

Insights from the Automated Extraction of Surfaces from the Bunda 3D Seismic Survey

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Abstract

The Lennard Shelf in the Canning Basin has long held the lure of commercial hydrocarbons. Home Energy discovered the Blina Oil Field in 1981, the first of several small fields found during the 1980's on the shelf. Buru Energy's predecessor ARC Energy took over the fields during 2007 and subsequently acquired the Bunda 3D Seismic Survey in 2009. This was the first 3D survey in the basin and was designed to image the existing oil fields and the surrounding leads and prospects.

Buru Energy has undertaken a comprehensive study of the 3D volume using an automated segmentation algorithm that was inspired by the Human Genome Project to globally and simultaneously identify virtually all trough and peak surfaces (GeoPopulations) that are related to a genetically common waveform (Genotype). A number of these surfaces and their attributes were extracted and selected for further analysis using sub-segmentation techniques for seismic facies mapping, and curvature analysis using an advanced implementation of differential geometry. The curvature analysis was undertaken on a series of surfaces surrounding the Laurel Formation (source rock interval), to investigate whether morphometric analysis of observed collapse features could be mapped vertically through the section. While fluid flow out of the Fitzroy Trough has been implied based on its structural position in the basin, observations based on indications from the seismic data attributes would validate perceived fluid pathways and help reduce risk associated with trap charge and reservoir development.

The interpretation of the Bunda 3D seismic volume reveals a number of untested features in formations that have already encountered hydrocarbons (e.g. the Permian Nookanbah, Poole, Grant & Betty formations, the Carboniferous Anderson, Laurel & Yellowdrum formations and the Devonian Gumhole and Nullara formations). Although the leads and prospects revealed from the automated methodology have yet

to be tested, the workflow has clearly demonstrated significant advantages. Namely, the objective assessment of the entire 3D volume enables the interpreter more time to focus on the meaning of the results rather than the mechanics of the process.

The integration of the 3D seismic coverage with well control and automated surface and object extraction highlights significant stratigraphic variability of both reservoir and seal. Consequently, reservoir/seal pair geometries as well as structure become key criteria for the assessment of new drilling prospects.

Introduction

Commercial interest in the Lennard Shelf in the onshore Canning Basin has increased significantly since Buru Energy's Ungani 1 well discovered light oil (-37°API gravity) in dolomitised limestones (Petroleum Western Australia, May 2012) on the Jurgurra Terrace (Fig. 1). This is the first significant oil discovery in the Canning Basin since the 1980s and is suggested to be a new oil play in the basin (Edwards & Streitberg, 2013).

Buru's existing fields, including the Sundown and Blina fields are now being reassessed and both new seismic data and new developments in seismic interpretation are being integrated with field histories. As the quantity and quality of seismic data available for analysis continues to increase, the industry needs to find more efficient methods to examine and utilise key information from these 2D/3D datasets. Automated analysis techniques can provide significant cost- and time-savings compared to conventional methods. Moreover, some of these techniques provide an objective and global examination of entire data volumes and deliver a pre-interpretation database of surfaces, features and attributes. With this database the geoscientist can develop an interpretive model based upon an analysis of all the data rather than just a small portion of it.

Using well control, automatically interpreted surfaces were correlated to the major geological formations including the, Betty Sandstone (Grant Formation), Anderson Formation, Carboniferous Laurel Formation and Yellowdrum Formation. Waveform and sub-waveform analysis techniques revealed

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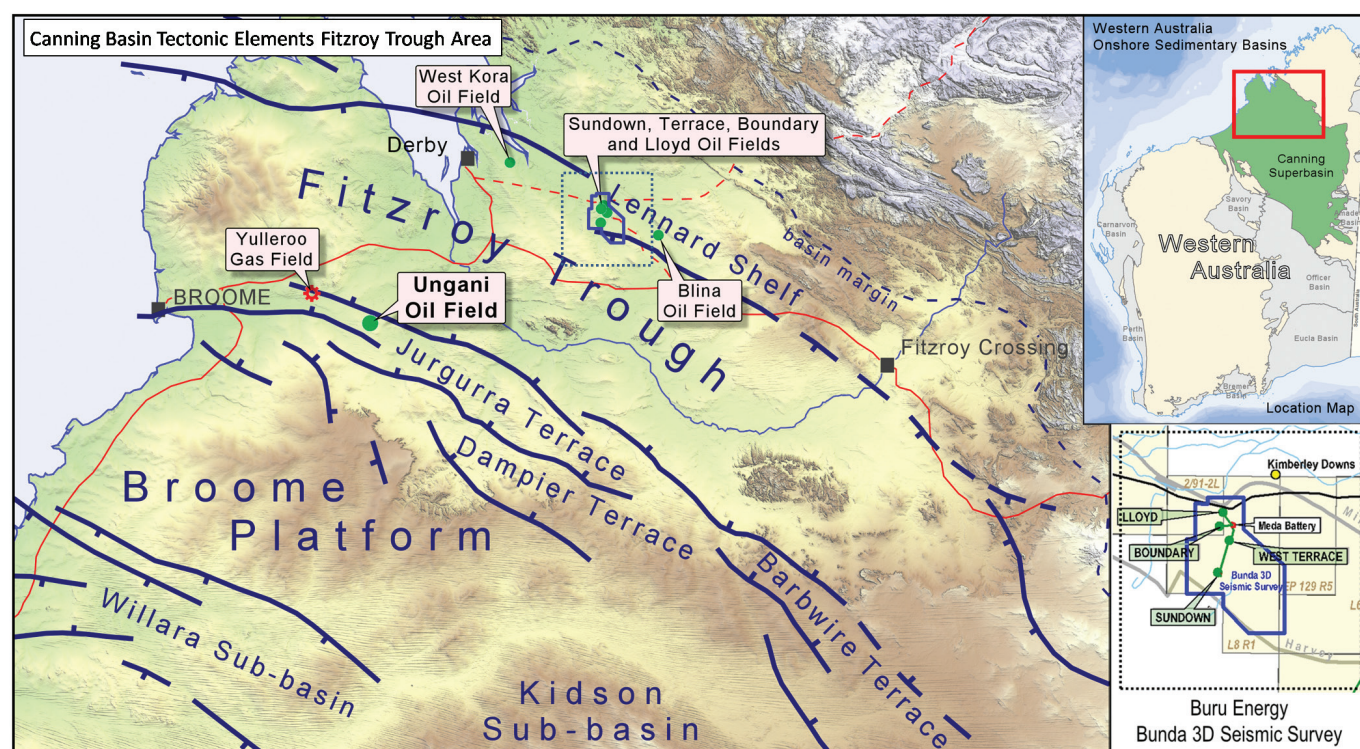


Figure 1. Location of the Bunda 3D with respect to Western Australia and the structural subdivisions of the Canning Basin (modified from Edwards & Streitberg, 2013). The bottom right hand corner of the figure shows the outline of the survey with respect to oilfield infrastructure, including wells.

additional insights and validation of both the structural and sedimentary morphology of the study area, highlighting the significant lateral variability of depositional facies within each geological unit.

Differential geometry analysis was applied to selected surfaces from the visual database to identify objects of convex and concave curvature. These features help identify and quantify subtle features that may have been over-looked by conventional interpretation methods. These areas of concavity and convexity, for example, may allude to areas that have experienced fluid flow events, such as hydrothermal fluids being expelled from the Fitzroy Trough and dolomitised limestones in selective locations.

Location

The Bunda 3D seismic survey was acquired in the Production Permits L6 and L8 and Exploration Permit EP129R5 in the onshore Canning Basin, Western Australia, 80-100 km east of the township of Derby (Fig. 1). The survey provides 3D seismic coverage across the following well locations: Wattle 1, Lloyd 1 & 2, Boundary 1, Boundary SE 1, West Terrace 1 & 2, Terrace 1, Loris 1, Scrubby 1, Leander 1, Sundown 1-4, Whitewell 1, Hangover 1, Sunup 1, Fairwell 1 and West Blackstone 1.

Geological Setting

The Canning Basin, covering over 430,000 km² in the north of Western Australia, is one of Australia's largest onshore sedimentary basins (Edwards & Rudge, 2010). It was established in the early Paleozoic as a broad cratonic sag depocentre and subsequently divided into two major NW-SE trending sub-units, the Fitzroy Trough Sub-basin and the Kidson Sub-Basin (Figs 1 & 2) (Kennard et al., 1994). The pre-Permian fill of these sub-basins are largely concealed beneath widespread Permian and Mesozoic sedimentary overlay. The Fitzroy Trough depocentre is estimated to contain up to 16 km of predominantly Ordovician, Devonian and Permo-Carboniferous sediments, is shown in Figure 1. The Fitzroy Trough was subject to a major cycle of thermal uplift followed by rift subsidence during regional Upper Devonian extensional tectonics.

Post-Devonian deformation created extensive faulting and structural inversion across the region, particularly the thick sediments of the Fitzroy Trough graben system. This activity peaked during the mid-Carboniferous 'Meda' and the Late Triassic 'Fitzroy' tectonic events (Shaw et al., 1994; Kennard et al., 1994), the latter tectonic event instigating mobilisation of deeply buried Silurian evaporite deposits, creating a band of mixed piercement and wrench structures aligned roughly with the midline of the Fitzroy Trough. Regional uplift and erosion associated with this deformation is estimated to have resulted

in the removal of hundreds to thousands of metres of upper Paleozoic section.

The Bunda survey was acquired over the northern margin of the Fitzroy Trough, where the Pinnacle-Harvey Fault system separates the Fitzroy Trough proper from the Lennard Shelf (Fig. 2). The fault system acted as a transitional zone and was active early in the rift phase. In addition to NE-SW trending faults, mid-Devonian rifting also generated a series of SW-NE trending offsets, often interpreted as transfer zones. These probably represent rejuvenation of earlier crustal weaknesses that developed near-perpendicular to the main Fitzroy Trough-Pinnacle Fault system. These features largely controlled Devonian sediment dispersal and accumulation along the Lennard Shelf and into the Fitzroy Trough. Transpressive reactivation, particularly along the Pinnacle-Harvey Fault System, locally reversed movement on the major faults and created compressional anticlines that form the Permo-Carboniferous hydrocarbon traps on the Sundown-Lloyd Trend (Crostell, 1998) (Fig. 2). In contrast, the Blina Oil Field, some 25 km to the east, is interpreted to have formed as a drape closure over a Devonian reef, with several phases and orientations of faulting creating fracture permeability in the carbonates (Jonasson, 2001). A generalised cross-section shown in Figure 2 provides a summary of the structural styles and hydrocarbon occurrences from the Fitzroy Trough in the southwest of the Napier Embayment in the northeast.

