature is broader and, therefore, difficult to differentiate from the channel features.

Outboard zone

The outboard facies region of the study area is covered by the Bonaventure 3D (Figs 9 and 10). Near top Triassic GeoPopulations were merged to produce a regional Top Triassic surface. Broad rotated fault blocks and horst are separated by narrower graben, trend north–south, and are controlled by the intersection of the north-northeast and north-northwest fault sets.

THEBE WEST TR26 FAULT TRAP CASE STUDY

The Thebe Gas Field lies in the northeastern corner of the Bonaventure 3D marine seismic survey (MSS; Fig. 9). It is an elongated north-trending horst with gas trapped in Mungaroo Formation (TR 29) delta front sands (Adamson et al, 2013). While a flat spot can be mapped at Thebe (il5500; Fig. 9b), the adjacent fault block to the west does not appear to have a flat spot in the top Triassic. Attribute analyses of Intra-Triassic (TR26) GeoPopulations and surfaces and interpretation of cross-line 5000, however, suggest a structural/stratigraphic trap may be present. Figure 9c is a colour-shaded TWT map that shows a narrow elongate feature cutting across the fault block with a convex top. The fitness map indicates a tram-track pattern similar to channels encountered elsewhere in the Mungaroo Formation, while the amplitude shut off suggests a possible gas water contact may be present. The convex top is indicative of differential compaction over coarser-grained sediments in the channel.

EENDRACHT HORST CASE STUDY

The Eendracht horst, located on the western edge of the Bonaventure 3D MSS, is a case study of outboard facies in the Mungaroo Formation. Eendracht–1, drilled in 1980, encountered five stacked gas sands in a 372 m thick marine sequence of the Mungaroo Formation prior to reaching a fluvial unit (Barber, 1988). Figure 11 shows attribute maps of the upper gas zone. The colour-shaded TWT structure map is corendered with high fitness and amplitude features that trend southwest across the horst. The amplitude map indicates strong conformance to structure, although the TWT shaded map shows the amplitude shuts off at a small normal down to the east, north–south trending fault. The crescent shape, uniform amplitude and divergent geometries contrast to the fluvial channels described at Clio in Figure 6 and are interpreted to be deltafront sands. This surface is displayed as TWT co-rendered with amplitude in the 3D view in Figure 10a with a GeoPopulation surface selected from below the total depth (TD) of Eendract–1. Although this event is below the fluvial sediments at TD, the high fitness, high amplitude and crescent geometries suggest the anomalies are marine and possibly delta from sands. This case study confirms that the facies of the outboard region are dominantly marine sequences.

FLOODING SURFACE CASE STUDIES

Maximum flooding surfaces or transgressive surfaces in the Late Triassic formations are marine shales with high dinoflagellate content and, on seismic, are often characterised by parallel continuous seismic events. Two maximum flooding surfaces—TR30.1 at the base of the Brigadier Formation, and TR26.5 (*H. balmei*)—are the most extensive flooding surfaces in the Late Triassic (Fig. 2).

