UNIVERSITY OF INDONESIA

COAL SEAM GAS IDENTIFICATION USING ACOUSTIC IMPEDANCE INVERSION IN SPINEL FIELD, COOPER – EROMANGA BASIN, SOUTH AUSTRALIA

UNDERGRADUATE THESIS

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DEPARTMENT OF PHYSICS
FACULTY OF MATHEMATICS AND NATURAL SCIENCE
UNIVERSITY OF INDONESIA
DEPOK
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DECEMBER 2011

HALAMAN PERNYATAAN ORISINALITAS

Skripsi ini adalah hasil karya saya sendiri,

dan semua sumber baik yang dikutip maupun yang dirujuk

telah saya nyatakan dengan benar.

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Has been successfully defended before the Board of Examiners and declared acceptable as a partial fulfillment of the requirements for the Degree of Bachelor of Science in Physics at Department of Physics, Faculty of Mathematics and Natural Sciences, University of Indonesia.

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Don’t Compete With Rivals,

Make Them Irrelevant.

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I thank God the Almighty who has given me the ability to finish this undergraduate thesis entitled "Coal Seam Gas Identification Using Acoustic Impedance Inversion in Spinel Field, Cooper – Eromanga Basin, South Australia".

This thesis has been written in partial fulfillment for the degree of Bachelor of Science in major subject Geophysics, Department of Physics, Faculty of Mathematics and Natural Science, University of Indonesia.

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Depok, December 2011

The Author

HALAMAN PERNYATAAN PERSETUJUAN PUBLIKASI TUGAS AKHIR UNTUK KEPENTINGAN AKADEMIS

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(Anita Hastari)

ABSTRACT

Name : Anita Hastari
Major Subject : Geophysics
Topic : Coal Seam Gas Identification Using Acoustic Impedance Inversion in Spinel Field, Cooper – Eromanga Basin, South Australia

The 3D post-stack data of Spinel Field were inverted to estimate the acoustic impedance of the Patchawarra Coal Seam Gas zones. The theory of model-based inversion is reviewed as the only method that had been used in this research in order to identify the Coal Seam Gas zones. The model-based inversion result shows that the thickest zone of Patchawarra Coal Seam Gas could be identified. While the band-limited nature of the seismic data and the resulting inversion does not resolve each sub-zone of the Patchawarra Coal Seam Gas, the parameter estimation appears to be quite reliable. The inversion result gave the higher acoustic impedance compares to the computed impedance in log data which shows 3000 – 4000 (m/s)(g/cc). The inversion result shows the low acoustic impedance anomaly (6000 – 7000 (m/s)(g/cc)), which is associated with reservoir. The low impedance anomaly allocated around Udacha and Middleton wells in the west to south of the research area, while the continuity of the thickest Coal Seam Gas disappeared around the Tennyson well. The interpreted northwest – southeast anticlinal faulted structures might affect the continuity of the thickest Coal Seam Gas indirectly, such as eroded surface caused by that fault plane.

Keywords : Coal Seam Gas, model-based, inversion, acoustic impedance, anomaly
xviii + 84 pages ; 40 figures; 1 tables
References : 11 (1991 – 2009)

ABSTRAK

Nama : Anita Hastari
Program Studi : Geophysics
Judul : Identifikasi *Coal Seam Gas* Menggunakan Inversi Impedansi Akustik Pada Lapangan Spinel, Cekungan Cooper – Eromanga, Australia Selatan

Data 3D *post-stack* Lapangan Spinel diinversikan dengan tujuan mengestimasi nilai impedansi akustik pada zona Patchawarra *Coal Seam Gas*. Teori mengenai inversi model-based dianalisa sebagai satu-satunya metode yang digunakan dalam penelitian ini dengan maksud mengidentifikasi keberadaan dan kemenerusan zona *Coal Seam Gas*. Hasil dari inversi model-based menunjukkan bahwa zona Patchawarra *Coal Seam Gas* yang paling tebal dapat diidentifikasi. Meskipun terdapat sifat band-limited dari data seismik yang digunakan dan juga hasil inversi yang tidak mampu mengidentifikasi tiap-tiap sub-zona dari Pathcawarra *Coal Seam Gas*, estimasi parameter tersebut dapat cukup meyakinkan. Impedansi akustik hasil inversi menunjukkan nilai yang lebih tinggi dibandingkan dengan impedansi akustik hasil perhitungan data log yang menunjukkan 3000 – 4000 (m/s)(g/cc). Hasil inversi menunjukkan bahwa anomali impedansi akustik yang sangat rendah (6000 – 7000) (m/s)(g/cc) yang mana hal ini menunjukkan keberadaan reservoir. Anomali impedansi akustik ini terpusat pada sekitar sumur Udacha dan Middleton di barat sampai selatan dari daerah penelitian. Sementara itu kontinuitas dari *Coal Seam Gas* yang paling tebal ini mulai tak terlihat pada seikitar sumur Tennyson. Struktur *anticlinal faulted* pada barat laut – tenggara diinterpretasikan dapat mempengaruhi kontinuitas *Coal Seam Gas* yang paling tebal ini meskipun secara tidak langsung, misalnya keberadaan bidang patahan yang kemudian menyebabkan erosi permukaan.

