Seismic and Well Interpretation of Fluvial Clastic and Coal Packages for Stratigraphic Traps Within the Patchawarra Formation, Cooper Basin*

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Abstract

Several stratigraphic traps have been discovered within the Permian-aged Patchawarra Formation on the western flank of the Cooper Basin. These traps contain gas within fluvial sandstones deposited within a sequence of mixed clastic and coal beds. Selected seismic and well data, from an area containing 866 km^2 of 3D seismic and 27 wells, are used to show basic interpretation techniques to define existing and potential stratigraphic traps.

A practical correlation between seismic scale reflectivity and well log data allows the interpretation of two component packages within the Patchawarra Formation:

- Clastic packages comprised of fluvial channel, point bar and proximal crevasse splay sandstones and flood-plain muds that typically shows a high seismic acoustic impedance (“Hard”) response. The target reservoirs are contained within these packages as relatively discontinuous sandstones encased by mud facies and coals.
- Coal packages comprised of thick coals and coaly muds that are seismically characterised by relatively low acoustic impedance (“Soft”) responses. These sequences are interpreted to have been deposited as relatively continuous, topographically raised areas of peat-mire and organic rich muds with rare, thin clastic sequences.

Stratigraphic trap potential is interpreted where the defined thick coal packages are observed to split, and an example is outlined at outcrop scale. Seismic attribute maps are integrated with seismically derived package thicknesses; well log character, interpreted facies, and depth structure to define trap geometries.

The method described allows integration of well and seismic data in the search for stratigraphic trap geometries within fluvial and coal measure sequences.

Introduction

The Patchawarra Trough located on the western side of the Cooper Basin (Figure 1) has generated significant quantities of hydrocarbons, as demonstrated by its record of oil and gas production. The relatively high hydrocarbon liquids content in the area makes production commercially attractive. One of the primary exploration targets is the Early to Mid-Permian aged Patchawarra Formation, where the principal reservoirs are channel sandstones deposited within a fluvial clastic and coal sequence. Stratigraphic traps within channel sands dominate the successful wells in this area of the Cooper Basin. There have been 11 gas discoveries (tested gas/oil flow rates) to date in the immediate area, commonly with two or more separate pay zones. Coals and carbonaceous mudstones from within the lower Patchawarra Formation are interpreted to be the source rocks for the hydrocarbons.

Early seismic interpretation was mainly confined to producing depth maps. The initial obvious features were drilled and yielded sufficient success to encourage further exploration. This paper outlines a package mapping method on a subset (230 km^2) of the larger (866 km^2) 3D seismic area (Figure 1) as an example that indicates improved mapping definition in the search for increasingly subtle traps. The work to date suggests there is more potential to be discovered in the area.

Stratigraphy, Reservoir

Detailed well log correlations were used to establish seven seismic scale clastic intervals bounded by coal packages over a study area of at least 900 km^2 and including 27 wells. The Patchawarra Formation stratigraphic context is extensively documented (Gravestock et al., 1998, Lang et al., 2001) and labeling in this study (Figure 2) follows some earlier definitions of seismic packages in this area by Stanmore and Johnson 1988. The coal marker reflectors use “V” as shorthand for Patchawarra Formation and the lower case “s” stands for seismic package horizon. Numbers on the labels are considered to be local and specific to this study area. The clastic packages bounded by the coal packages are informally given the name of the well that is considered typical for the interval. Sparse palynology data supports the correlations, although on a coarser scale. The Canunda package falls within the palynology zone APP223 - Sakmarian stage of the Permian (Purcell, 2015).

Seismic Quality

The Irus 3D seismic data was acquired in 2012 and reprocessed in 2013 using Pre-Stack Time Migration. Acquisition parameters were designed to maximize data quality at the target depth of approximately 2500 m with long offset 4.8 km and wide azimuth. The Irus 3D survey was processed with overlapping surveys resulting in a total area of 866 km^2. The bin size is 20 m^2 with fold at target level greater than 100 after interpolation. The predominant frequency in the Patchawarra in the full stack volume is 35-40 Hz, but decreases with depth through the Patchawarra. The dataset has been processed to zero-phase (symmetrical wavelet) and displayed according to Australia/U.K. North Sea convention (Simm and White, 2002). On the seismic displays a downward decrease in acoustic impedance across an interface (e.g. top of coal) is a “soft” loop (blue, positive amplitude, peak). The corresponding increase in acoustic impedance (e.g. top of a clastic package/base coal) is a “hard” loop and displayed as (red, negative amplitude, trough).

The biggest hurdle to seismic stratigraphic interpretation within the Patchawarra coal measures sequence is that the relatively thin, discontinuous fluvial sandstone bodies are imbedded within variably thick clastic packages that are inter-bedded with more continuous coal packages. Individual sand bodies of typically 5 m thick channel sandstones are seismically not resolved from either the harder response of the intervening clastic package or the large soft response associated with the adjacent coal packages.

This reflectivity series, combined with the seismic frequency, tuning and coal related peg-leg multiples, compromised historical efforts to better define distinct sedimentary intervals within the seismic and so prompting an alternative interpretation approach.