Exploration History

Exploration in the Lennard Shelf commenced in 1967 and the 40 exploration and appraisal wells drilled to date in this area have resulted in oil production from Devonian carbonates at Blina Oil Field (1981) and Permo-Carboniferous sandstones at the Sundown (1982), Lloyd (1987), West Terrace (1985) and Boundary (1990) fields. Encouragement had been gained from drilling Meda 1, WAPET's first well on the Lennard Shelf. This well recovered oil on DST (WAPET, 1967) from Early Carboniferous dolomitic sandstones immediately above a Devonian carbonate section within which minor oil and gas shows were also recorded. Blackstone 1 also recorded minor oil and gas shows, but no effective reservoirs were present within the Devonian section. With other wells drilled along trend on the Lennard Shelf recording mostly discouraging results, a long hiatus ensued in the Sundown-Blina area drilling until 1981 when a Joint Venture led by Home Energy discovered producible oil in the Famennian carbonates in Blina 1, their first well in the basin (Crostell, 1998).

Blina 1 was followed by successful appraisal leading to commercial development and, in 1982, by the discovery of commercial oil in Permo-Carboniferous sandstones

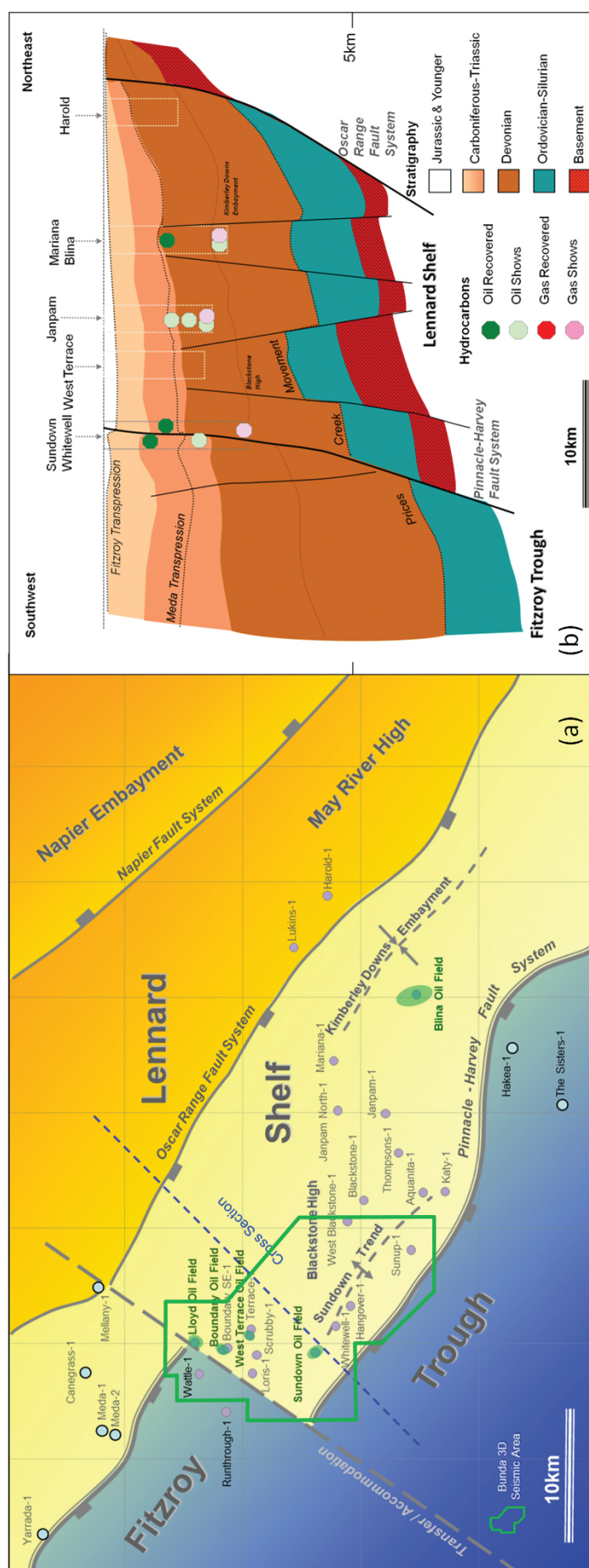


Figure 2. a) structural elements of the Lennard Shelf, along with well locations; b) Geological cross section of the Lennard Shelf oil fields.

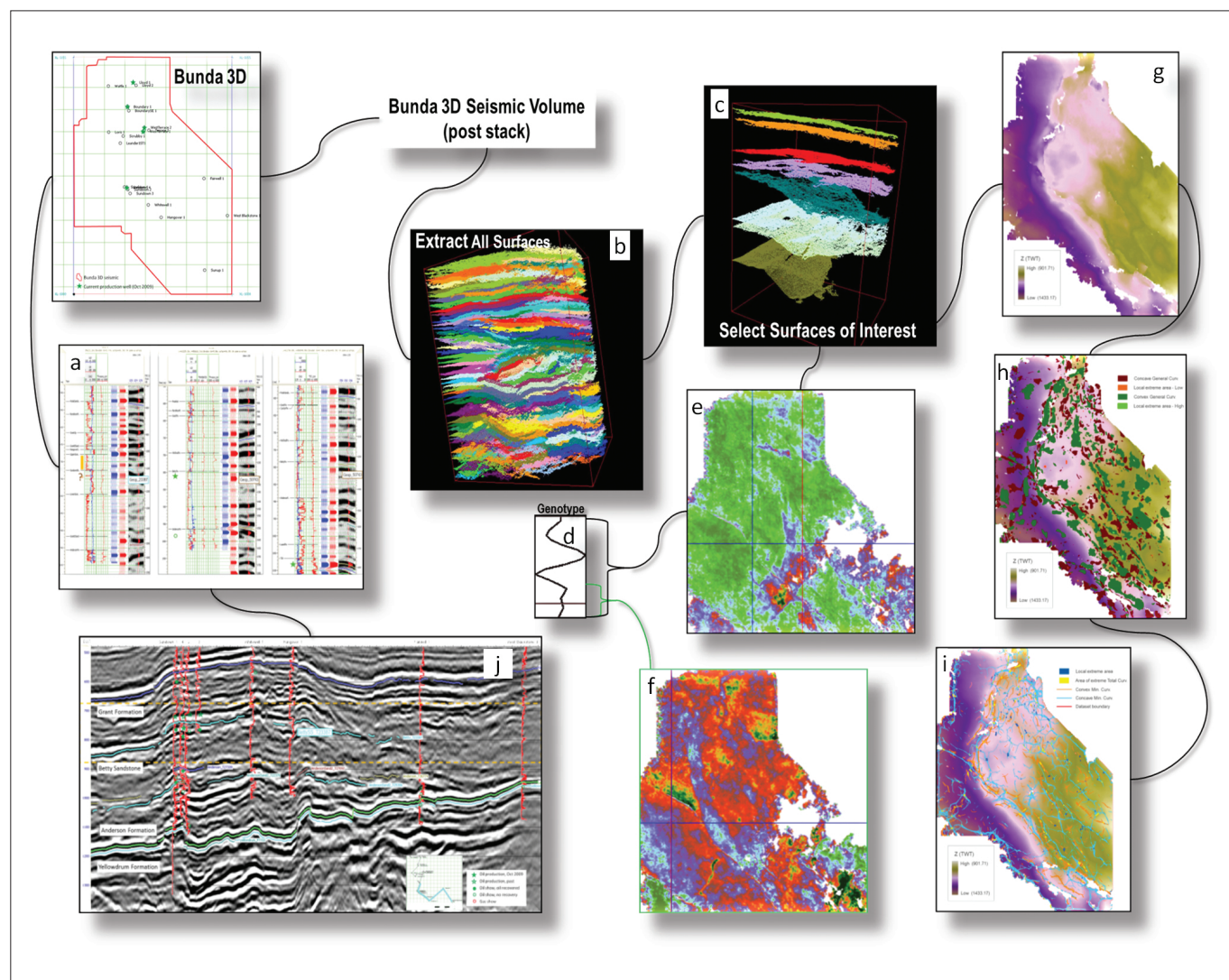


Figure 3. Workflow Applied to the Bunda 3D Seismic Survey. a) Create a Well Database (HRS) to QC/edit and create a suite of log-generated synthetic seismograms. Correlate synthetics with the various versions of seismic to validate the integrity of the seismic, well log and geological log interpretation; b) Fully automated segmentation process creates visual database containing all peak and trough surfaces. Each surface consists of a population of genetically related waveforms (Seisnetics); c) Review visual database of pre-interpretation surfaces for GeoPopulations of interest using TWT, amplitude and Fitness attributes; d) A Common Waveform (Genotype) is associated with each GeoPopulation; e) The “fitness” attribute provides a measure of “genetic likeness” for each member in the population when compared to the common waveform of the same population. This fitness criteria distinguishes between individuals within a single GeoPopulation. An effective way to assess the genetic variability within a population is to view the fitness values as a map. The fitness map shows areas of high fitness (green) with lower fitness values (blues and reds). The high fitness areas can be thought of as direct relatives whereas the lower fitness values are still significant but more like 1st or 2nd cousins; f) By selecting a specific portion of the Genotype a more targeted fitness map or volume can be generated; g) Surface analysis using advances in differential geometry. A recent breakthrough in mathematics enables the automated identification and vectorization of objects with multi-scale resolution (without artefacts) (GeoProxima); h) Attribute maps of convex and concave structures. i)-Vectorized attribute maps of normal, maximum and minimum curvature; j) Interpret horizons from time-indexed well logs.

at Sundown 1. Other discoveries in this play were made at West Terrace 1 (1985) and Lloyd 1 (1987). Numerous other follow-up wells pursuing both the Devonian carbonate and Permo-Carboniferous plays were drilled as oil prices peaked in the mid-1980s, with many recording shows, including sub-commercial oil in the Permo-Carboniferous at Terrace 1 (1984) and in the Devonian in Janpam North 1 (1987) (Jonasson, 2001).

With falling oil prices, Home Energy exited the basin in the late 1980s and Petroleum Securities assumed operatorship, discovering the Permo-Carboniferous Boundary Oil Field in 1990. Since then, activity has focussed mainly upon appraisal/infill drilling under the operatorship of Minora (Sundown 5 & Blina 4 Deepening in 1993), Bow Valley (Wattle 1 in 1994), Santos (Sundown 3H in 1995), Capital Energy (Loris 1 in 1997) and Terratek (Lloyd 3 in 1998 and Boundary Southeast 1 and Scrubby 1 in 2006). ARC Energy entered the fairway with 100% equity in 2006, subsequently re-assigning its interest to Buru Energy in 2008.