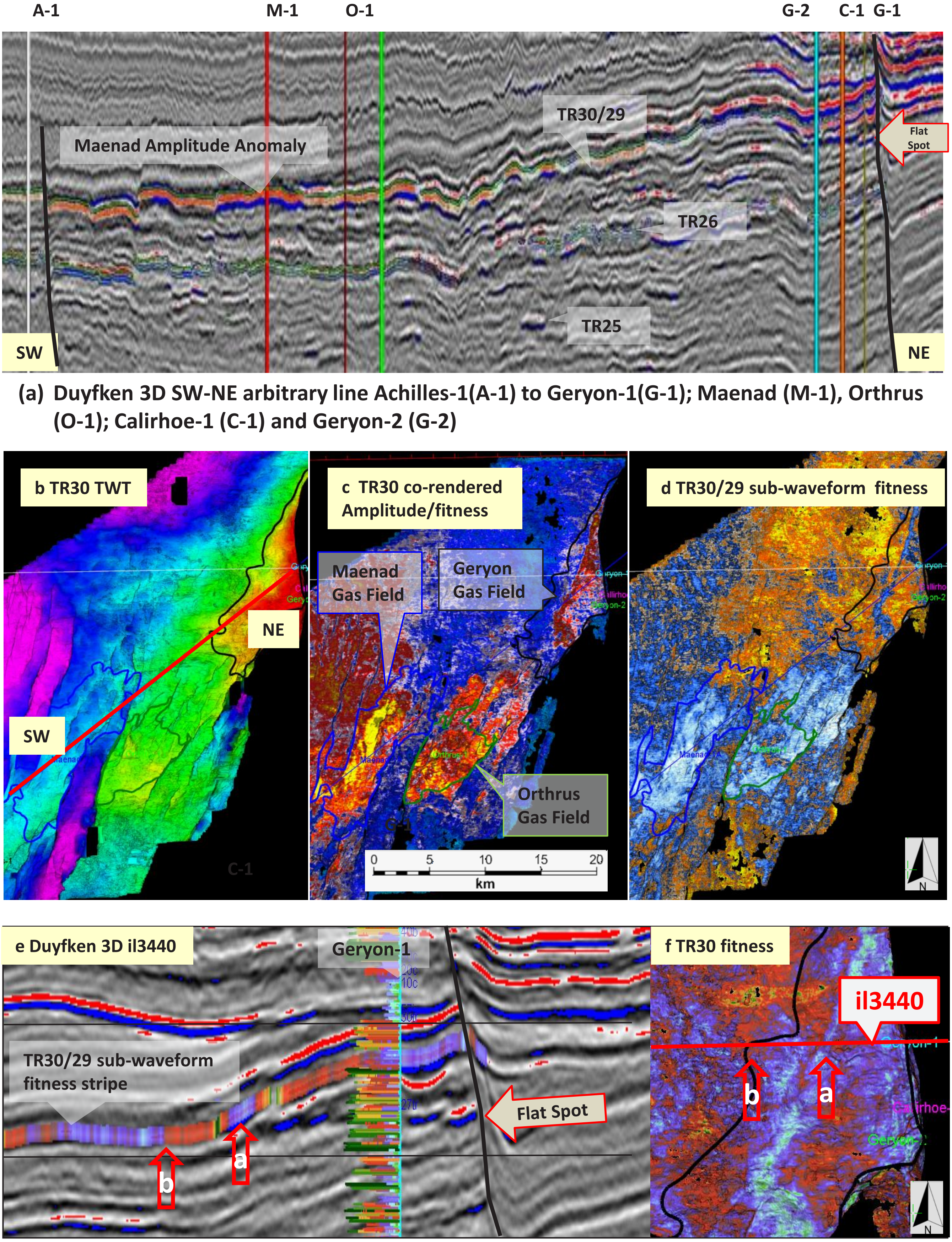

Figure 7. The Geryon (black), Maenad (blue) and Orthrus (green) gas field outlines are compared to the near top Triassic (TR30) time structure (7a), co-rendered amplitude/waveform-fitness (7b), and sub-waveform fitness (7c) maps. At Geryon, both fitness and amplitude show strong conformance to structure. The bright yellow/red colour on the co-rendered amplitued/fitness map defines the Maenad Field and the southern part of Orthrus. The Orthrus anomaly, however, extends north to the spill point to Geryon. Arrows in 7e compare the TR30 fitness strip with the Geryon flat spot and field limit, while in 7f the field outline (b) is compared to high-fitness anomaly (a).

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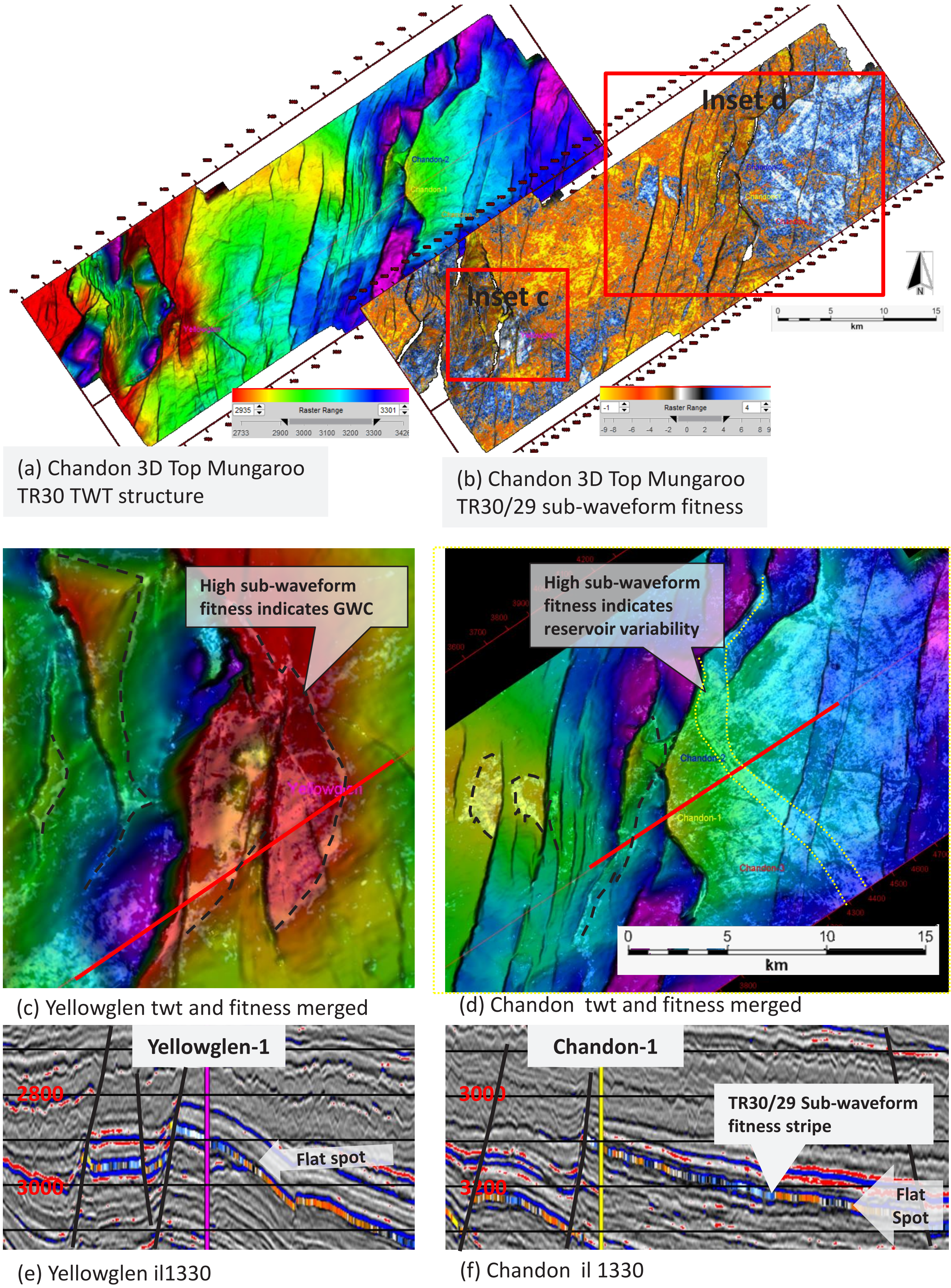