Interpretation: Concept, Method, and Results

Concept

Since the Cooper Basin is not exposed at the surface for outcrop study, analogies to better understand the geometries within the Permian coal measures system must be sourced elsewhere. The present day Siberian Ob region in Russia seems to be a reasonable analogy in terms of extent, depositional lithologies, and relative to palaeo-latitude (Strong et al., 2002; Lang 2014). In Australia are outcrops and mines in equivalent Permian coal measures systems (Figure 1) to inspect and study the depositional form of potential seismic-scale stratigraphic traps. These Permian outcrops have the added benefit of displaying burial compaction effects that closely represent the subsurface effects observed in the Cooper Basin. Relevant examples from the Bowen Basin, shown in Esterle 2010 and summarized in Gravestock 1998, demonstrate that thick coals and their associated fine-grained clastics are the primary continuous packages and markers on a scale appropriate to the vertical and areal extent of the seismic data in the study area. In addition, examples from the analogs of coal seam splits were on a scale that should be observable within the seismic data. These splits frame potential stratigraphic traps of clastic wedges that contain sandstone bodies of more irregular geometry not directly resolved by seismic. Synthetic seismograms derived from well logs in the study area reveal that the main reflectivity observed within the Permian section is at the top and base of the coal package response (Figure 2, Figure 3, and Figure 4).

Well Correlation

This study has used well correlations matched to broad character mapping of seismic scale packages. The method is built upon seismic stratigraphic examples and concepts promoted by earlier workers in this area (Stanmore and Johnson 1988; Lang et al., 2001).

Well-to-well coal correlation was assisted by high gamma ray spikes in some areas, intra-coal character, and a technique of flattening on the main coals to visualize the correlations. An example final correlation result is shown in Figure 3 for the Canunda package demonstrating typical coal packages split by a clastic wedge that is resolved by seismic.

Interpretation, Seismic Pick, and Character

Auto-tracking seismic pick techniques are problematic within the Patchawarra because of the splitting coal geometries; therefore line-by-line horizon picking was required in some areas. This was beneficial as seismic stratigraphic character was noted such as onlap, downlap, and truncation. Compaction and loading effects are known from coal exploration literature (Thomas 2012). Commonly the coal packages in the study area exhibit seismic tuning (thinning/brightening and dimming) effects and can appear as broad diffuse doublet blue loops. The clastic packages show similar effects, although as red "hard" loops. Where the coal packages split, a clastic package was resolved as a "hard" red amplitude loop (e.g. the Canunda package). Around the Canunda wells, the mapped coal surfaces give the appearance of compaction drape over the encased clastic package. This is particularly evident in image maps such as shown in Figure 5.

Interpretation, Packages, Structure, Thickness, and Amplitudes

The first step to visualize the thickness and amplitudes of the packages was to extract the seismic amplitude (minimum amplitude values) from the interval defined between two coal surfaces. The amplitude was calculated as an average of individual amplitude extractions from six seismic volumes (near, mid, and four azimuthal stacks) that reduces the noise from individual seismic volume extractions. The clastic (hard seismic response) and coal dominated (soft) thickness areas were visualized by multiplication of the package isochron by the average amplitude. The result is an enhanced image that includes seismic tuning effects. The map reveals the edges of sinuous clastic packages and channel belt features as inferred from well control (Figure 5).

Interpretation: Results

Reservoir engineering interpretation of test and production data from several wells in the area suggests each reservoir is characterized as a narrow body with nearby no-flow boundaries but an undefined orientation. The seismically derived maps indicate edges and packages that form distinct orientations and a sinuous and ribbon-like geometry, as demonstrated in the Canunda package map (Figure 5 and Figure 6). A channel belt orientation in a strike direction relative to structural dip would offer a seismically interpreted different stratigraphic trap risk than a channel belt that is aligned with the dip.

The Canunda wells are located in a wide channel complex trending east and curving north that seems composed of a series of narrower belts. Trending to the northeast of Canunda is a thinner looped individual channel belt (100 m wide) with potential splays that is partially overlapped by another and seems to extend for some 20 km to the north. Eight kilometres northwest of Canunda is an indication of a thin but higher frequency-looping channel with an east-west trend (Figure 6).

One can speculate a channel belt model whereby a series of sand channels (Donselaar and Overeem 2008; Ghazi and Mountney 2009) within the clastic packages cut into, or across each other, in a sinuous or twisted rope-like fashion along the channel belt and create in some portions a vertical stack of sands. Such sand stacks, after differential compaction would generate in the overlying coal package a sinuous set of compaction mounds that could be interpreted using the seismic (Figure 7). In addition, areas that are mainly coal prospective with minor clastic floodplain deposits (soft seismic responses) can be outlined.

Overall, the maps give the impression of a network of loops and curving features with variable fills of soft and hard seismic response packages, with shapes rather like present day satellite images of fluvial clastic and peat systems (Smith and Alsdorf 1998). The amplitude and package thickness attributes were draped on a depth structure map and matched with Canunda package well log signatures to interpret channel belt orientation and limits around the Canunda discovery (Figure 7). It is expected that these techniques can be applied to other package intervals to better predict the location and orientation of potential channel belt traps.

An important component of interpretation was to integrate the engineering information such as pressure test data and particularly Extended Production Test (EPT) results that all contributed to define column height, boundaries, drainage area, and trap size. This proved useful in the Canunda Field where estimates of volume derived from the geological and geophysical methods matched ranges from the EPT material balance methods, and thereby gave some confidence to the seismic package mapping.