Buru Energy acquired the first 3D seismic survey in the onshore portion of the basin, focusing on imaging the existing fields and maturing nearby leads and prospects to drillable status. The Bunda 3D seismic survey was acquired in August/September of 2009 by Terrex Seismic and processed by DownUnder GeoSolutions Pty Ltd.

Buru's first well in the area was Fairwell 1, drilled in 2010 and targeting the Stephanian sands in the Upper Grant Formation, encountering only trace oil shows present at this level. A secondary target was a low-relief carbonate build-up in the Lower Laurel Formation; however there were no hydrocarbon shows at this level (Buru Energy, 2011). This was followed by Leander 1 targeting a low relief Viséan Anderson Formation sands overlying a basin edge reef build-up in the Tournasian Laurel Formation. The secondary target consisted of both the lower Laurel and Yellowdrum formations. The well penetrated and evaluated the primary objective, however no hydrocarbon shows were recorded within the Anderson Formation. Poor oil shows were present in the secondary objectives. The well was plugged and suspended for possible re-entry to test a collapse feature directly to the west of the well (Buru Energy, 2011).

Methodology

With the advent of new technologies that use global (i.e. entire data-set) interpretation methods, traditional workflows for the interpretation of seismic data are changing to accommodate the larger datasets and extract additional information. The methodology applied to the Bunda 3D data combined global pre-interpretation segmentation (Dirstein & Fallon, 2011), advanced curvature attribute analysis (Ihring & Hroncek, 2012) and sub-segmentation waveform analysis techniques.

The workflow commenced with a review of the available data volumes in terms of Signal-to-Noise-Ratio (SNR),

spectral integrity and overall imaging. When required, adjustments were made to fine tune the data volume prior to pre-interpretation analysis to improve SNR and best recover the spectral distribution of the reflectivity while preserving the spectral integrity of the seismic data. Since the pre-interpretation processing applied is fully automated (Fig. 3b), often more than one version of the data can be processed to enable a more quantitative comparison between alternative volumes. Using a genetic processing algorithm (Dirstein & Fallon, 2011), the traces in the seismic volume (analogous to chromosomes) are first automatically segmented into waveforms (analogous to genes). From here populations of waveforms begin to simultaneously evolve globally within the entire input volume based upon their genetic similarity (fitness). With each generation the growing population passes on some of its genetic material as the common waveform (genotype) associated with the population continues to evolve. The process continues until virtually all populations of Trough and Peak surfaces (TWT, fitness, amplitude, genotype) have been identified and placed into a 3D visual database of uniquely named Geo-Populations. The 3D visual database of all the populations was then reviewed using a number of different criteria to identify and select surfaces based on the specific objectives and needs of the interpreter (i.e. overall geo-model, reservoir/seal pairs, population size, geohazards, processing QC, etc.) (Fig. 3c). This approach helped to develop a geological model based on all the available data rather than just a small subset of it. Since all surfaces have been extracted from the volume using the same methodology and criteria, the results provided both a consistent and unbiased assessment where each surface consisted of a population of genetically related waveforms. Moreover, a measurement of the genetic variability within the population is provided using the fitness attribute (Figs 3d, 3e, 3f).

Using these high quality surfaces as input, analysis was undertaken utilising GeoProxima's differential geometry technology that addresses limitations of other curvature analysis algorithms (e.g. Roberts, 2001; Woods, 1996). Most of these algorithms calculate curvature using second-derivative-based methods making the simplifying assumption that the second derivative is a direct measurement of curvature (only true for zero dip) (Roberts, 2001). Consequently, these techniques introduce high frequency artefacts of coherent energy when applied to surface analysis and their implementation is usually limited to the calculation of volume based attributes (where further smoothing of the data takes place). Since this new methodology does not use the second derivative (or any other documented technique) to calculate curvature, or use similar simplifying assumptions, the results are more stable (without the introduction of coherent noise) (Ihring & Hroncek, 2012).

With the application of this technique to different horizon surfaces subtle morphometric features could be identified and quantified. Some of the surfaces examined were those associated with the Laurel Formation (source rock) revealed the presence of collapse features (Figs 3g, 3h, 3i) which could be measured

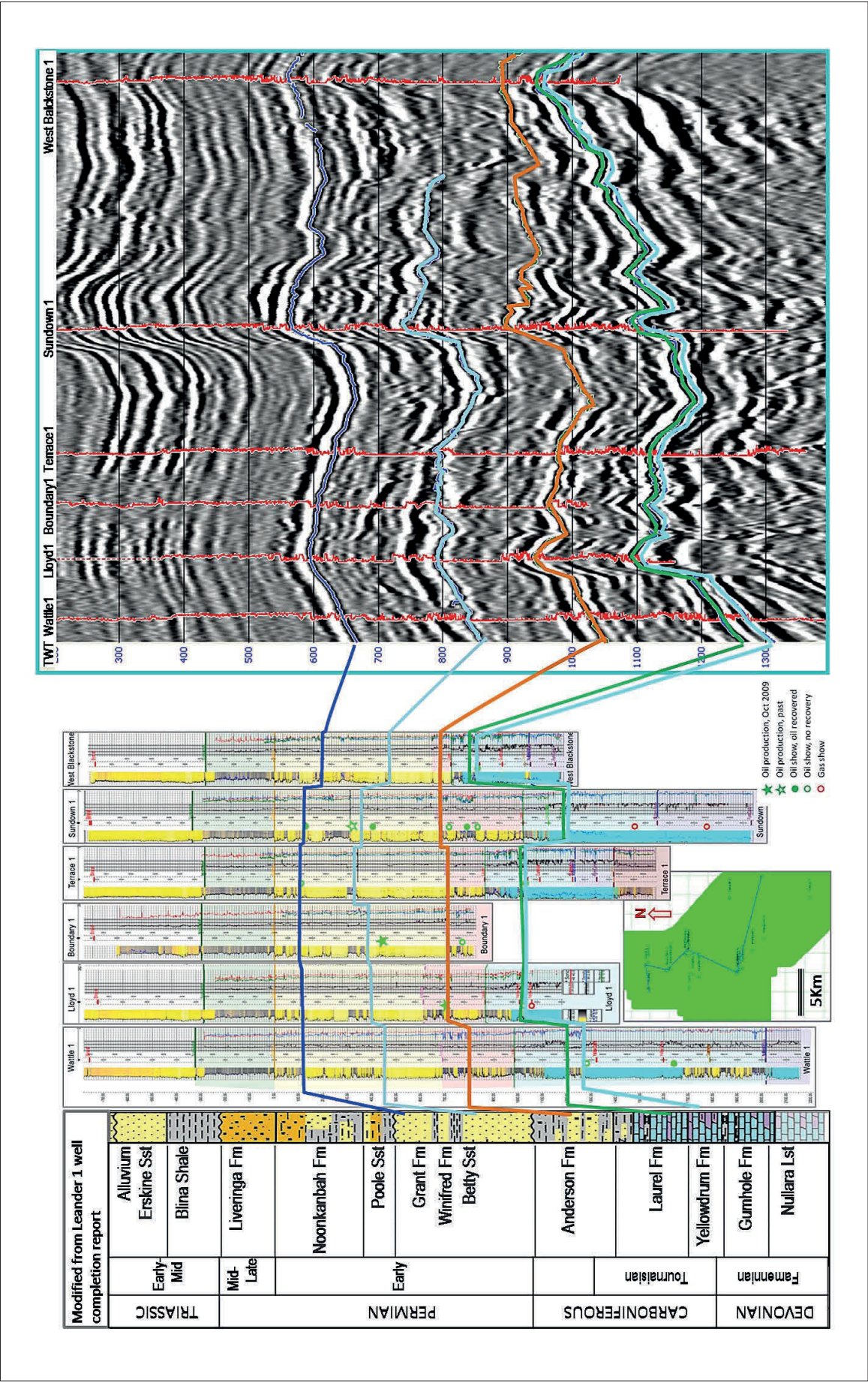


Figure 4. Stratigraphic column depicting Devonian to Triassic sedimentary units, correlated to well data and an arbitrary seismic line through the Bunda 3D. The figure highlights the seismic expression of major reservoir units and the location of some oil and gas production zones.

quantitatively to help provide insights into fluid flow from the Fitzroy Trough and mitigate potential hydrocarbon charge risk and reservoir diagenesis.

The digital geophysical logs from the twenty wells located within the Bunda 3D survey area were reviewed and edited prior to the creation of a suite of log-generated synthetic seismograms (Figs 3a & 3j). These synthetics were then correlated with the various versions of the 3D seismic data to identify specific geological features on the seismic data and to validate the integrity of the logs, seismic data and geological correlations. A stratigraphic column is correlated to selected wells, an arbitrary seismic line and key seismic surfaces as they relate to the cross-section of log data in Figure 4.

The Grant Formation (top reservoir/base regional seal), Betty Formation (production), Anderson Formation (production), and Laurel Formation (shows and age-equivalent to producing section at Ungani 1) were identified as primary zones of interest. On the basis of these seismic to well correlations and also trying to understand the stability within the population of waveforms, targeted sub-segment waveform analysis was undertaken to provide insights into specific zones of interest; that is sedimentary depositional sequence, extent of sealing units, reservoirs and potential new prospects (Seismic Facies Analysis).

Key Findings

The study revealed many new insights into the Sundown Field. A few selected examples from the stratigraphic column are presented.

Grant Formation: Base Seal/Top Reservoir

The top Grant Formation horizon is often considered to be the interface between top reservoir and base regional seal. The fitness map from this surface shows the genetic similarity between the waveform segment common to the population (genotype) and each individual trace (Fig. 5a). The green colours represent the areas where the waveforms have the highest genetic similarity (direct relation) and the areas of blue and red fitness show areas of less genetic similarity (1st or 2nd cousins). The fitness map shows areas that have predominantly high fitness values (green). One area which shows lower fitness (blue, red, yellow and dark green) is located in the central portion of the map and is trending roughly NE-SW. Initial interpretation suggest a broad channel (blue fitness) with a central portion showing possible meandering (red, yellow and dark green fitness). Viewing the image poses the question "What is the significance of this feature and does the observed waveform variability reflect changes in the Grant Formation reservoir or the overlying seal?"

When the seismic volume is automatically processed for peak and trough surfaces, the segmentation of the seismic data is mathematically constrained. The final population consists

of a group of similar waveforms based on this mathematical segmentation.

Examining the waveform sub-segments above and below a particular surface reveals its relative stability or variability revealing insights about the structure and stratigraphy providing an indication of the horizons suitability for various attribute analyses. Geologically, this analysis technique enables the interpreter to examine different depositional domains that may be captured within a single seismic waveform. Fitness attribute maps were generated from sub-segments of the common waveform at the Top Grant Horizon (Fig. 5) and were reviewed for insight in the upper portion of the Grant reservoir and overlying seal.