Figure 8. The Top Mungaroo/Base Brigadier surface (TR 30.1 TS) was identified on the Chandon 3D and displayed in 3D views with amplitude (8a), time (8b) and fitness (8c) attributes. The Yellowglen and Chandon structures are located in the southeast and northwest of the survey, respectively, and the complex faulting in the adjacent graben is mapped precisely (8b). Sub-waveform attributes from below the surface reveal reservoir detail such as fluid contacts and channel forms (8d and 8e).

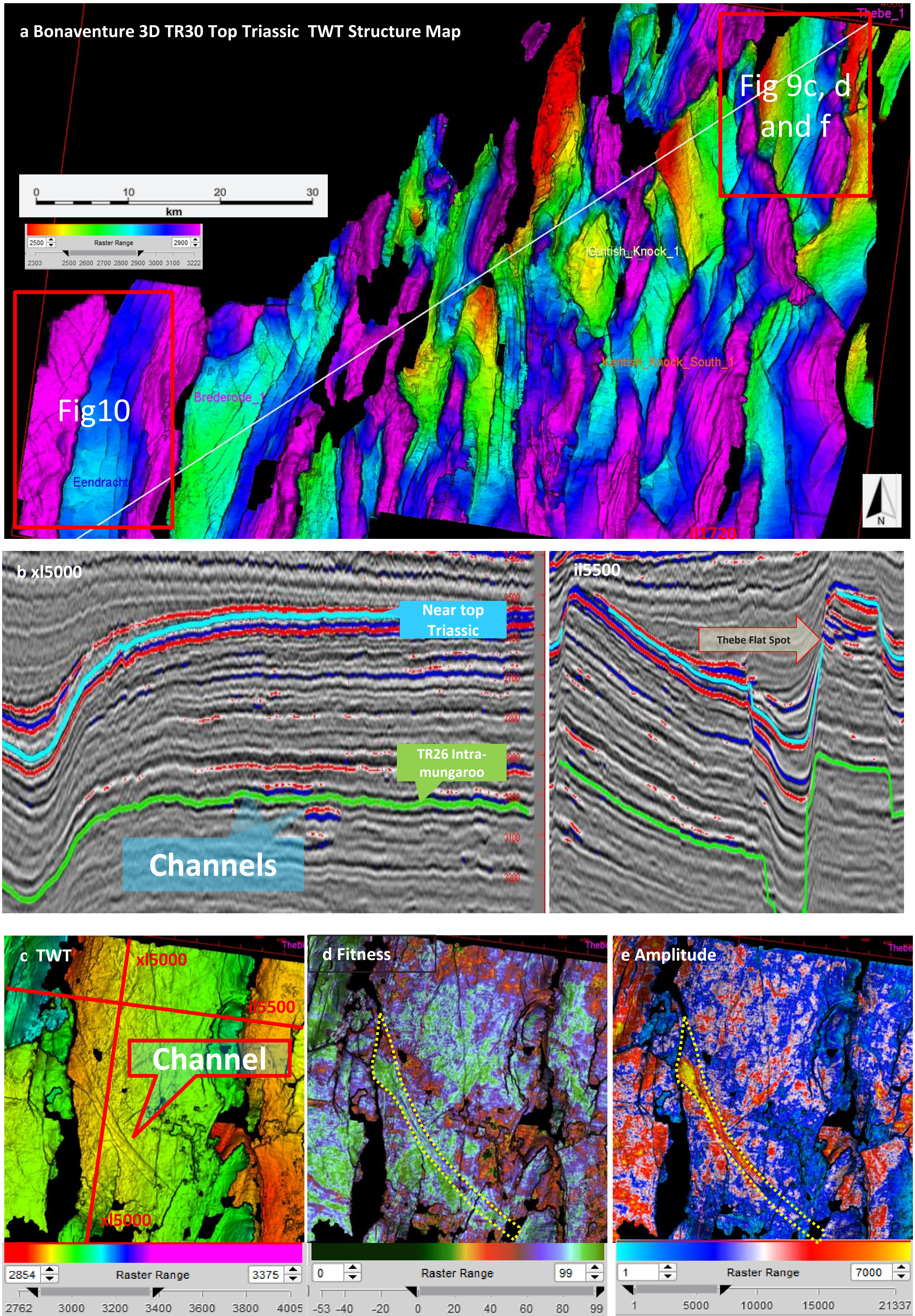

Figure 9. Bonaventure 3D medial to outboard facies; top Triassic surface merged from several GeoPopulations shows the series of structure horst and rotated fault block separated by deep narrow graben (9a). 9b shows in-line 5000 and cross line 5500 across the Thebe West Fault block. The TWT colour shaded map in 9c shows a feature with a concave top and high amplitude and fitness. The bright hummocky features on cross line 5000 are interpreted to be channels.