Summary

The technique of seismic package mapping has been a practical and useful method of scoping volumetric potential within this coal measures sequence. In general, the well control to date supports the interpreted seismic based facies maps and the stratigraphic trap geometry for the Canunda package.

The Canunda package is one of the clearer examples of the seismic scale prediction of facies in this area. Not all packages have character as well defined as this interpretation, probably due to additional splitting of the main coal markers in the other packages resulting in several seismic waveforms. Finer picking of intervening coal packages is required and would benefit from higher specification seismic. Additional interpretation and visualization techniques such as picking on the near offset, blended frequency decomposition or weighted average volumes are work in progress.

Conclusions

Seismic scale interpretation of packages shows promise in better definition and thereby prediction of:

- Areas of coal-dominated facies and clastic dominated facies
- Orientation of likely channel belts away from well control
- Depth to main coal packages
- Thickness of mappable packages
- Location of potential stratigraphic trap edges

Accurate predictions, at specific well proposal locations, remain problematic for:

- Net sand thickness
- Depth to top reservoir within a clastic package
- Hydrocarbon charge

Future Considerations

It seems likely that increased study of the coalmine outcrops such as those in the Bowen Basin and other Australian coal workings (Martin and Morris 2013) will provide a rich source of analogue material to not only understand the coals but also the details of packages containing potential reservoir sands and how they relate to seismic scale stratigraphic trap mapping (e.g. Donselaar and Overeem 2008). Studies based on the published material and new work on measured digital sections could be very useful and could include, for example, synthetic seismic models (Gochioco 1992), synthetic image log interpretation and net/gross models.

The package mapping approach would seem to have wider application to other areas and basins that have similar fluvial clastic and coal systems. Further refinement of the seismic scale packages with well sequence stratigraphy and details from the image logs may also be a benefit to mapping. Resolving the problem of high frequency well ties in the realm of thin bed tuning and coal peg-leg multiples remains elusive and requires considerable industry effort to solve. The aim of the effort would be to deliver higher frequency attribute mapping that can match the more refined well log data. Ultimately, direct detection of gas charge in the relatively low acoustic impedance channel sands would be a stretch objective.

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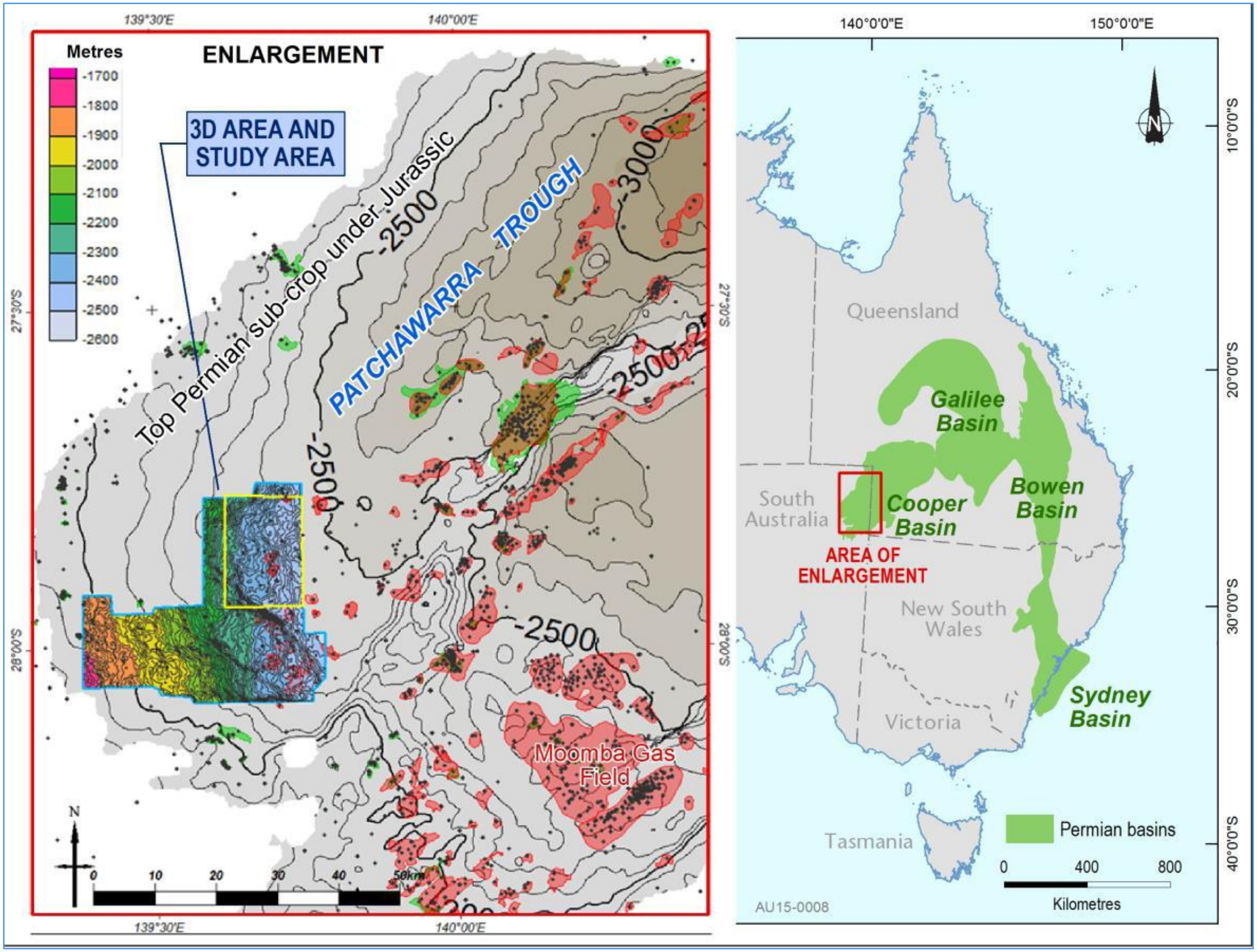