The sub-segment fitness maps at and above the Top Grant surface are quite similar to the fitness map from the full waveform segment (compare Fig. 5a to Figs 5c, 5d, 5e) suggesting a degree of stability and consistency over this portion of the full waveform. However, the fitness map from the lower sub-segment of this waveform is profoundly different (Fig. 5f) with a narrower channel-form trending perpendicular (NW-SE) to the previously identified channel seen on the fitness map. Consequently, in this case, the fitness maps from the full waveform are more representative of the variability above the Grant, implying that, in places, the top Grant seal may not be effective, resulting in hydrocarbons migrating into coarser, channelised facies within the Poole Sandstone Formation and overlying Nookanbah Formation. Conversely the fitness map from the lower part of the waveform is more indicative of variability in the upper portion of the Grant Formation. In this example focussing the analysis on the lower portion of the segment reveals the more subtle features in the waveform and interval. Additional subtle features could be targeted, for example by using a reflectivity volume as input for automated surface extraction as the wavelet (and sidelobes) are minimised, more detail would be revealed.

Further integration with the geophysical logs helps to develop the seismic facies map into a geological facies map showing different stratigraphic domains. While only one of the well locations is shown in Figure 6, drilling results at other locations confirms the presence of a fine-grained cut-and-fill channel feature, orientated roughly north-south and draped across structure. Consequently, a portion of non-eroded Grant Formation reservoir could be trapped against the up dip abandonment channel and the bounding fault to the south providing a potential trap. Note there is also an area of low fitness (blue) that highlights the up dip extent of the feature.

Grant Formation: Channel Features

There is a precedent for targeting the flanks of channels identified in the Grant formation; both West Terrace 1 and 2 targeted the flanks of an incised glacial channel (Home Energy, 1985). These wells produced oil, in contrast to the Terrace 1

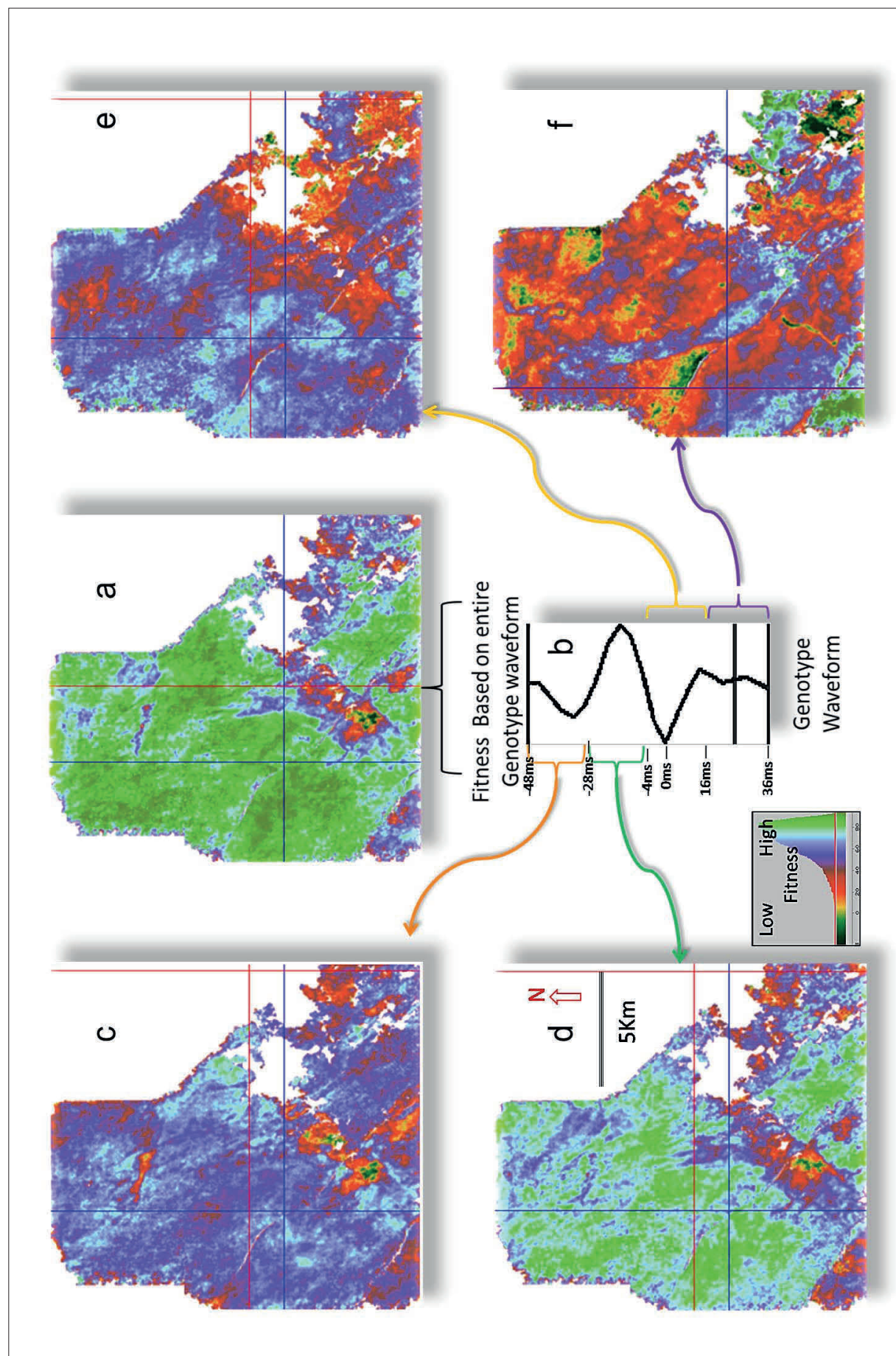


Figure 5. Full segment and sub-segment fitness maps. a) Full waveform fitness map, which demonstrates the genetic similarity between each individual (trace) in the population and the common waveform (Genotype), shown in b); c) The sub-segment fitness recalculated based on the upper portion of the full waveform; d) & e) The sub-segment fitness recalculated based on the lower portion of the full waveform, revealing significantly different features to those on other fitness maps.

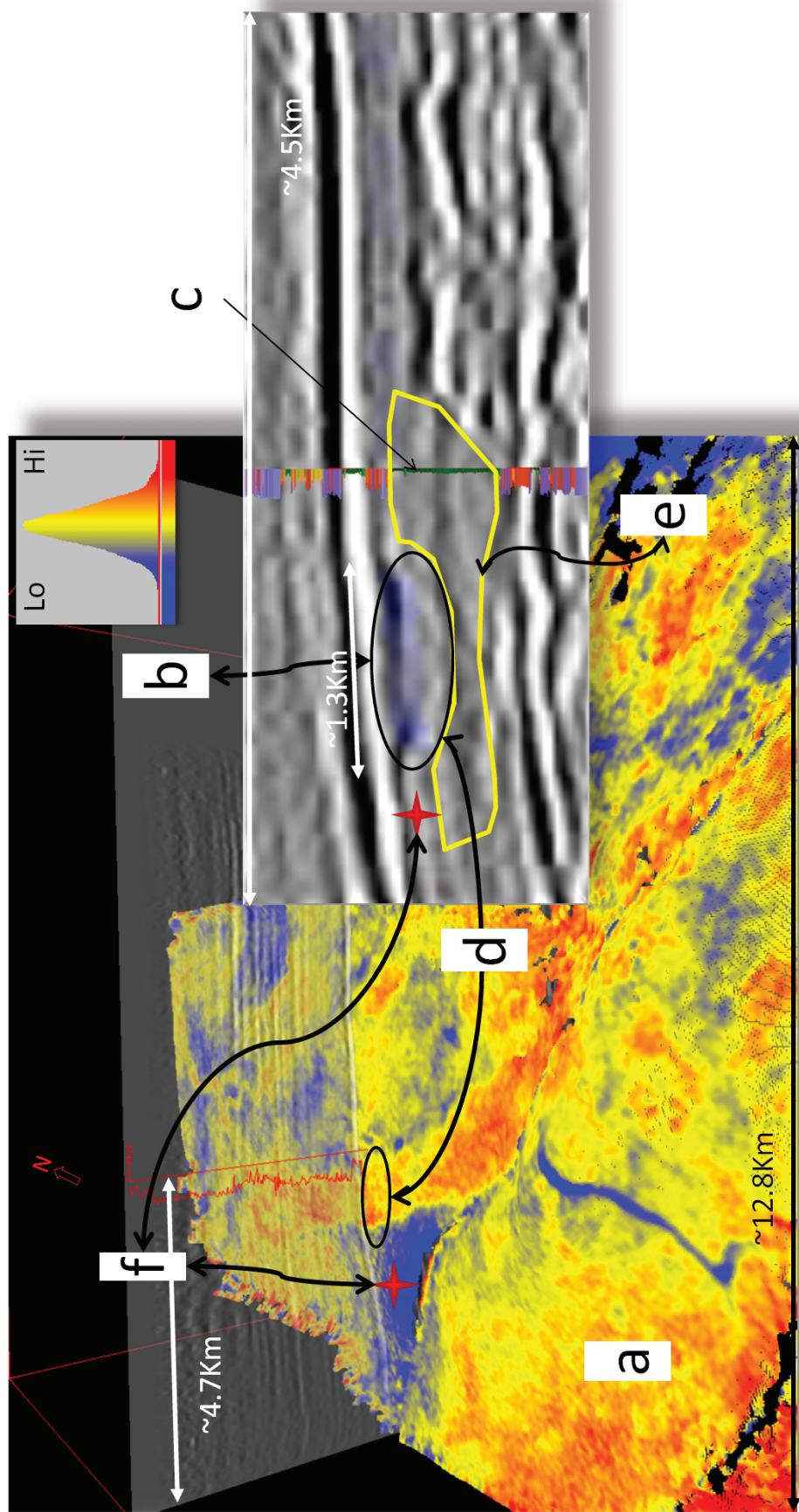


Figure 6. Integration of sub segment fitness with well control. a) sub-segment fitness map of lower portion of well; b) Upper Grant Formation abandonment channel (fine grained non-reservoir); c) Gamma log [reverse scale] showing Grant reservoir; d) Location of channel on fitness map and seismic; e) Polygon shows outline of Grant channel; f) Portion of upper Grant Formation reservoir potentially stratigraphically-trapped against abandonment channel.