Kata Kunci : *Coal Seam Gas*, *model-based*, inversi, impedansi akustik, anomali
xviii + 84 halaman ; 40 gambar; 1 tabel
Referensi : 11 (1991 – 2009)

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CHAPTER 1
INTRODUCTION

1.1 Background

Today's hydrocarbon exploration is not as easy as the same exploration several decades ago. It is caused by the easy-to-find hydrocarbon reservoir and conventional energy resources are no more available or at least its productivity has been declined. Meanwhile, demands for hydrocarbon or fossil energy increase exponentially day by day. In order to fulfill those demands, exploration must expand to found the more-difficult-to-find hydrocarbon reservoir, develop the preceding reservoir, or explore the unconventional energy resources, in such a way that more reliable reservoir characterization also along needed.

Laterally, Coal Seam Gas (CSG), or as known as Coal Bed Methane (CBM), becomes one of the alternatives hydrocarbon energy. CSG is one of the highest quality and cleanest forms of thermal energy in the world, typically comprising less than 2 % CO_2 and about 95 % methane. Because of this, it produces less greenhouse gas emissions than conventional natural gas, which can contain up to 50 % CO_2 when brought to the surface. CSG's significant potential is being recognized around the world – it already provides 15 % of the USA's gas supply and close to 90 % in Queensland, Australia.

Although the coal thicknesses are relatively thin compare to rocks formation around, CSG could be easily identified in seismic data because of its physical properties which give the strong acoustic impedance response. But it does not means that reservoir characterization by using advanced seismic interpretation no more needed. This reservoir characterization is still needed.

Reservoir characterization plays a crucial role in modern reservoir management because it optimizes integration of multi-disciplinary data and knowledge and so do the reliability of the reservoir predictions. It will bring us to a more realistic tolerance for the reservoir model uncertainty which helps reservoir management decisions to be taken and improves the asset of the exploration companies.

Many challenges popped out when facing the characterization of reservoirs with substantial heterogeneity and fracturing, or when meet research area with poor data quality, limited well control, and seismic coverage.

One of the solutions is finding some kind of relationship between reservoir properties and seismic data which then use to predict the distribution of reservoir parameters in the zone of interest. In another words, we attempt to do the model based approaches in order to build detailed reservoir models. Thus, a number of methods are needed to integrate data sources. Therefore, the important data source beside well log data is seismic data.

Seismic data which had been processed and ready to interpret is used. Seismic trace itself has several parameters which different one to each others, it known as seismic attribute. Analyzing seismic attribute allows us to get some qualitative information of subsurface geometry and physical properties. For example, amplitude is an important factor in determining physical properties, such as acoustic impedance, reflection coefficient, velocity, etc.

Seismic data and well log data are the main data which always used both in exploration and development of oil and gas field. Seismic data has good horizontal resolution but poor in vertical. However, well log data has very good vertical resolution but very poor in horizontal. Integrating seismic data and well log data will give the better 3D interpretation as the result. One of geophysical methods which might integrate seismic to well log data is acoustic impedance (AI) inversion.

Basically, acoustic impedance inversion allows us in getting the information about physical properties of reservoir and fluid indication directly from seismic data and well log data. This is an inverse geological approach which will show geological subsurface and enables us to identify the character and distribution of reservoir.

In exploring CSG, knowledge of the distribution of the acoustic impedance properties of the target zone and rocks formation surround is essential for the prevention of unexpected rock failures that can disrupt production and jeopardize exploration safety. Thing that must be remembered in exploring CSG is: the coal seams distribution might not continue in the whole basin, although mostly relatively continues. It is not always appears as the thick coal seams but possibly sandwiched with the surround rocks, and gas shows only phenomenon is still possible to happen. Model based acoustic impedance inversion integrates borehole and seismic information to allow assessment of the porosity properties.

Coal measures in South Australia itself are primarily of Permian, Triassic, Jurassic, and Tertiary age. Almost all known deposits have been evaluated for coal extraction potential, but not for Coal Seam Gas potential. Nowadays, CSG is an important source of gas in eastern Australia, especially Queensland, and its potential is now being explored in South Australia.

This research focused on Permian Coal Seam Gas in Patchawarra FM of Spinel Field, Cooper – Eromanga Basin, South Australia. By using model based acoustic impedance inversion, it might give the more reliable coal seam gas distribution map. Thereby, the coal seam gas distribution could be better predicted and allows the new prospect zone to be identified.