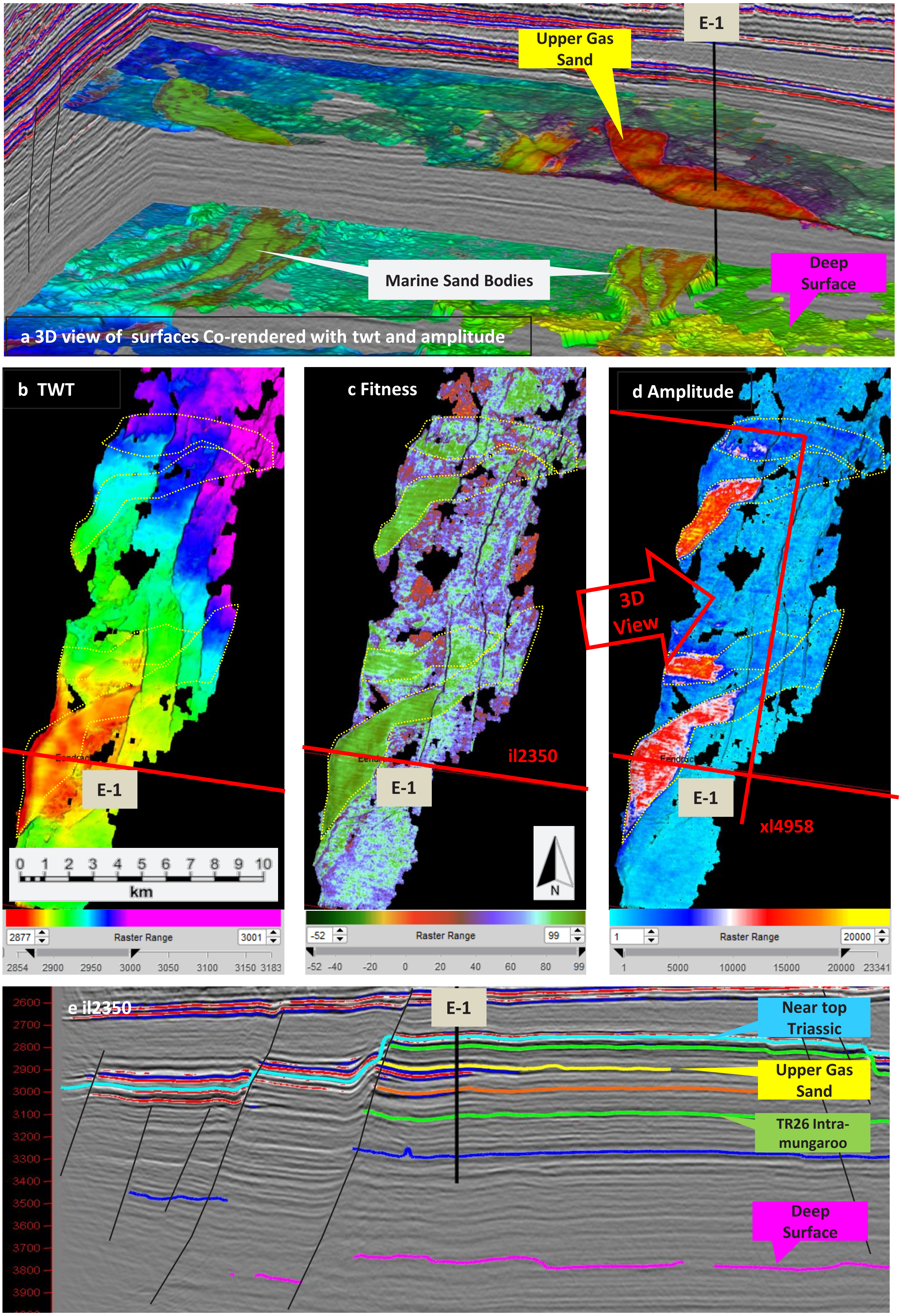

Figure 10. Bonaventure 3D outboard facies region. 10a is a 3D view looking at two Eendracht surfaces, co-rendered TWT and amplitude. 10b, 10c and 10d are attribute maps of TWT, amplitude and fitness. 10f is inline 2350 showing GeoPopulation surfaces selected that correlate with gas sands in Eendracht–1. Interpreted channel forms in 10b, 10c and 10d are outlined in yellow.