Figure 1. Basin-wide Top Permian (Base Jurassic Unconformity merged) depth structure map in metres from open file Department of State Development (DSD). A large northeast trending ridge in the middle separates the Patchawarra Trough from the rest of the Cooper Basin. The area (230 km^2) discussed is highlighted in a yellow rectangle. The colour inserted map and legend is based on the Irus 3D seismic mapping (866 km^2). The map is Top Murteree Shale (Artinskian age) depth that is the deepest Permian auto-track seismic horizon in the study area. (Continued on next slide)

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This is merged with Base Jurassic unconformity from the 3D mapping in the west. This structure map reveals subtle northwest trending flexures intersected by westerly basement trends. The colour bands across the flexure panels show the structural dip to the southeast and east. Wells are small dots and gas fields in red and oil in light green. The large-scale map locates Permian basins in Eastern Australia and Bowen and Sydney basins with outcrop examples.

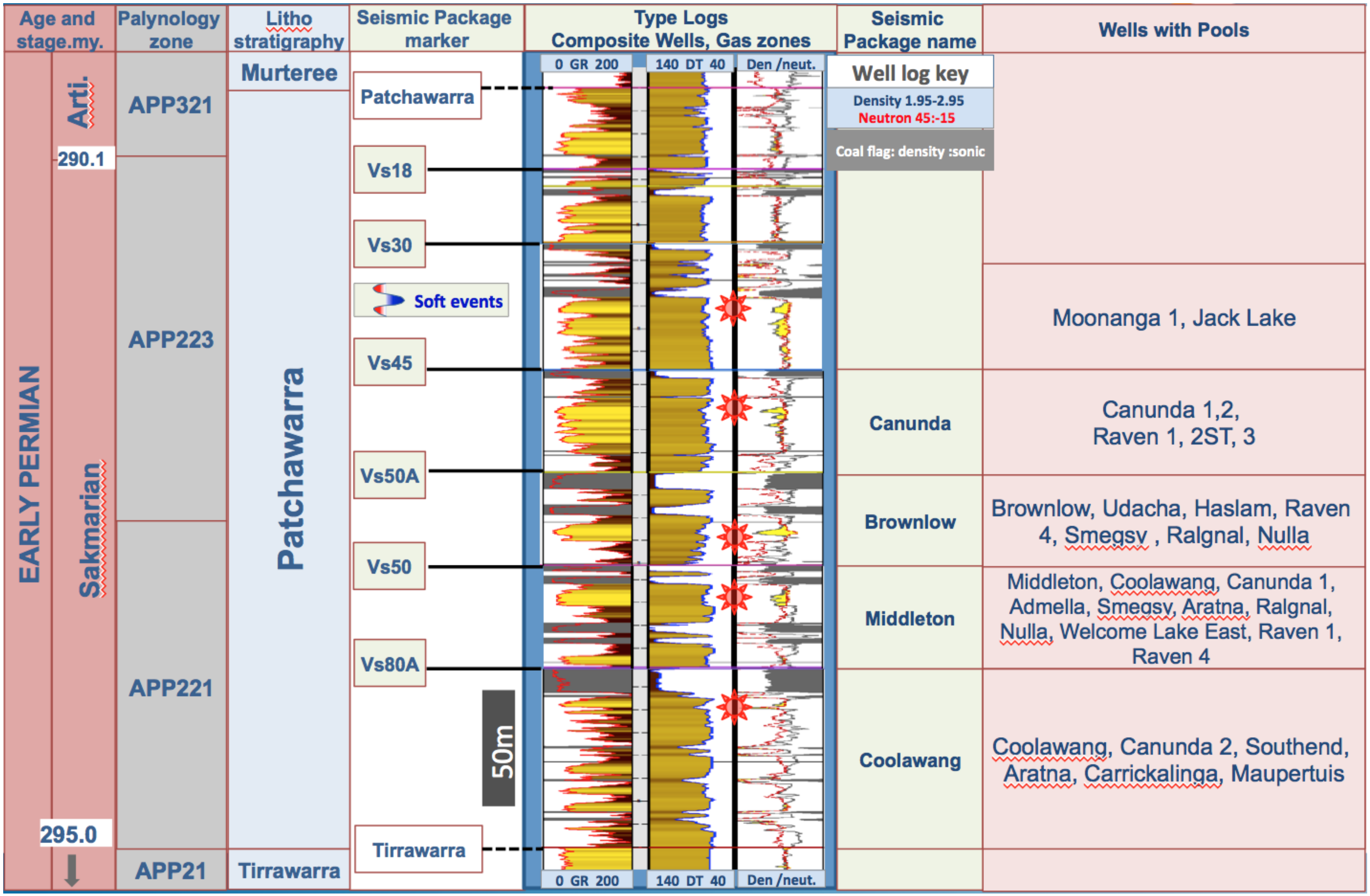

Figure 2. Patchawarra Formation stratigraphic column for the study area, key seismic marker labels and package terminology, gas pool zones. Standard gamma ray, sonic, density, and neutron logs for type wells, concatenated to form a composite as a guide. The ages from the 2015 Chronostratigraphic chart (Cohen 2013; updated) and the palynology is from Purcell 2015.