1.2 Objectives

This research has some objectives to reach to, those are:

1. Characterizing the Coal Seam Gas of Spinel Field, Cooper – Eromanga Basin, South Australia by predicting its acoustic impedance using model based acoustic impedance inversion to 3D seismic data with well log as controlled tools.
2. Creating the distribution map of coal seams gas zone which will strength the identification of coal seam gas continuity. So it could give more help in determining prospect area even drilling the more reliable well location.
3. In partially fulfillment of the requirements for the degree of Bachelor of Science, Department of Physics, Faculty of Mathematics & Natural Sciences, University of Indonesia.

1.3 Problem Limitation

This research focused on:

1. Research area limited to Spinel Field, Patchawarra Trough, Cooper – Eromanga Basins, South Australia.
2. The target zone to be identified is the Coal Seam Gas package, not the single layer of Coal Seam Gas.
3. Using 3D seismic data in zero phase, post-stack time migration data, along with 3 complete wells within the research area.
4. Coal Seam Gas identification focused by using model based acoustic impedance inversion.

1.4 Research Methodology

In order to reach those objectives with fine-quality result as expected, this research will follow these steps:

1. ***Problem identification and determining research objectives***
2. ***Literature Review***

   Comprise to reference books reading, related papers/publication, and software review.
3. ***Data Preparation***

   This is the basic 3D seismic data and well log interpretation which are comprise to basic rock physics analysis, well to seismic tie, structure picking, and horizon picking.
4. ***Data Processing***

   It will include creating the initial model which will be used in the whole research. Then model-based AI inversion could be performed.
5. ***Creating Acoustic Impedance Distribution Map***
6. ***Interpretation***

   Finding Coal Seam Gas zone which indicated by low acoustic impedance zone and determining effective drilling location.

1.5 Workflow

The workflow of this research defines in the Figure 1.1.

1.6 Thesis Structure

Systematically, this bachelor thesis will divided into 6 chapters, each of them comprise to several part. Summary of those chapters would be like this below:

Chapter 1 (Introduction) will explains about background and the objectives of this research, scope of study, methodology will be used, and the workflow of this research. Chapter 2 (Regional Geology focused on regional geology explanation of the research area, it will comprises to its geographic setting, exploration history, basin setting, tectonic events, stratigraphy review, and its coal seam gas play.

Basic theory that related to this research will be explained on Chapter 3 (Theoretical Review). It covers to basic concept of seismic reflection, synthetic seismogram, acoustic impedance inversion model-based, and seismic subsurface response of coal seam gas.

Chapter 4 (Methodology) will focused on the research methodology which consists of well correlation, basic rock physics analysis, creating synthetic seismogram, seismic-well tie, structural picking, horizon picking, initial model building, model-based acoustic impedance inversion, and creating the acoustic impedance distribution map.

The result of model based acoustic impedance inversion and coal seam gas distribution map will be explained in Chapter 5 (Result and Analysis) along with its analysis.

And then by considering all of the result and analysis of this research, Chapter 6 (Conclusions and Recommendations) will summarized this research and give some recommendations for the better future work.