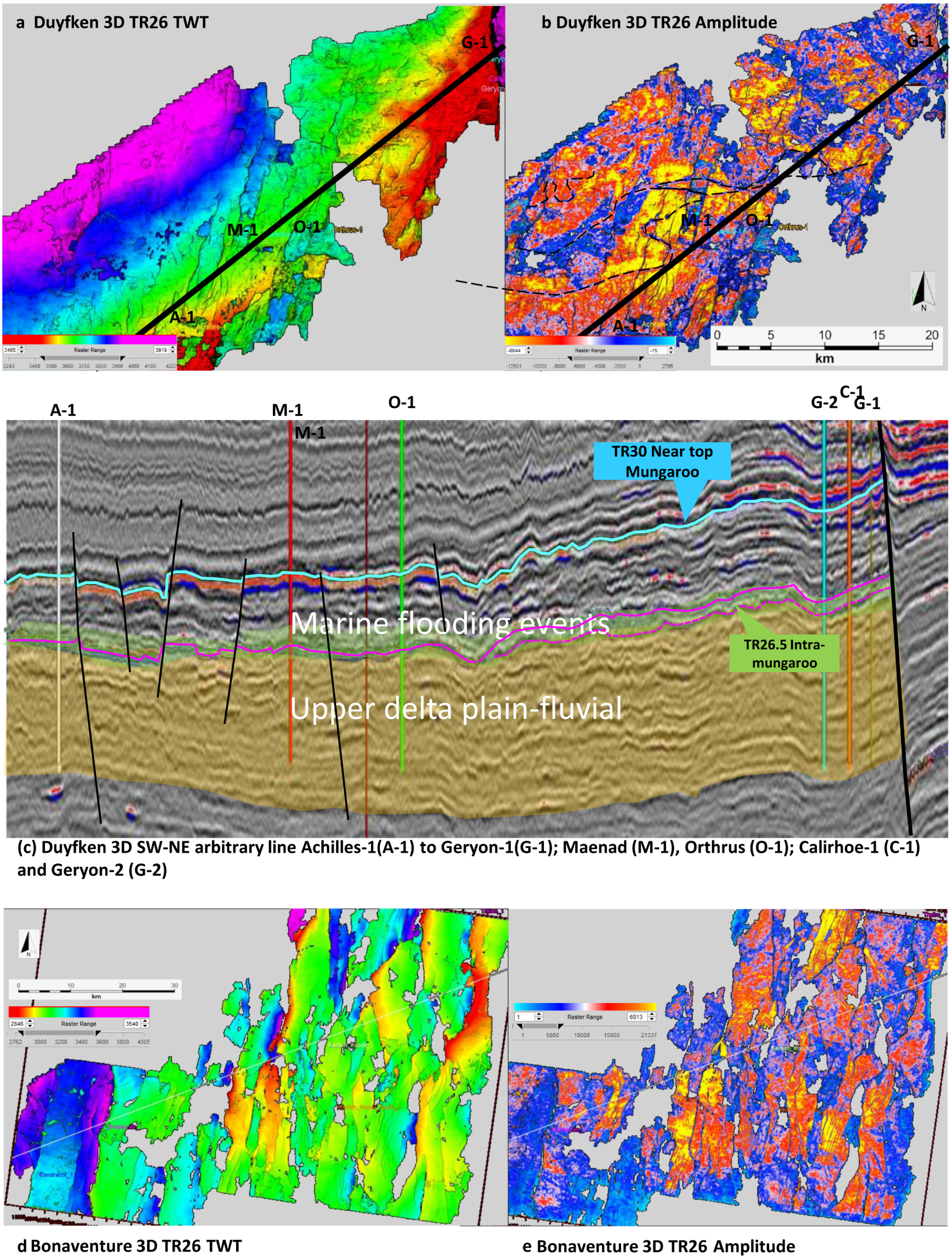

Figure 11. Duyfken 3D TR26 TWT (11a) and amplitude (11b) are compared to the Bonaventure 3D TR26 TWT (11d), and amplitude (11e). 11c is an arbitary seismic line from the Duyfken 3D showing the TR26 surface.

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H. balmei, TR26.5

GeoPopulations correlating to *H. balmei*, or TR26.5 maximum flooding surface (MFS), in Calirhoe–1 were selected on the Duyfken 3D (Fig. 11). On the western flank of the Achilles structure in general, the event lies in a seismic facies which has a parallel, high amplitude and continuous character. TR20 GeoPopulations with similar seismic characters were selected from the Bonaventure 3D (Figs 9 and 10) and the Glencoe 3D (Fig. 12). Minken et al (2011) interpret Intra-Triassic incised valley fill sequence from well correlations.

Figures 11 and 12 compare GeoPopulation surfaces selected from the Glencoe 3D and Bonaventure 3D TR20 play interval, which have similar seismic character to the TR26.5 MFS (*H. balmei)* on the Duyfken 3D. The seismic character in the map view changes from east to west as the dominant facies above and below the transgressive interval change from fluvio-deltaic in the eastern medial region to marine in the western outboard region. At Eendracht on the Bonaventure 3D, the dominant facies are marine prodelta shales, and the TR20 seismic events are continuous and parallel with variable amplitude and occasional channel features. On the Glencoe 3D in the medial region, the seismic character shows patches of parallel continuous events and patches of broken discontinuous events. These show networks of meandering low amplitude/fitness forms captured within them, and are interpreted to be entrenched areas or incised valleys. Further inboard on the flank of the Achilles structure on the Duyfken 3D, the character is sub-parallel to wavy and partially discontinuous. The low amplitude/fitness channel forms vary from narrow (<500 m) to broad (>2 km) and are sinuous. These do not appear confined to incised valleys. Other discontinuities in the surface may also be the result of merging several different downlapping GeoPopulations with similar character.