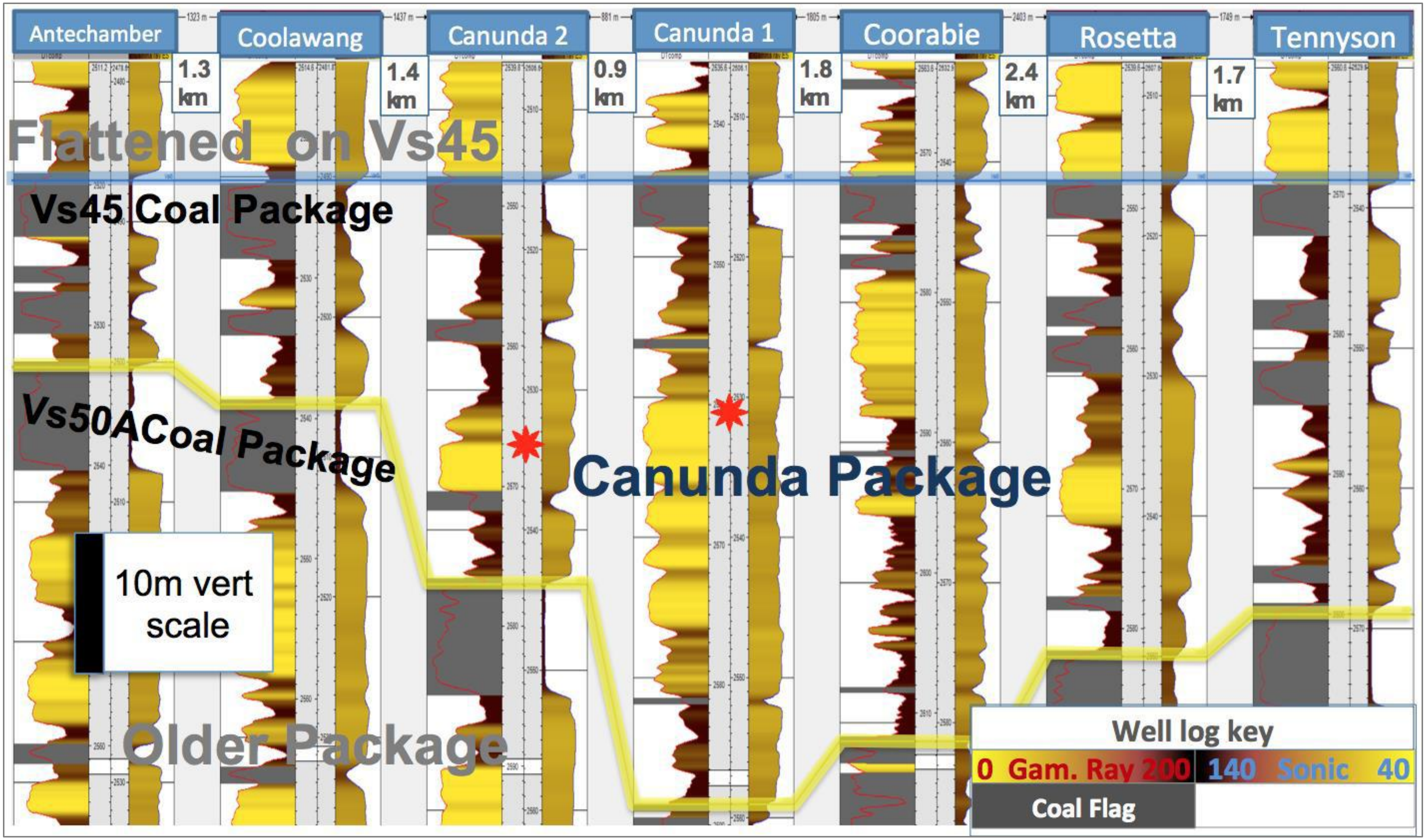

Figure 3. Section from north to south of the Canunda seismic package flattened on Vs45 Coal. Well log key applies to all figures. Red stars indicate gas zones. Thin coals within the clastic package are likely to be radioactive carbonaceous muds or high ash coal and may merge between wells with main coals.