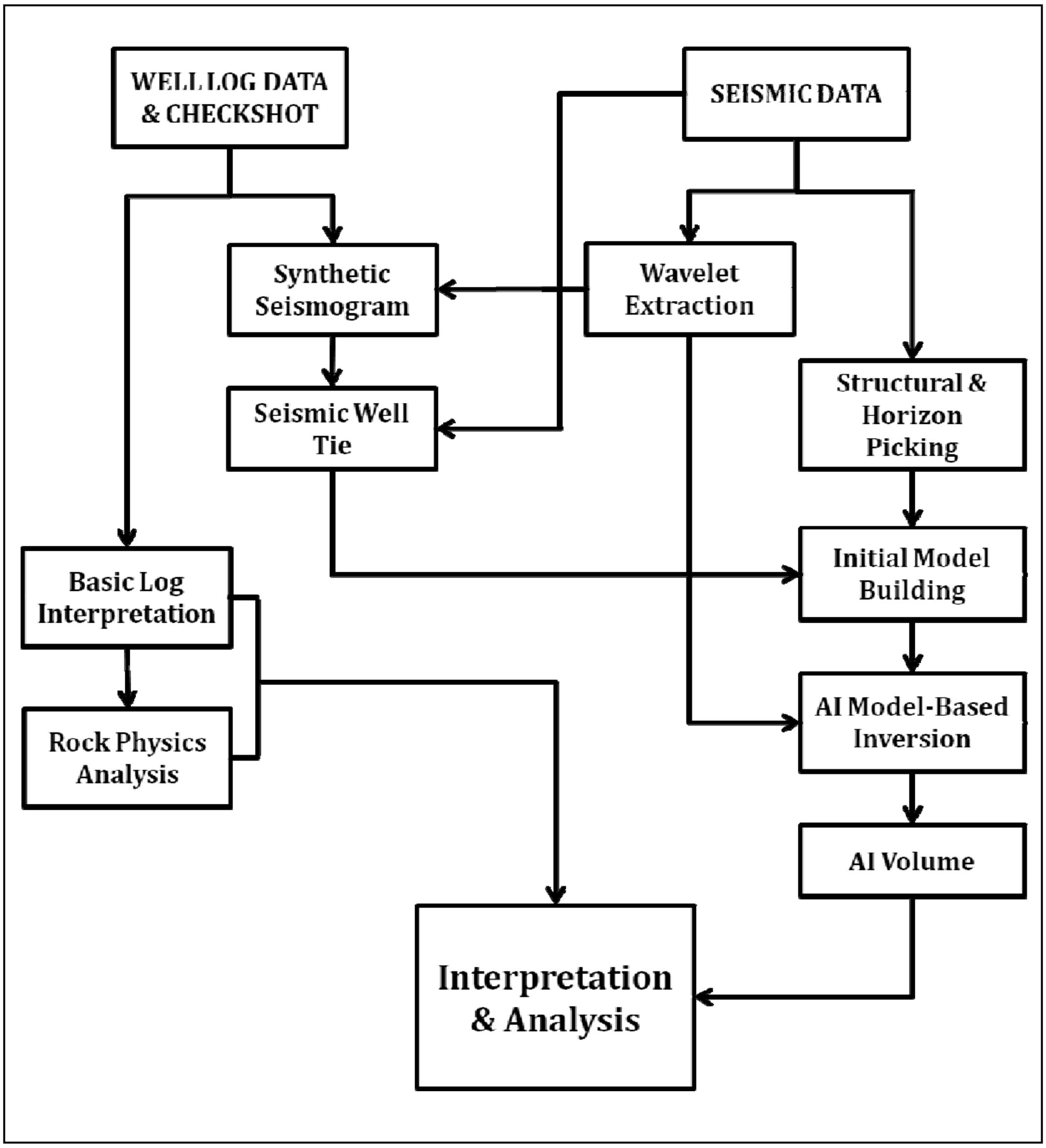


Figure 1.1 The workflow of model based acoustic impedance inversion.

CHAPTER 2
REGIONAL GEOLOGY

2.1 Cooper-Eromanga Geographic Setting

Spinel Field as the research area is located in PEL-106, Cooper-Eromanga basins which is a northeasterly oriented intracratonic basin. 1/3 of this basin located in the northeast of South Australia and another 2/3 in the southwestern Queensland. It is approximately 600 km long and 300 km wide from total area of 130.000 km.

Geographically, the Cooper-Eromanga basins are bounded by the Birdsville Track Ridge in the west, the Canaway Ridge in the northeast, and by the Thargomindah Shelf to the east and south.