The TR20 Intra-Mungaroo surfaces at Eendracht are interpreted to be marine delta front claystones and silts and the channels may be deposited in a coastal environment. The channels observed in the TR20 intra Triassic play level on the Glencoe 3D, however, are interpreted to be nested or captured in a coastal to lower delta plain incised valley, while those observed on the Duyfken 3D are interpreted to be upper delta plain features.

Basal Brigadier/Top Mungaroo (TR30 TS)

The Brigadier Formation overlies the Mungaroo Formation and is relatively thin (<100 m) across most of the study area, and mainly consists of fine-grained argillaceous marine carbonates. Grain et al (2013) describe carbonate build-ups to the west, and the fluvial-deltaic sequences developed inboard to the east are described by Adamson et al (2013).

The TR30 GeoPopulations correlating to the Top Mungaroo/Basal Brigadier are extensive, and exhibit high uniform fitness with strong amplitude on 3Ds in the medial and outboard regions of the study area. Inboard on the Draeck, southeastern Duyfken and Wheatstone 3Ds along the Rankin Trend, the Late Triassic subcrops the IJU (Fig. 5). Surfaces generated for the medial to outboard TR30 are discussed in Figures 3 and 8 for the Chandon 3D, Figures 9 and 11 for the Bonaventure 3D, and Figures 7 and 11 for the Duyfken 3D. The colour-shaded TWT surfaces show the dominant north–northeast to north–northwest extensional faulting pattern in great detail, imaging complexities such as multiple horst tail faults and fault scarps.

The case study of the Glencoe 3D looks at the sub-waveform analysis of the TR30 surface to investigate TR20 facies in the medial to outboard region where the interval is dominated by finer-grained delta plain facies (Minken et al, 2011) and fluvio deltaic facies (Barber et al, 1988). In contrast, the TR30 sub-waveform case studies at Chandon (Fig. 8) and Geryon (Fig. 7) looked at coarse-grained amalgamated sheet sands in the upper TR20 sub-plays.

TWT attribute from the Top Mungaroo (TR30.1 TS) shows the complexity of the Triassic fault block structure present across the Glencoe 3D, and the amplitude and fitness attributes are relatively featureless but for a few pockmarks (Fig. 13). The sub-wave form fitness attribute was extracted from a window 24–44 milliseconds below the TR30 surface, revealing a pervasively channelised unit. There are two distinctive features: highly sinuous extensive southwest-trending narrow features with mainly high fitness, and 1–2 km wide, 5–10 km long east–west trending features. The narrow features with high fitness are more obvious in the structurally low areas. These are interpreted to be abandonment channels with mixed sand and shale fill. The other channels have low fitness and are located mainly on the structural highs where the TR30 amplitude is high. These channels are interpreted to be amalgamate sheets of poor-quality reservoir sands and silts. Fitness changes from off to on structure (Fig. 13d) may be due to low gas saturations of these sediments.

DISCUSSION

The pre-interpretation processing applied is considered an extension to the seismic processing sequence, providing the interpreter with a database of information to mine and integrate with geological and other relevant information. Pre-interpretation surfaces can reveal detail missed with traditional fast-tracked interpretation workflows such as gridding of seed line picks. Pre-interpretation surfaces can be similar to propagated surfaces, however, there are several orders of magnitude more pre-interpretation surfaces. Moreover, the pre-interpretation surfaces use the same mathematical criteria consistently applied to the entire volume, whereas manually targeted horizons are customised for each surface by the user, resulting in a more biased outcome. While more than 95% of the pre-interpretations surfaces were of a very high quality, some of the GeoPopulations occasionally bleed across faults when the waveform from foot-wall to hanging-wall is spatially compatible. These surfaces require editing and merging prior to finalising a surface for analysis.

The GeoPopulation surface case studies give examples of how detailed fault patterns, stratigraphy and direct hydrocarbon indicators are used to assess structures, seals and reservoirs, and how sequence stratigraphic models can be validated. The case studies also demonstrate how interpretation workflows that include pre-interpretation processing are beneficial at a number of other levels. Interpreters armed with a pre-interpretation database early in the interpretation phase can make detailed evaluations in relatively short timeframes and then use them to improve overall outcomes. A subsurface team with access to all surfaces in a seismic volume is enabled to think more about the geology and make better evaluations using all the data, rather than working on the mechanics of generating the best surfaces. Since the surfaces are readily available, consistent and relatively unbiased, several 3Ds (and their different offset volumes) can be studied simultaneously.

The focus of this paper was the Triassic and Brigadier formations in part of the Northern Carnarvon Basin. The same pre-interpretation databases can be used for other studies such as fluid flow in basin analysis and geohazard assessment in well planning. They are also available to be used immediately in subsequent processing projects such as pre-stack depth migration.