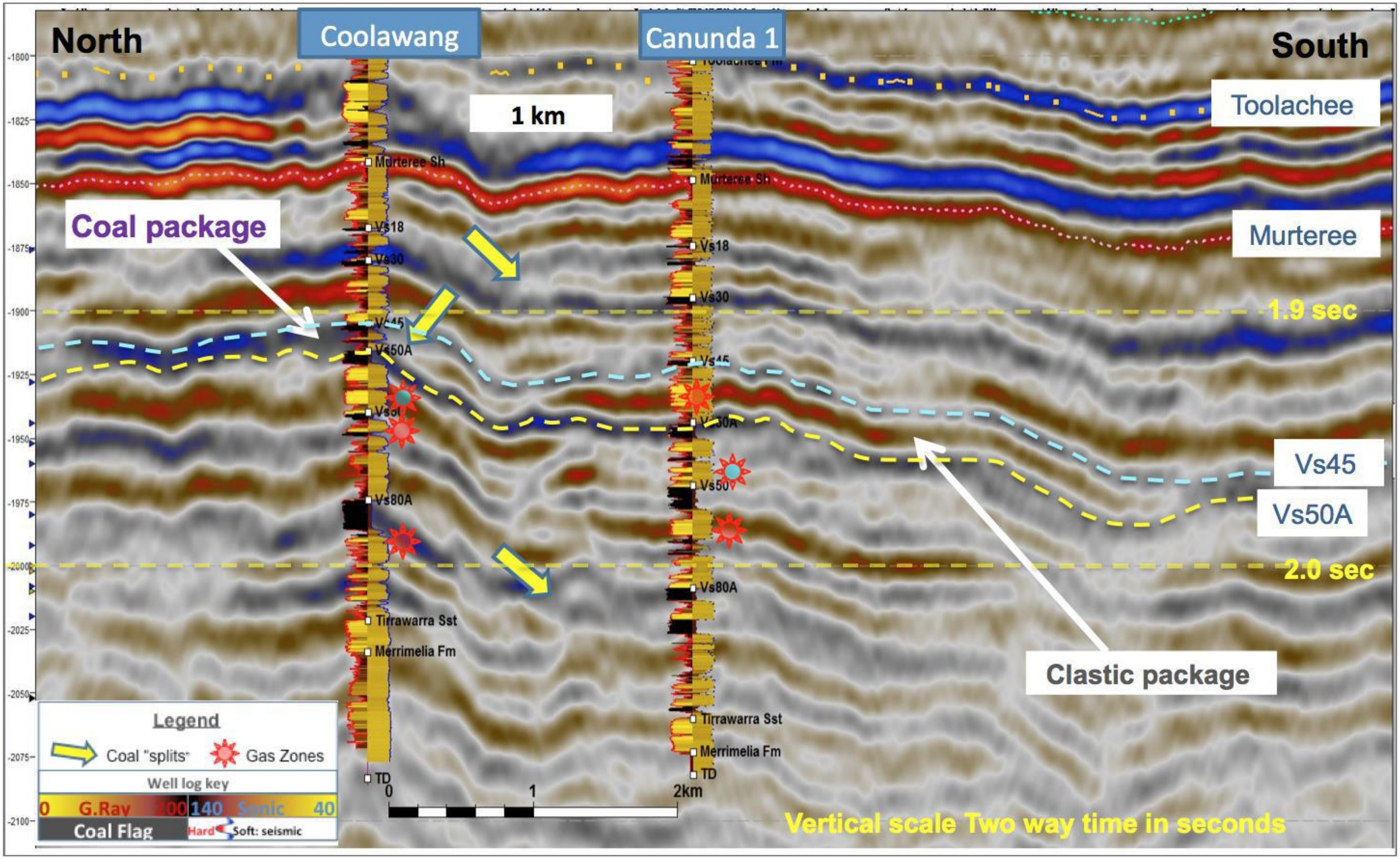

Figure 4. Full stack seismic line showing typical seismic response of coal/clastic splits. Some seismic stratigraphic character is shown such as onlap, downlap, and truncation. The Canunda package is highlighted with the coal and clastic character packages.