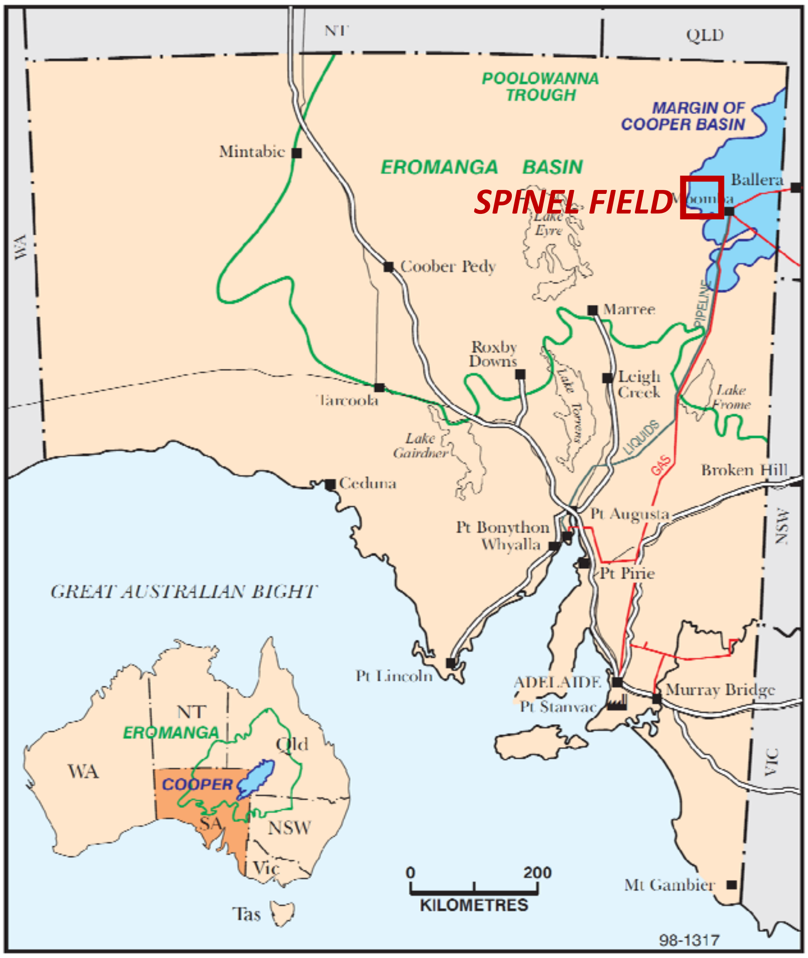


Figure 2.1 Location map of Spinel Field, Cooper – Eromanga Basins, South Australia shows in the red rectangle (PIRSA, 1998)

Generally, Late Carboniferous, Permian, and Triassic sediments of the Cooper Basin are overlain by Jurassic and Cretaceous sediments of the Eromanga Basin.

The Cooper basin contains up to 2000 m of sediments unconformably overlying flat-lying to deformed Cambro-Ordovician sediments, metamorphic, and Carboniferous granitic intrusive of the Warburton basin. The overlying Eromanga basin comprises a thick sequence of up to 3000 m of Mesozoic sediments which effectively blanket the older sediments of the underlying Cooper basin.

2.2 Tectonic Setting of Cooper-Eromanga Basins

There was minimal syndepositional tectonic activity in the Eromanga basin apart from subsidence and the main depocentres largely coincide with those of the preceding Permo-Triassic Cooper basin (Wecker, 1989). A summary of the main tectonic events which affected the Cooper-Eromanga basins area are summarized below:

2.2.1 Late Cambrian (Delamerian Orogeny)

This period comprise to Delamerian Orogeny, a series of major tectonic events that affected the Adelaide Geosyncline and Paleozoic mobile belt to the east in the late Cambrian. Compression produced thrust and recumbent folds, granitiods, and mafic magmas were intruded and regional metamorphism occurred in the southern Delamerian Orogen (Preiss, 1995).

2.2.2 Devonian – Carboniferous (Alice Spring Orogeny)

In this period, Alice Springs Orogeny strongly influenced the structural grain of the Cooper and neighboring basins with northwest-southeast orientated compression and uplift associated with the Devonian – Carboniferous Alice Spring Orogeny. Crustal shortening of the order of 20 km and uplift and erosion of 3 km are indicated by compressional structures in the Marla overthrust zone (Gravestock and Sansome, 1994). Overthrusts in Cambrian rocks form NE – SW arcuate domal trends (e.g. Gidgealpa – Merrimelia – Innamincka (GMI) Ridge and the Birdsville Track Ridge) in the northeastern South Australia.

Highlands produced by compressional tectonism were glaciated during the late Carboniferous and remained as topographical features during early Permian deposition.

2.2.3 Early Permian – Late Permian

This is the Daralingie unconformity period, a relatively minor episode of tectonic activity which caused uplift and widespread erosion, particularly on the ridges and margins of the Cooper basin. In the Nappamerri Trough, the Daralingie unconformity had minimal effect.

This periode represents a depositional episode terminated at the end of the early Triassic by regional uplift, tilting, and erosion. The basin contains a number of stacked non-marine depositional sequences that are contained within the late Carboniferous – late Permian Gidgealpa Group and the late Permian – Early Triassic Nappamerri Group.

2.2.4 Early Triassic – Middle Triassic

This period is the final of the deposition of the Cooper basin. This is terminated with regional uplift, westwards tilting of the southeastern Cooper basin, and resultant erosion from the basin margin of Early Triassic sediments.This resulted in the gradual northerly shift of depocentres from the Middle Triassic period. These movements were related to orogenic events along the eastern edge of the continent.

2.2.5 Jurassic – Cretaceous

Deposition in the Eromanga Basin commenced during the early Jurassic and was controlled by the topography of the unconformity surface. In the Cooper region, palaeo-topography on the Nappamerri unconformity surface strongly controlled Poolowanna facies (lower Hutton Sandstone deposition). No major depositional breaks occur indicating a period of tectonic quiescence.

However, during the early Cretaceous marine inundation of large areas of the Australian continent occurred in direct contrast to global sea level at the time. Conversely, uplift in the late Cretaceous and cessation of Eromanga Basin deposition corresponds to maximum global sea levels, these large-scale vertical movements, without substantial folding or faulting, were the result of the passage of a cold subducted slab underneath the Australian continent following the demise of subduction on the Pacific margin of Australia.

2.2.6 Cenozoic

Lake Eyre basin was deposited in this period. Its sediments unconformably overlie Eromanga basin sediments after these had incurred a period of erosion and deep weathering. This period also characterized by the movement of the continental compressive stress from an east-west to north-south direction as continental Australia drifted in a northeasterly direction from Antartica. It is causing the occurrence of major surface anticlines such as Innamincka Dome and the Birdsville Track Ridge.