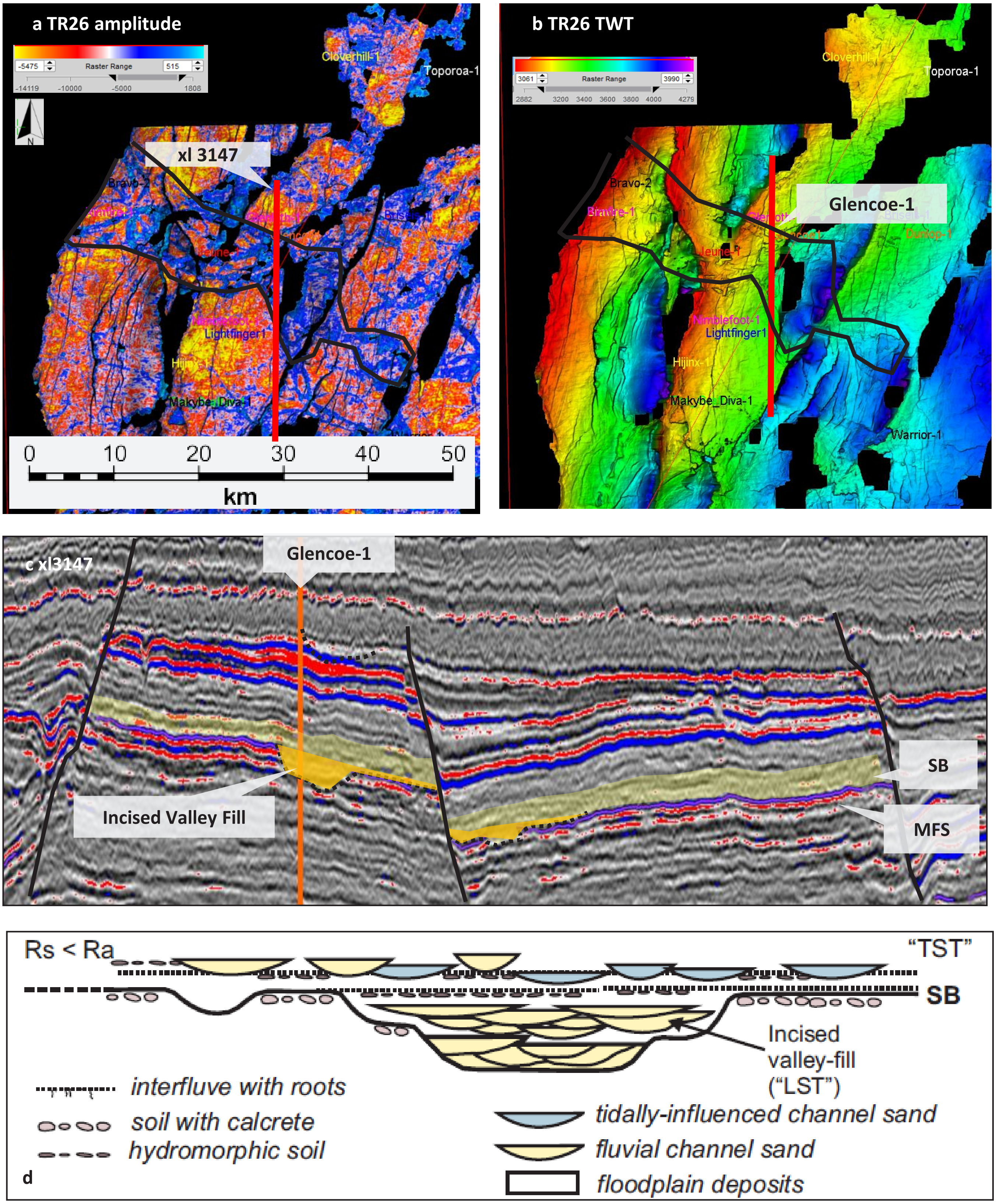

Figure 12. Glencoe 3D, Medial facies region; Intra Mungaroo (TR26.5) flooding surface, high amplitude (12a), (yellow-red) with low amplitude incised valley fill (blue); incised valley trends northwest perpendicular to main north–northeast trending faults (12b). 12c is cross-line 3147, which shows the high amplitude and continuous seismic character of the flooding surface and the sequence boundary and incised valley. 12d is modified after Catuneanu (2011); it is a schematic sequence model for ravinement of non-marine systems. Rs equals rate of sedimentation and Ra equals rate of accommodation.