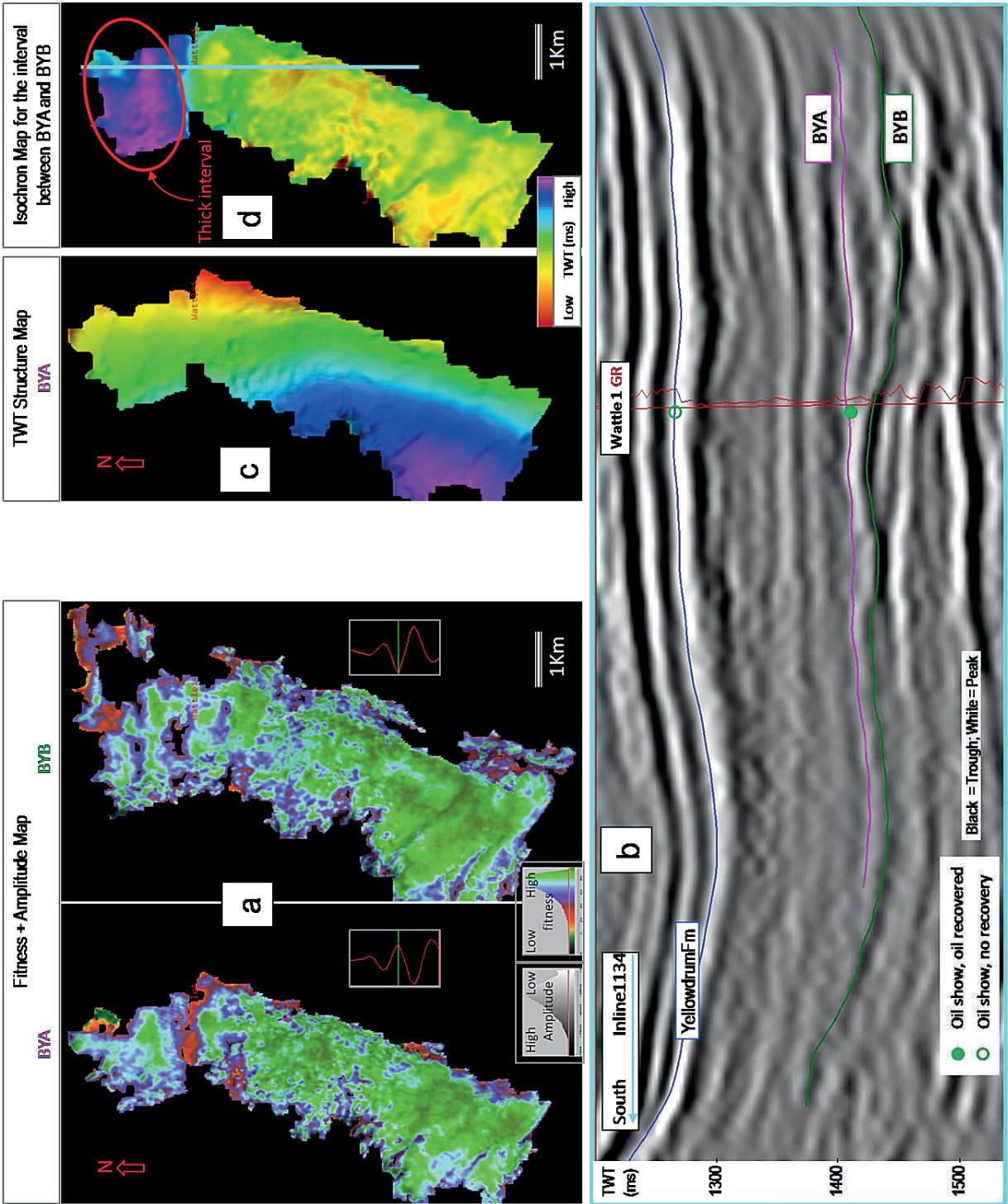


Figure 7. Perspective view showing the incising glacial channel around the Terrace 1 and West Terrace 1 wells. a) Blended TWT and Amplitude attribute map of a surface corresponding to the oil production zone at the West Terrace wells; b) Gamma-ray logs of the Terrace 1 and West Terrace 1 wells, with high and low gamma counts indicated by purple and green respectively; c) Cross-section of the incising channel, which is approximately 425m wide at its top.

well which drilled directly into the channel and appears to have a poor top seal (Fig. 7).

The blended TWT and Amplitude map of the surface displayed in Figure 8 corresponds to the oil-producing zone at the West Terrace wells. The surface extract terminates close to the West Terrace 1 well because the younger incised glacial scour/scoop results in a seismic waveform change. Gamma ray logs from the two wells shown in Figure 8 indicate that the channel has been infilled by coarser clastics whilst the flanks of the channel have retained a complex interbedding of sandstone and shale units.

The Terrace 1 well penetrated near the channel axis and is thought to have failed because of an erosive breach of the seal at this level. Oil shows observed at the top of the Grant Formation confirm that oil had migrated through the coarser clastic channel fill. By contrast West Terrace 1, recovered oil from the Grant Formation, presumably because the complex interbedded shale units on the channel flank provided a more effective seal. Using high quality seismic data, combined with a visual database of surfaces and their attributes is an appropriate way to address the complex stratigraphic geometries with a view to mitigate seal risk and identify favourable reservoir development.

Yellowdrum Formation: variability in reservoir and seal thickness

Review of seismic waveform changes from the pre-interpreted surfaces within the Yellowdrum Formation suggest considerable heterogeneity of both reservoir and seal (i.e. smaller populations) over the entire survey. In the vicinity of the Wattle 1 well a good example of this variability was observed in the basal Yellowdrum Formation (2529–2550 mMD) (Bow Valley, 1994). Oil was recovered on DST from a calcarenite unit in Wattle 1, the reservoir is thin and tight and notably not located on a structural high. However, examination of the seismic data (Fig. 8) shows the interval thickens up-dip to the north and to the east as part of the hanging wall of a major fault. This substantial thickening also can be observed as variability in the waveform fitness map and also as an increase in the TWT isochron map. Given the oil recovery at the edge of this thickening calcarenite unit and its position in the hanging wall of a major fault, favourable reservoir enhancement as a result of depositional facies change or diagenesis could create a significant stratigraphic trap. The observed seismic variability in the Yellowdrum Formation within reservoir-seal pairs is an important consideration in the assessment of risk for the ranking of leads and prospects.

Laurel Formation: Morphometric analysis of collapse features

Morphometrics here refers to the quantitative description of shape and size. While our application is focussed on geomorphology, the methodology is applicable to any type

of surface (Ashraf, 2010). The horizon attributes extracted provided an objective dataset for surface analysis accepting that the genetic algorithm uses a consistent, global methodology to extract the surface, the quality of the surfaces is ultimately related to the quality of the seismic volume being analysed. This method implements a fresh approach for geodata surface analysis, the result of fifteen years of scientific research in digital signals, curves, images, surface and volume analysis (Dirstein et al., 2013). Existing methods such as; Operators (Canny, Prewitt, Sobel, Kirsch); krigging, splines, inverse distance weighting; geostatistics, fast fourier transform, discrete cosine transform (transforms in general); wavelets; Gaussian decomposition; worms; derivatives (1st, 2nd, etc.) are not ideally suited for the analysis of surfaces and the technique uses differential geometry with automated parameterisation yielding accurate and robust results without the introduction of coherent noise. The results generated include maximum and minimum curvatures, object recognition, automated vectorisation and allocation of geometric properties of objects (Ihring & Hroncek, 2012). All objects and their properties are then stored in a database enabling further analysis and interpretation. One of the analysis steps involves the calculation of Dupin's Indicatrix at each and every point on the surface (Dupin, 1813). The Dupin indicatrix is an osculating paraboloid describing all localised curvatures of a surface and is a method for characterising the shape of a surface in a small neighbourhood (Mathworld; <http://mathworld.wolfram.com/DupinsIndicatrix.html>). The directions of axis of the Dupin indicatrix are often referred to as principal directions. Curvatures associated with these directions are known as principal curvatures and their values form maximum and minimum normal curvatures. The product of the principal curvatures is called total (or Gaussian) curvature and their average is known as mean curvature. These curvatures can be used to help characterise structural elements within a dataset. Figure 9 provides a pictorial example of a concave and convex shape of a slope line and a contour line with inflection points locating the transitions from one shape to another. Dashed lines are shown tangential to both the slope (orange) and contour (grey) lines. Slope curvature (or dip curvature), is a curvature of the normal section passing through the tangent to a slope line (in other words, a normal curvature in the direction of gradient). The crest of the hill shows convex curvature along the slope line, (orange) with the valley or saddle showing concave curvature. Tangential curvature (or profile curvature) is a curvature of normal section passing through the tangent to a contour line (and is perpendicular to the gradient direction). The grey line shows a side ridge and gully showing tangential convex and concave curvature respectively. The combination of the horizontal and vertical curvatures is used to classify a surface into four groups based on the convex or concave shapes. This approach is widely used to characterise processes of erosion and deposition. In the subsurface (Fig. 9) the curvatures associated with the footwall (FW) and hanging wall (HW) of a normal fault can help differentiate between normal