This structural movement also interrupted the 3 phase of deposition. The second phases become the considerably phase because it is reactivating pre-existing faults and causing localized folding and faulting.

2.3 Structural Setting of Cooper-Eromanga Basins

Three major troughs in the Cooper basin (Patchawarra, Nappamerri and Tenappera) are separated by structurally high ridges (GMI and Murteree Ridges) associated with the reactivation of NW – directed thrust faults in the underlying Warburton basin. These troughs formed loci of subsidence during deposition of the Cooper, Eromanga, and Lake Eyre basins.

2.3.1 Patchawarra Trough

It is situated in the northwest of the Gigdealpa, Merrimelia, Packsaddle, and Innamincka Ridges. This is a complex depocentre with generally northwest trending structures interpreted to reflect the wrench fault system of the underlying Warburton basin. The thickness of Permian sediments in this trough is less than half lies in the Nappamerri Trough due mainly to non-deposition or erosion at the Daralingie unconformity.

This trough contains up to 2500 m of Permo-Carboniferous to Triassic sedimentary fill overlain by as much as 1300 m of Jurassic to Tertiary cover. However the Permian sediment contains the thickest coal seams up to 60 m which is suggesting prolonged tectonically stable conditions prior to uplift.

2.3.2 Nappamerri Trough

It is lies between the 2 major ridge complexes: the arcuate Gidgealpa, Merrimelia, Packsaddle, and Innamincka Ridges to the north; and the Murteree and Della-Nappacoongee Ridges to the southern margin.

Nappamerri trough contains the deepest and the thickest section approximately 2500 m of Cooper basin sediments including an almost complete section of up to 1500 m of Patchawarra FM sediments.

2.3.3 GMI Ridges (Gidgealpa – Merrimelia – Innamincka)

The GMI Ridge, an arcuate series of NE-SW en-echelon structures, forms the major trend in the Cooper region. At the onset of deposition in the Eromanga basin, these structures formed basement highs with a thin cover of Permo-Triassic sediment. In places, the ridges are bald of Permo – Triassic sediments. Mesozoic structuring over these ridges is due more to compaction of thick sediment in the adjacent Patchawarra and Nappamerri Troughs, rather than loading and subsidence.

Very little fault movement occurred during deposition of Eromanga basin sediments, subsidence, and compaction dominated. An episode of slippage down the Big Lake Fault during the early cretaceous resulted in the arcuate adjustment fault which cuts through much of the Eromanga section.