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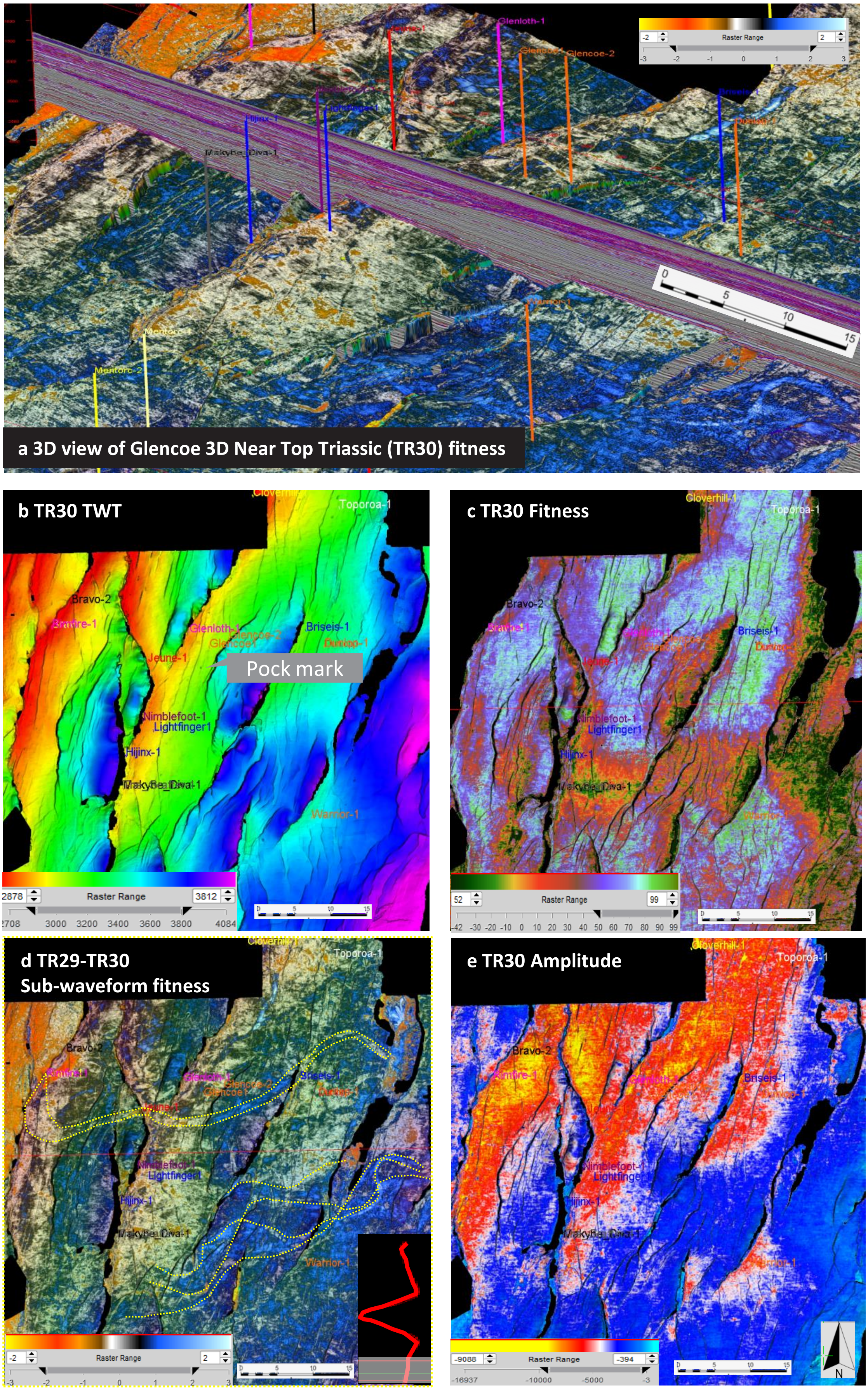

Figure 13. The TR30.1 TS or Top Mungaroo, Base Brigadier amplitude (13a), time (13b) and fitness (13c) show the strong north–south structural grain. The amplitude and fitness patterns are probably related more to the down-lapping offshore carbonate facies of the TR30 or Brigadier, while the sub-waveform analysis below reveals belts of narrow sinuous channels and other wider, more subtle channel forms both cutting east–west across the structures.

CONCLUSION

Through the application of pre-interpretation data processing to several large open-file 3D seismic surveys from the Carnarvon Basin, nine case studies of the Late Triassic Mungaroo Formation were able to be completed without the use of a traditional seismic interpretation software package.

The case studies show how access to pre-interpretation data can enable a sub-surface team to not only fast-track their interpretation, but also improve planning and the desired outcomes.

ACKNOWLEDGMENTS

The authors wish to thank Nabil Tnacheri (Seisnetics inventor and patent holder) and the team at Seisnetics for the processing of the open-file volumes from the North West Shelf for all trough and peak surfaces.

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THE AUTHORS

Cliff C. Ford studied geology at the University of Western Australia, gaining his BSc (Hons) in 1980, and geophysics at the Western Australian Institute of Technology. He worked for West Australian Petroleum Pty Ltd (WAPET), Santos Ltd and WMC Petroleum until 1997, as a geologist, geophysicist and explorationist. Since then Cliff has consulted as an Interpretation Geophysicist to the exploration industry. Member: American Association of Petroleum Geologists (AAPG) and Petroleum Exploration Society of Australia (PESA).

cliff.ford@iinet.net.au

Jim K. Dirstein studied geology and geophysics at the University of Toronto, graduating in 1980. With more than thirty years of international experience in the oil industry, including the past twenty years as the founder/director of Total Depth Pty Ltd, Jim has developed a diverse set of skills, working in a wide range of geological and corporate settings.

Aside from his activities with Total Depth, Jim has helped with the commercialisation and application of many new technologies. Recently, this has included the refinement of a patent for a new airborne geophysical technique, a Seisnetics-patented processing algorithm, and establishing Geoproxima Pty Ltd. Jim is a member and past WA branch president of the Australian Society of Exploration Geophysics (ASEG). Member: Society of Exploration Geophysicists (SEG), PESA, AAPG, Society of Economic Paleontologists and Mineralogists (SEPM) and European Association of Geoscientists and Engineers (EAGE).

jim@totaldepth.com.au

Alistair J. Stanley received his BSc from Durham University in 2009, studying natural sciences, where he majored in geology. Alistair is experienced in the oil industry having worked with both Pinemont Technologies on airborne exploration projects, and with Total Depth. His work with Total Depth has included the processing and interpretation of seismic data from a variety of sedimentary basins throughout Australia for both petroleum and coal exploration projects. Alistair spends most of his time developing the pre-interpretation processing technology Seisnetics™ and GeoProxima™, having actively contributed to its application in both academic research projects and corporate workflows.

alistair@totaldepth.com.au