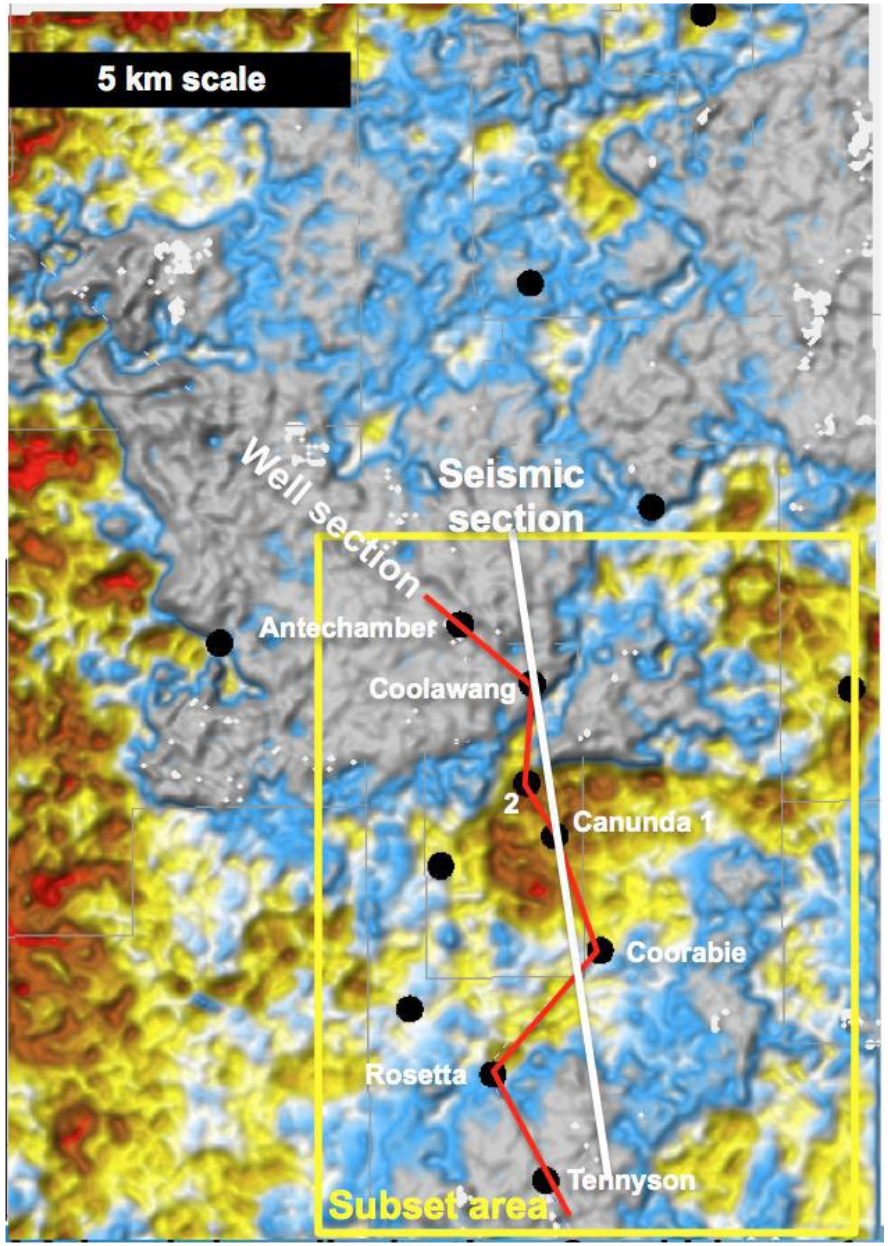

Figure 5. Image map on the Canunda package two-way time thickness (isochron) on a 50 m grid. Colour drape is from isochron multiplied by the average of near, mid, and, four azimuthal volumes and the extracted minimum amplitude. Warmest colours are largest hard (clastic package) amplitudes and the grey is the soft amplitude (coal dominated) seismic response. Blue colours are faint and thin, hard (clastic) amplitudes. Well locations as black dots. The subset area in yellow is an area with additional detail in the Figure 7.