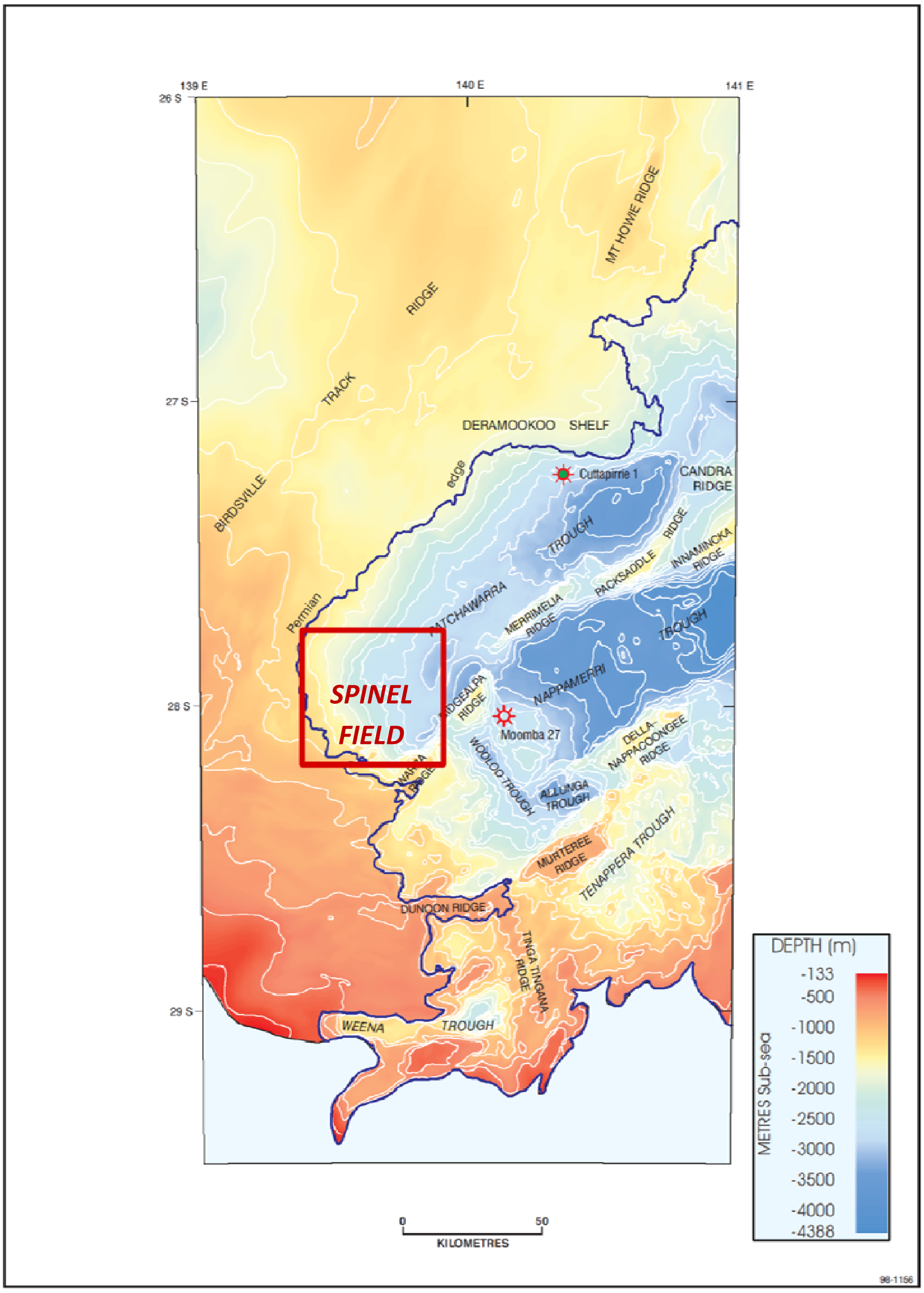


Figure 2.2 Nomenclature of principal structural elements of the Cooper – Eromanga Basins. The Spinel Field located in the red rectangle (PIRSA, 1998)

2.3.4 Murteree Ridge

The NE – SW – oriented Murteree Ridge was a basement high when deposition of Eromanga basin sediments commenced. A seismic line orientated across the ridge shows billiard table-like flatness over the crest with very minor structural relief in the Eromanga basin sediments. This structuring is interpreted to be entirely due to differential compaction.

2.3.5 Other Structures

Eromanga basin sediment thickness is consistent and conformable except where a compression stress field has caused reverse fracturing and uplift. Horizontal beds between the structures indicate that this was a catastrophic short-term tectonic event with brittle fracturing along the faults.

2.4 Stratigraphy Setting of Cooper-Eromanga Basins

The Cooper basin unconformably overlies flat lying to compressively deformed Cambro-Ordivician Warburton strata and Mid-Carboniferous granitic intrusive. Then it is overlain by as much as 2200 m of Eromanga basin section. Since coal deposited in the non-marine environment, then formations discussed here are the formation which deposited in non-marine environment only, which are explained below.

2.4.1 Merrimelia FM

Merrimelia FM is now defined as the suite of glacigenic rocks which comprises the lowest formation of the Gidgealpa Gp. Merrimelia FM is a complex unit of conglomerate, diamictite, sandstone, conglomeratic mudstone, siltstone and shale; each lithotype may be thin or thick, monofacial, or characterised by rapid facies transitions.

Petrologically, this formation contains sedimentary, metamorphic, igneous, and pyroclastic lithologies (Cubitt in Chaney et al., 1997). The top of the Merrimelia FM in the interface sequence is commonly marked by deep-water glaciolacustrine mudrock which interpret to mark the end of the depositional phase of the Merrimelia FM.

The formation occurs in troughs and onlaps topographic rises to the mid-flank regions of ridges throughout the Cooper basin in South Australia. Merrimelia FM unconformably overlies flat-lying to vertical eastern Warburton basin strata and can be confused with weathered upper levels of the latter (Boucher, 1997a).

2.4.2 Tirrawarra Sst

Tirrawarra Sst is composed chiefly of brown and white, fine to coarse-grained, moderately well sorted sandstone (sublitharenite) with minor shale interbeds and rare, thin coal seams and stringers. Conglomerate beds are locally well-developed, notably in Gidgealpa and Big Lake Fields.

Three part subdivision of the formation was recognized as: a basal unit of erosional channel conglomerate, a middle unit of uniform well-bedded sandstone of probable braided stream origin and an upper unit of channel conglomerate, sandstone, and floodplain siltstone with occasional coal beds.

2.4.3 Patchawarra FM

Patchawarra FM defined as the interbedded sandstone, siltstone, shale, and coal beneath the Murteree Shale and above the Tirrawarra Sst, Merrimelia FM, or pre-Permian rocks. Patchawarra FM consists of interbedded fine to medium-grained, locally coarse-grained, and pebbly sandstone; siltstone, shale, and coal.