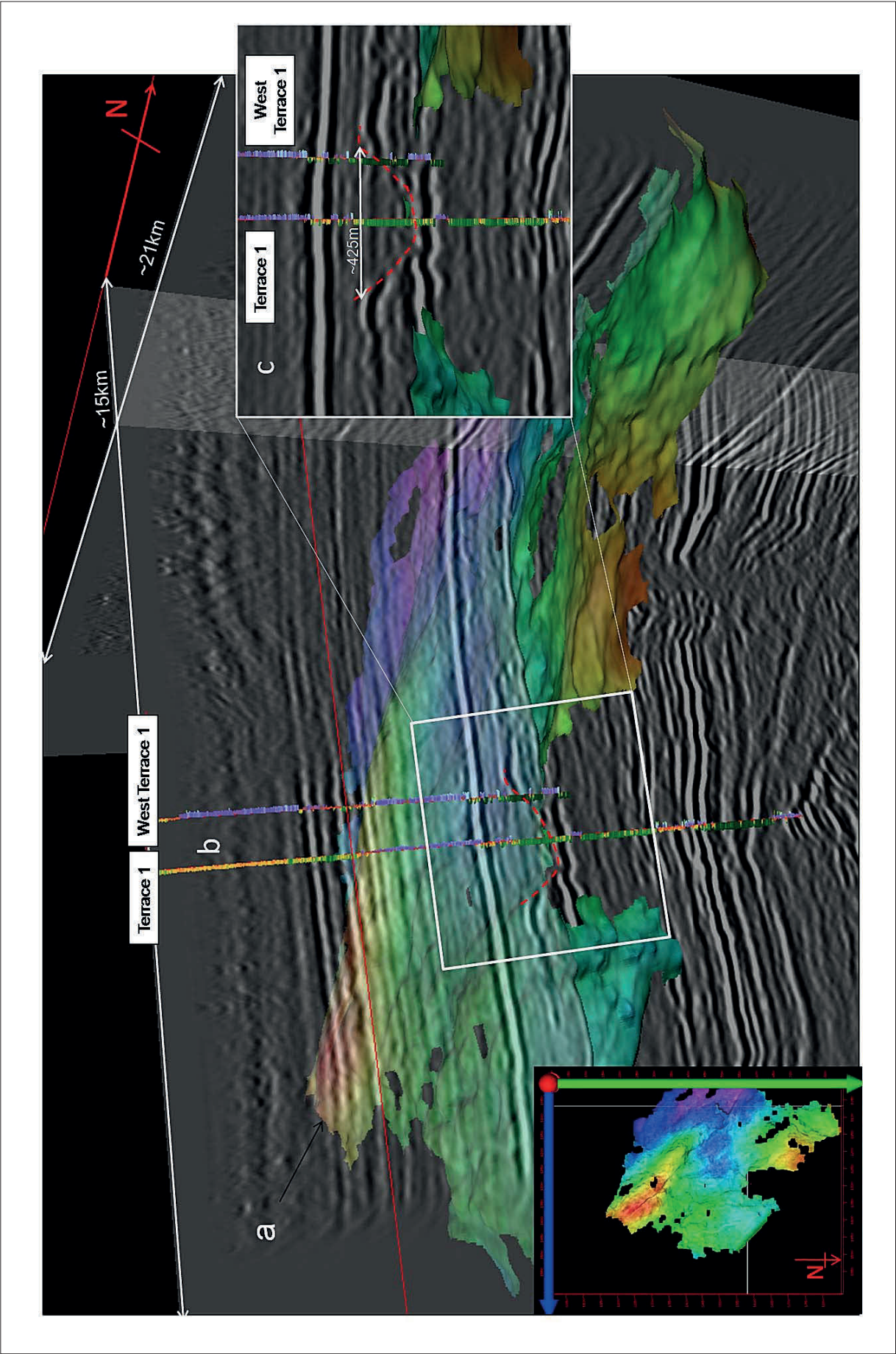


Figure 8. a) Merged fitness and TWT attribute map of BYA and BYB. A band of low fitness on the BYA and BYB correlates to the oil recovery at Wattle 1; b) Seismic section of inline 1134 showing selected GeoPopulations™ interpreted to be the top (left) and base (right) of the Yellowdrum Formation (BYA and BYB), based on Wattle 1. Oil was recovered near BYA and BYB in Wattle 1; c) Structural (TWT) map of GeoPopulation BYA, the surface exhibits no anomalous features; d) Isochron map between BYA and BYB, showing significant thickening to the north.

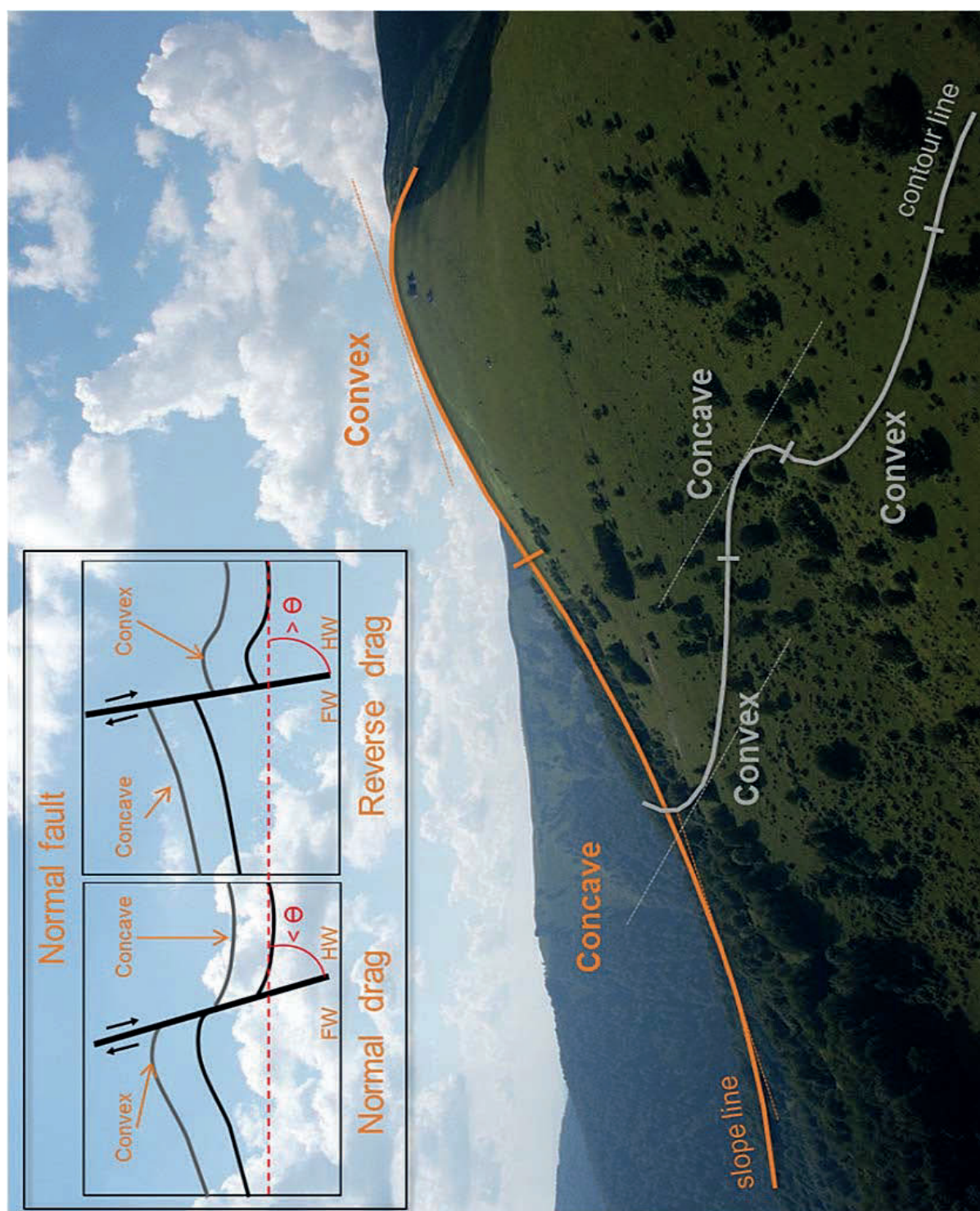


Figure 9. Illustration of convex and concave shape of a slope line and a contour line. Inflection points locate transition from one shape into another. White dashed lines are tangent to slope line and contour line (Hroncek et al., 2012 unpublished course notes).

and reverse drag. Moreover, areas of reverse drag may provide an indication of post-failure deformation zones along existing faults (Katz & Reches, 2005)

In addition to automated object identification and vectorisation, the database of surface curvature attributes can be queried for specific elements of interest, and at multiple scales of resolution.

This surface analysis technique was applied to number of automatically extracted surfaces from the Bunda 3D volume. The results documented here used a two-way-time (TWT) surface extracted near the top of the Laurel Formation (Fig. 10). This zone is of particular economic interest because it is age-equivalent to the oil-bearing dolomitised reservoirs discovered recently at the Ungani Field (Edwards & Streitberg, 2013). The objective of the study was to quantify aspects of the surface attributes to develop a model of the likely flow pathways utilised by hydrothermal fluids.

The TWT map of the Laurel Formation is displayed with a false-colour palette allowing the identification of only the gross structural changes. The detail of the map that is lost within the subtle gradation of colours, can be partially addressed by the application of surface rendering and light shading, but the improvement is qualitative. Moreover, the false-colour palette does not identify or describe any objects or features within the population.

The differential geometry analysis of the database of automatically calculated surfaces and attributes identifies many features and objects. In Figure 11, the Laurel Formation TWT map has been overlain with the extracted objects which are colour coded to illustrate areas of the surface which are locally concave (red) and convex (green). Examination of these objects identifies the location of subtle anticlinal and synclinal areas, as well as areas of faulting (pairs of parallel trending convex and concave objects). The concave and convex objects can also help identify faults with normal or reverse drag (i.e. convex in the direction of slip or concave in the direction of slip) (Grasemann et al., 2005) (see insert on Fig. 9). Highlighted on Figure 11 are objects of local extreme values shown for both convexity and concavity (bright green/extreme convex, orange/extreme concave). The combination of convex and concave objects, together with their extremes, provides an indication of object morphology with respect to relief and shape/symmetry. A query targeting only the deepest concave objects (Fig. 12) reveals objects adjacent to faults, with the highest concentration in the north and east central portions of the study area. Placement of the objects onto the rendered surface helps provide validation of both rendering parameters and object extraction.

Vectorising the localised minimum and maximum curvature reveals localised anticlinal and synclinal trends (Fig. 13). There are several sets of vectors displayed, which correspond to vectorisation of different realisations of the object curvature. Also shown on Figure 13 are areas of extreme total curvature (also referred to as Gaussian curvature) which is the product of the principal curvatures calculated in Dupin's

Indicatrix). When the product of the two principal curvatures (minimum and maximum) is zero, simple isometric folding is inferred. However, when total curvature is positive, it suggests more complicated deformation is responsible and the surface has been stretched, squeezed and/or ruptured. Errors in the calculation of principal curvatures can create small positive or negative curvature values and the application of a stable technique, with a minimum of simplifying assumptions, is important as is a focus on extreme positive and extreme negative values of total curvature (or extreme absolute values). The areas of extreme total curvature (Fig. 13) are mainly located along or adjacent to faults and localised anticlinal or synclinal trends. The highest concentration of the positive total curvature objects is located in the same areas as the deepest collapse features, suggesting that these are areas where the most complex deformation of the surface has occurred. These may be areas of higher fracture density or fracture swarms, and important aids in the interpretation and prediction of paleo-fluid flow.

Discussion

Implementing the workflow to interpret the Bunda 3D seismic survey presented a range of challenges additional to the traditional problems faced by interpreters. The use of a global interpretation method to extract all the surfaces meant that there was never a shortage of waveform populations (i.e. horizons) and consequently, most of our time was spent thinking about the significance of the results rather than the mechanics of surface extraction. In that regard, the automated process was a very thorough, timely and efficient process. The visual database of pre-interpreted surfaces becomes the new starting point and interpretation is more about integration of geological and other relevant information with the seismic data. The full benefit and value of this methodology is especially realised when the seismic data is combined with cross-sections of well data, as well as seismic/geological facies maps and other relevant geotechnical information. Moreover, the surface extraction process is objective as well as fast, there is more opportunity for more collaborative interaction between different geotechnical disciplines using the 3D visual database of surfaces as a common point of reference. The team can decide what features warrant further attention and which surfaces would be best incorporated into the data-driven geological models.