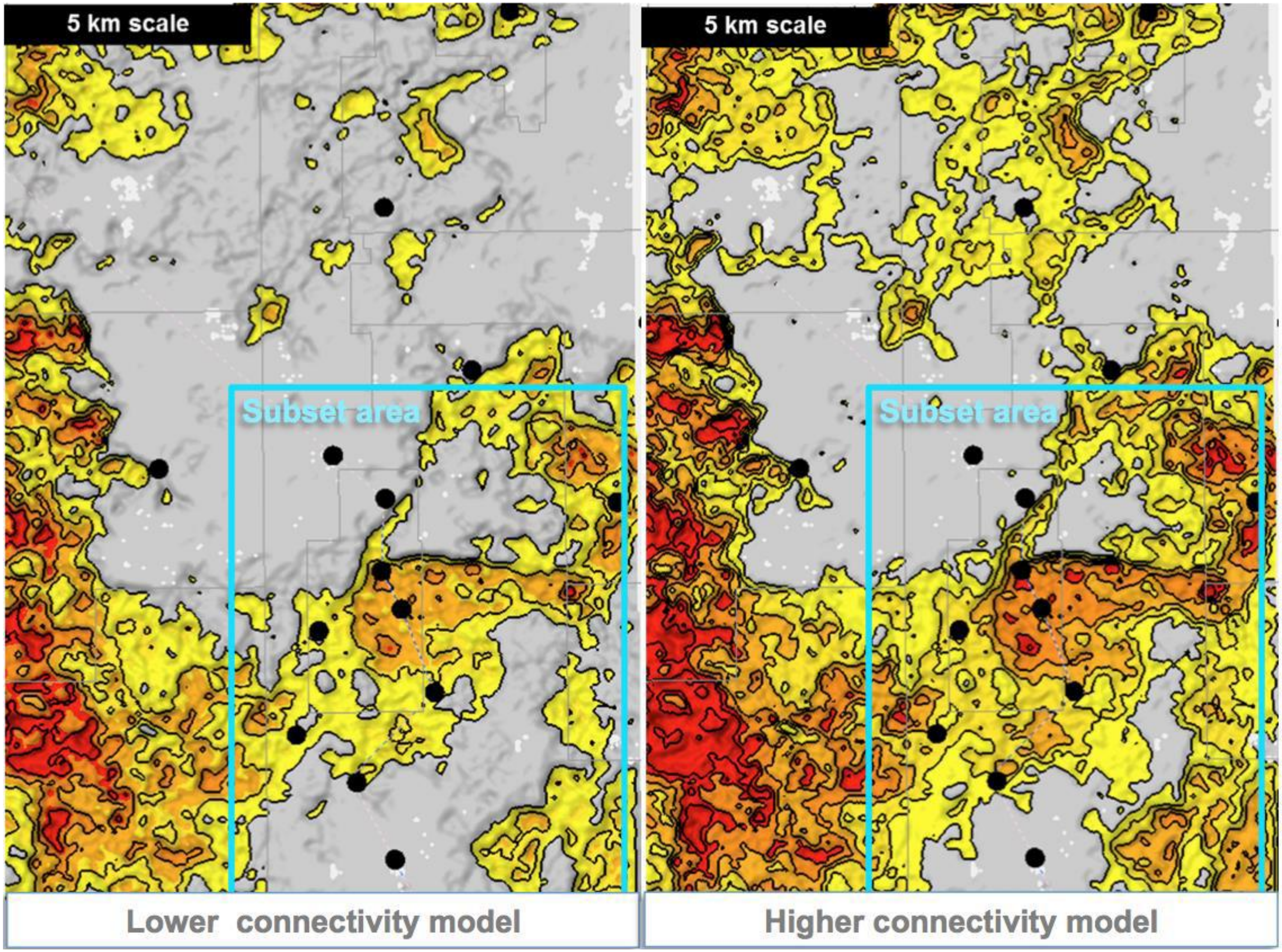

Figure 6. Isochron (thickness) multiplied by amplitude and block coloured drape to demonstrate two possible qualitative models for sand content of the clastic packages. Warmest colours are thick and grey the coal-dominated facies. Based on concept of Donselaar and Overeem 2008, scaled up to channel belt dimensions. Potential clastic/channel belts of different widths show several orientations and sinuous character that stretches over at least 20 km.

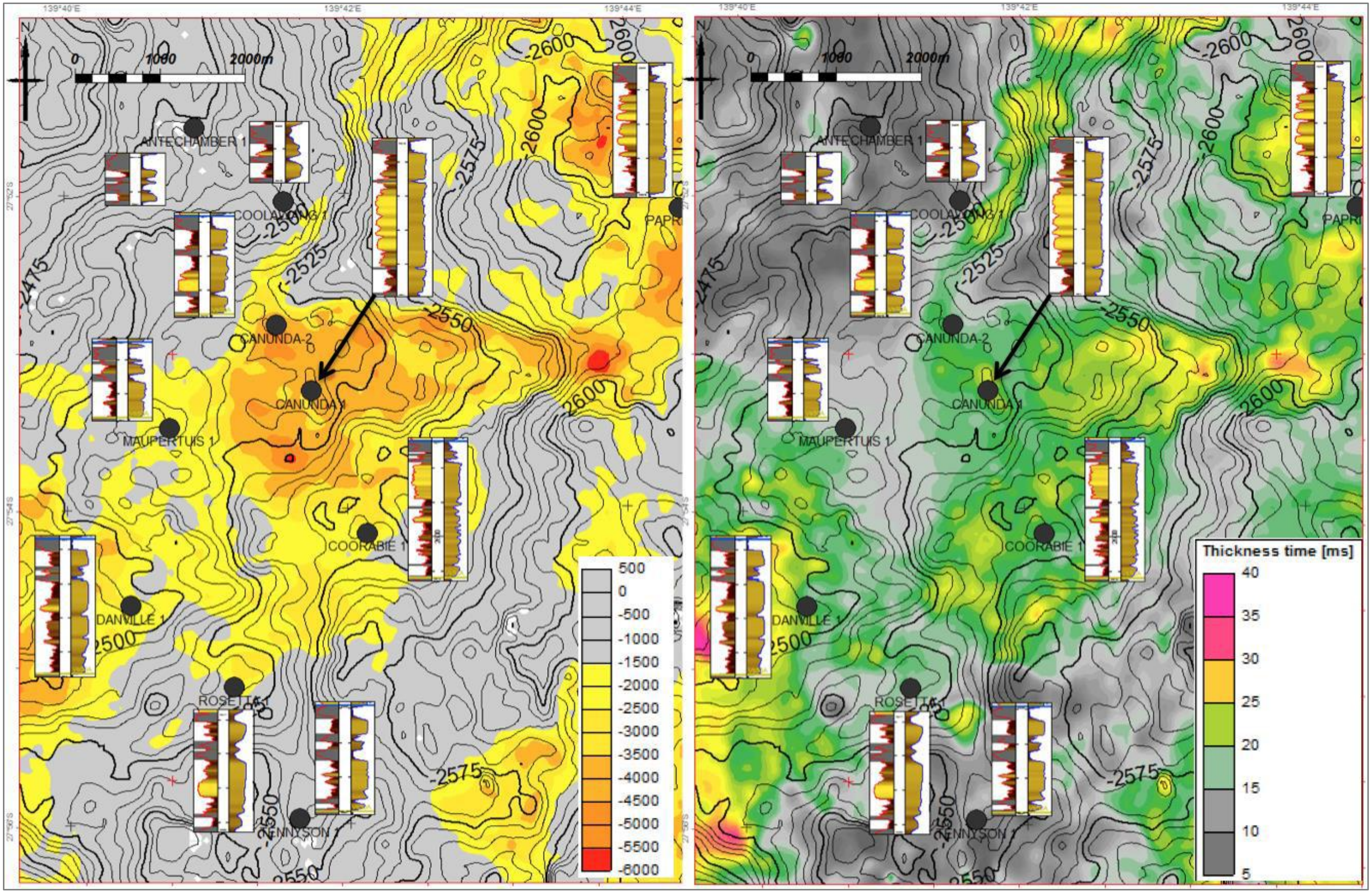

Figure 7. Canunda trap visualization using attributes draped on Vs45 depth structure contour map. The map on the left uses amplitude multiplied by the two-way time thickness as an attribute and colour draped on the depth map. Warm colours are clastic package attribute with a low connectivity channel/clastic belt model. Some seismic frequency tuning effects on the amplitude are suggested by comparing to the map on the right, which has a package isochron block coloured and draped on the depth map. The grey shades are thinner areas that are unlikely to contain thick channel sands. Package well log signatures qualitatively support the seismic interpretation of the facies and potential channel belt edges and orientations.