The method did not reduce the overall time spent on interpretation but it maximised the time to interpretation and prospect generation. Having the visual database of all surfaces enabled the interpreter to quickly extract and interpret the additional surfaces as desired. Consequently, the response time between a new thought, or a colleague's observational insight and the testing of that concept was minimized, making for an efficient way of cycling through a range of different data consistent scenarios. Moreover, any of these populations/

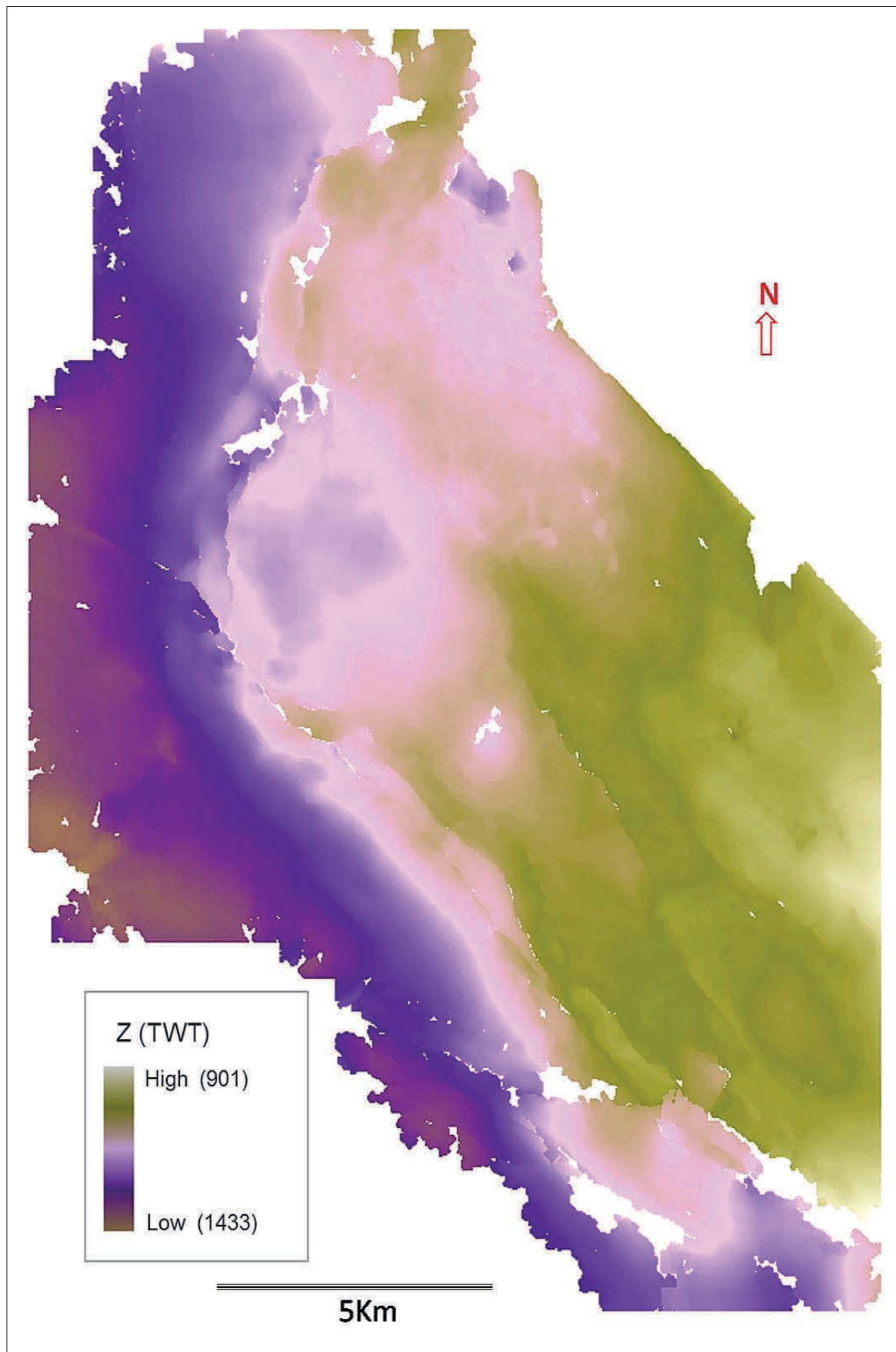


Figure 10. TWT map of the (automatically extracted) Laurel Formation.

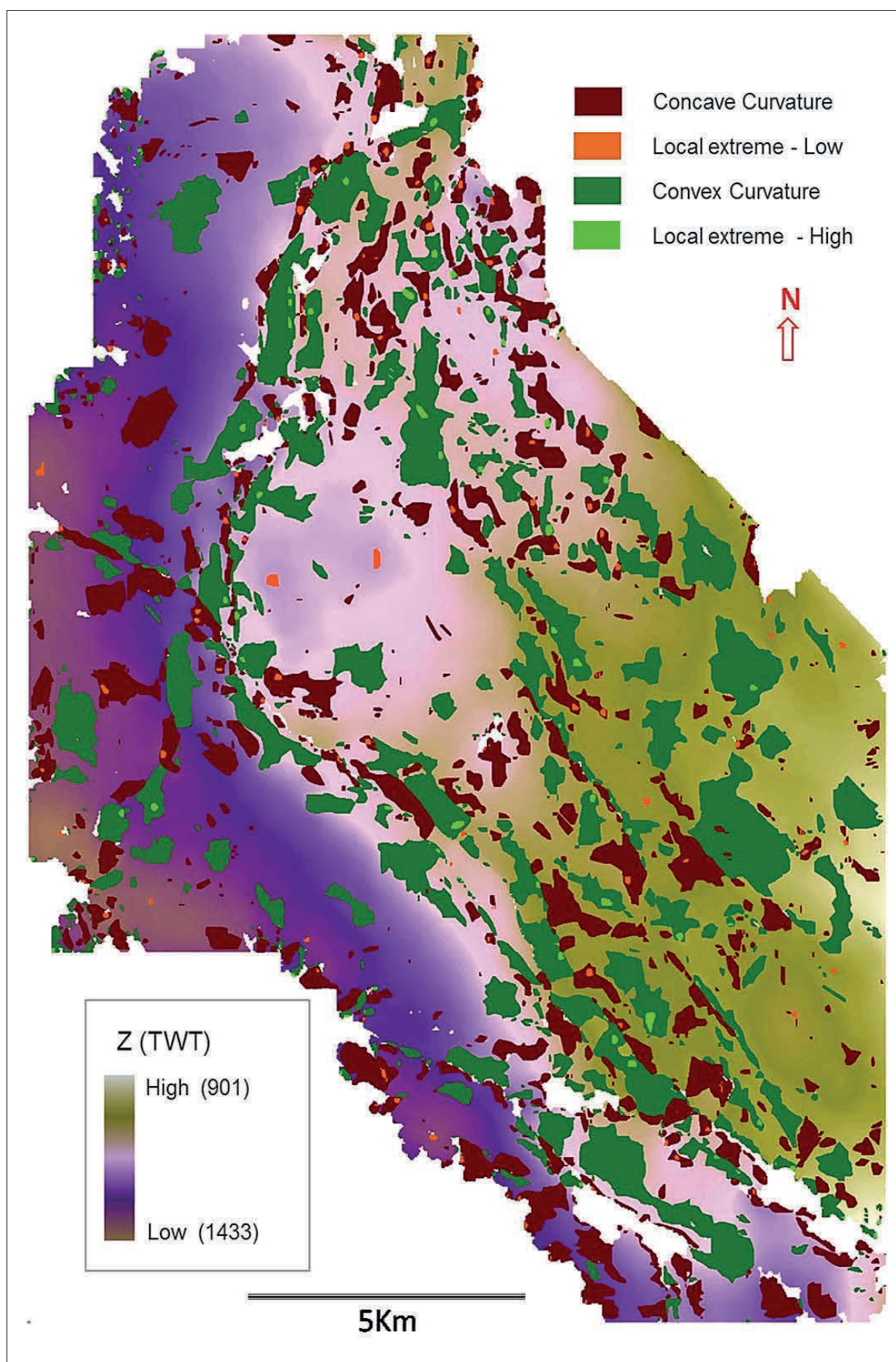


Figure 11. TWT map of Laurel Formation, with isolated curvature features highlighted. Convex (green), concave (red), curvature, extreme concave curvature (orange), and extreme convex curvature (lime green).

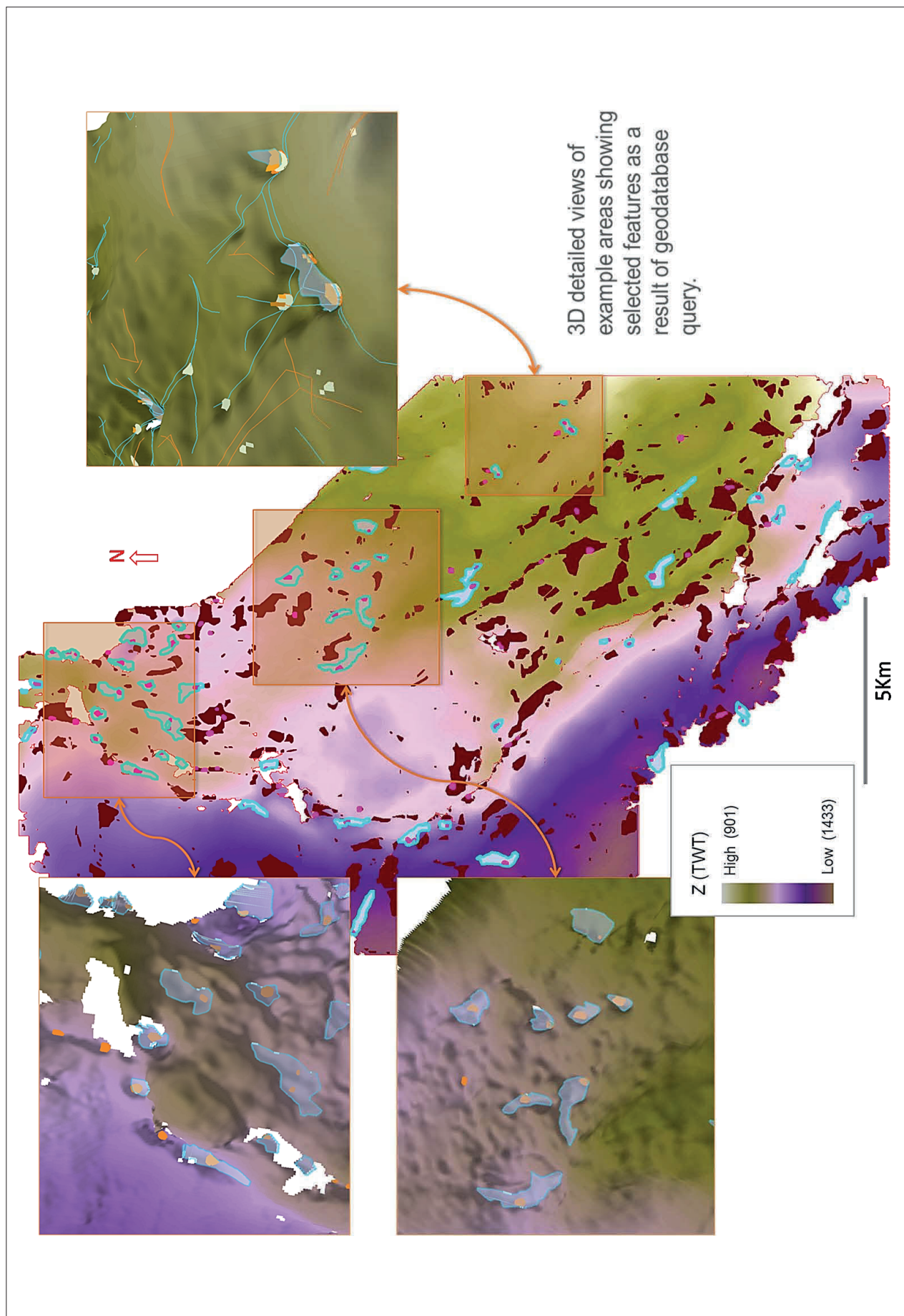


Figure 12. TWT map of Laurel Formation showing extracted concave objects and highlighting (blue polygons) the deepest features. The three zoom images demonstrate the how well the objects fit into the rendered surface.

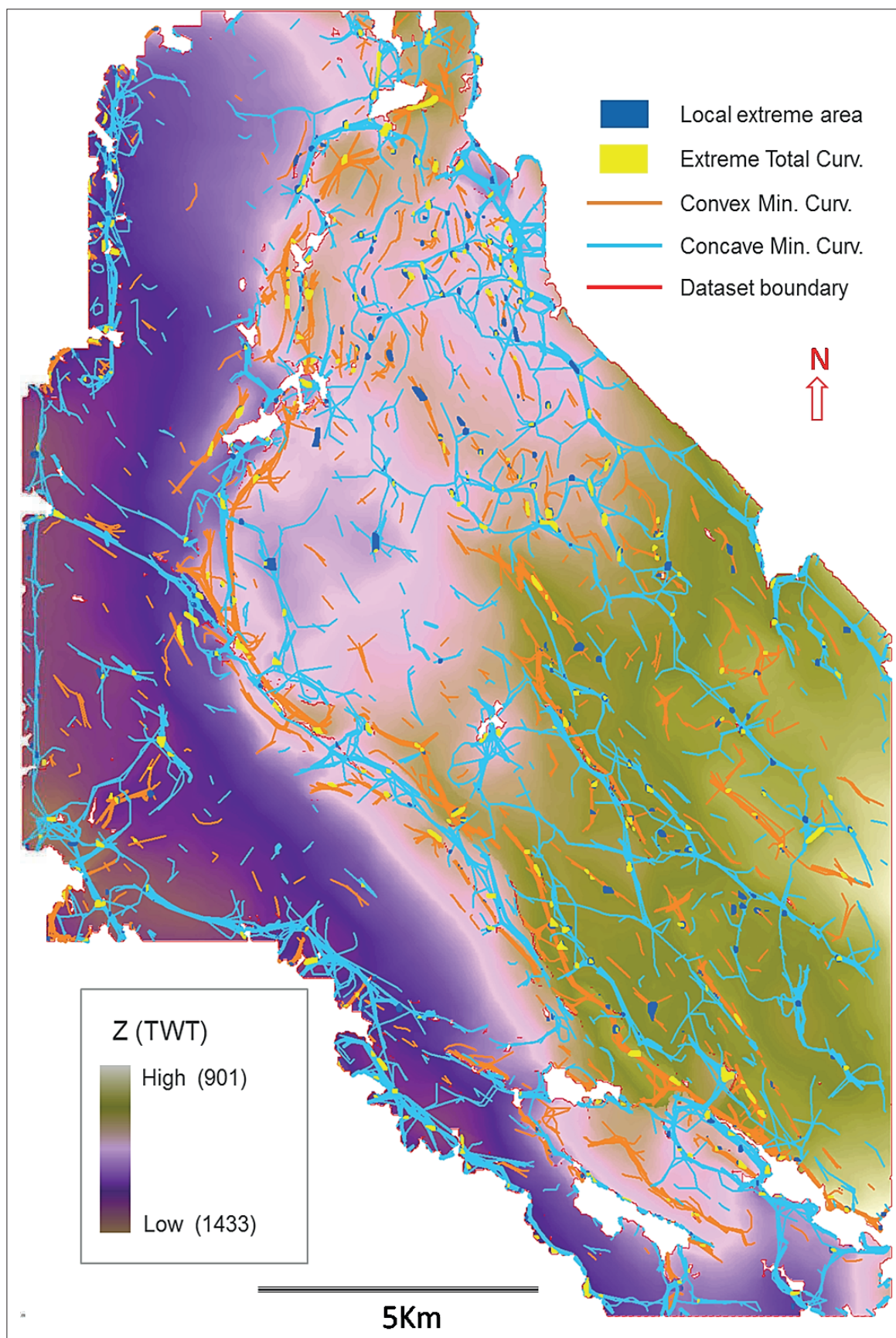


Figure 13. TWT map of Laurel Formation, overlaid with the results of automated vectorisations applied to several different realisations of curvature analysis. The blue and orange lines indicate localised synclinal and anticlinal trends. Parallel blue and orange lines indicate a fault. Also shown are areas of the largest values of Gaussian or total curvature.

surfaces/horizons, individually or in groups, can be subjected to high-resolution surface analysis to help quantitatively identify structural and stratigraphic morphology. While the examples shown focussed on zones which have historically revealed hydrocarbons in the form of either recovery, production and/or shows, the methodology also has application in processing QC, geohazard assessment as well as multi-volume or pre-stack analysis and attribute data mining. The benefits of the automated and objective methodology becomes even more apparent as the 3D seismic volume(s) area and density increases from hundreds to thousands or tens of thousands of square kilometres.

Conclusions

The analysis of the Bunda 3D presented here has built upon several decades of exploration work in developing opportunities in untested stratigraphic and structural plays on the Lennard Shelf. The 3D dataset offers continuous coverage of quality seismic data over an area containing more than twenty wells that include production from a number of different formations. The data provides an opportunity to develop a better understanding of the nature of reservoir, seal, structure and fluid flow and thereby identify additional economic opportunities within existing fields as well as new prospects.

The well control and seismic data demonstrate the highly variable nature of both reservoir and seal. Since there are a number of dry holes drilled on structural highs, the stratigraphic nature of the reservoir-seal pairs is of primary importance. The channelling, which is observed at many levels has a profound impact upon the effectiveness of seal and the development of reservoir, thief zones or seals. Channelling in the uppermost portion of the Grant Formation presents opportunity for both structurally enhanced stratigraphic trapping, and leakage into younger Poole Formation reservoirs, and challenges the effectiveness of the Top Grant Formation as a regional seal. Deeper into the Grant Formation, the channel banks associated with progressive stages of erosion and fill are noted locations for the accumulations of hydrocarbons. However, the high frequency variability in the seismic, inferred to reflect changes in the geology, still presents an interpretation and imaging challenge.

The deeper opportunities in the Laurel Formation inspired by recent success at Ungani has placed new focus on the exploration of dolomite reservoir plays, which require development of a model for fluid flow and fracturing at the reservoir level to explain both charge and reservoir diagenesis.

The application of automated and objective analysis offers a parallel, independent and complimentary workflow to the biased approach we traditionally apply as interpretative geoscientists. While we are employed for our experiential based bias, knowing when all the essential elements have been

extracted from a dataset and being confident that we have not missed something, is at times challenging, particularly as the size of datasets continues to increase dramatically. Having access to a visual database of surfaces and objects extracted using unbiased automated helps validate that sufficient efforts have been made to adequately capture the variability in the data volumes. Moreover, an interpretation based on pre-interpretation surfaces and features extracted from a 3D visual database will be easier to validate build upon by other interpreters looking at the same data. While the methodologies described are helping Buru Energy develop data-driven geomodels based upon a review of more data, we expect ongoing refinement of the process is required before the Canning Basin reveals all her secrets!

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Biographies



Jim 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 last 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. He has a proven track record with both small and large companies identifying, and applying, new and existing technology to improve corporate exploration/exploitation work flows.

He is currently involved in conventional petroleum exploration, Coal Seam Methane, Coal mining and airborne exploration projects which include aspects of prospect generation/appraisal/development, training, research and business development.

Aside from his activities with Total Depth Jim has helped with the commercialization and application of many new technologies. Recently, this has included the refinement of a patent of a new airborne geophysical technique; Seisnetics patented processing algorithm and establishing Geoproxima Pty Ltd. Jim is a member and past WA branch president of ASEG and has current memberships with SEG, PESA, AAPG, SEPM and EAGE.



Tony Rudge studied a Bachelor of Science at Monash University, where he majored in Earth Sciences and graduated with a B.Sc in 1997. Tony then went onto complete an M.Sc in reflection seismology at Monash University in 2001. After completing his M.Sc he then moved to Perth to take up a position of processing geophysicist with CGG Australia. He has also held positions as a metallurgist at Ammtec Ltd and Senior Geoscientist at Central Petroleum. He is currently the Senior Geophysicist at Buru Energy where he is responsible for seismic acquisition, processing and part of the interpretation team. He is also responsible for potential field acquisition and microseismic projects. His current research interests include extracting the most out of the geophysical data, passive seismic technology and airborne gravity gradiometry. He is a current member of the ASEG and PESA.



Ruiping Li graduated with a PhD in Geophysics from Curtin University of Technology in 2003. After 3 years working as a post doctorate for Curtin University and CO2CRC, she took a position as a Senior Geophysicist for RPS Energy and DownUnderGeoSolutions. She joined Total Depth Exploration Services at the beginning of 2010 and has worked on seismic data enhancement, well seismic calibration, seismic inversion, spectral hydrocarbon detection, and seismic interpretation for a variety of petroleum and coal exploration projects. Her major interests are in seismic inversion, seismic facies analysis, and seismic interpretation. She is also a member of SEG.



Alistair J. Stanley received his B.Sc. 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 Total Depth Pty Ltd. His work with Total Depth Pty Ltd has included the processing and interpretation of seismic data from a variety of sedimentary basins throughout Australia for both petroleum and coal exploration projects. He spends most of his time developing the pre-interpretation processing technology Seisnetics™ and has actively contributed to its application in both academic research projects and corporate workflows.