Sandstones are dominated by monocrystalline quartz with common polycrystalline quartz and minor chert and sedimentary rock fragments. Feldspar is present in trace amounts. Quartz overgrowths together with kaolinite and dickite cements are common; minor illite, smectite, chlorite, and carbonate (dolomite and siderite) cements have also been observed.

There are three facies assemblages within Patchawarra Trough, where the formation reaches its maximum thickness. Lowest assemblage consists of carbonaceous siltsone, with minor sandstone and thin coal seams. The middle assemblage is dominated by sandstone, with grey-black shale interbeds and thick coal seams. The upper assemblage consists of siltstone and shale with minor sandstone interbeds.

2.4.4 Murteree Sh

Murteree Sh consists of argillaceous siltstone and fine grained sandstone. It becomes sandier in the southern Cooper Basin. Fine-grained pyrite and muscovite are characteristic and carbonaceous siltstone occurs. Murteree Sh is widespread within the Cooper Basin in both South Australia and Queensland, but has been eroded from structural highs and from crestal areas of other ridges.

Murteree Sh conformably overlies and intertongues with the upper Patchawarra FM and is conformably overlain by Epsilon FM. Murteree Sh is composed of horizontally-laminated siltstone, with minor linsen bedding, rare wave ripples and wavy bedding and occasional turbidites and rhythmites (Williams, 1995). Slump folds and microfaults occur, indicating slope instability or possibly, seismic activity (Gravestock and Morton, 1984). Dropstones are locally abundant either related to ice or vegetation rafting.

2.4.5 Epsilon FM

Epsilon FM was defined as the series of sandstones, shale, and minor coals overlain by Roseneath FM and underlain by Murteree Sh. Epsilon FM consists of thinly bedded, fine to medium-grained, moderately to very well sorted, sandstone with carbonaceous siltstone and shale, and thin to occasionally thick coal seams.

There are three major depositional stages: a lower stage which consists of a sandy upwardcoarsening cycle capped by shale and coal, a coal-dominated middle stage, and an upper stage consisting of upwardcoarsening sandstone. Epsilon FM is widespread across the Cooper Basin and occurs from the Tenappera Trough in the south to the Patchawarra Trough in the north.

2.4.6 Toolachee FM

Toolachee FM consists of interbedded fine to coarse-grained sandstone, siltstone, and carbonaceous shale, sometimes sideritic with thin coal seams, and conglomerates.

Basal conglomerates occur adjacent to structural ridges and may contain clasts of reworked Warburton Basin rocks. Channel lag conglomerates contain pebbles and cobble-sized quartz as well as mudstone and siderite cemented mudstone intraclasts. Abundant glossopterid leaves are well preserved on bedding planes in laminated siltstone, and laterally continuous (field-scale) coal seams are common.

The Toolachee FM is widespread across the Cooper Basin, but has been eroded off crests of the Murteree Ridges. It is also absent in the southern Tenappera Trough due to Late Triassic uplift.

Toolachee FM disconformably overlies Daralingie Formation and unconformably overlies older rocks including the Warburton Basin on ridges. The top of this formation is the contact between the organic-rich lithologies of the Toolachee FM, and the organic-poor lithologies of the Nappamerri FM. However, in seismic mapping, the top Toolachee Formation is taken as the top of the uppermost coal.

2.4.7 Nappamerri Gp

Nappamerri Gp define as the Triassic sediments with redbed characteristics conformably overlying the Gidgealpa Gp (Toolachee FM) and unconformably overlain by the Eromanga Basin (Poolowanna FM and Hutton Sst). The Nappamerri Group is widespread and best developed in the Nappamerri and Patchawarra Troughs. It onlaps structural ridges except the Murteree Ridges and has been eroded around the margins of the Cooper Basin.

2.4.8 Poolowanna FM

The Poolowanna FM consists of interbedded carbonaceous siltstone, sandstone, and rare coal seams. Sandstone consists of plutonic quartz with minor metamorphic quartz and traces of potassium and plagioclase felspar.

The interpreted environment was one of high-sinuosity fluvial channels meandering across a floodplain with minor coal swamps. In the Cooper region, palaeotopography on the Late Triassic unconformity surface strongly controlled Poolowanna facies – lower Hutton Sst deposition.

2.4.9 Hutton Sst

Hutton Sst consists of mineralogically mature, fine to coarse-grained quartzose sandstone with minor siltstone interbeds. Thin calcite and silica-cemented horizons occur in the upper Hutton Sst (Gravestock et al., 1983). Sands are at least second or third cycle and were originally sourced from a cratonic provenance. The Hutton Sst contains clasts reworked from Triassic, Permian, and older sediments.

In-channel sand and gravel bars, crevasses plays and subaqueous abandonment fill features. Calcite and silica cemented horizons in the upper Hutton Sst indicating episodic sedimentation.

2.4.10 Namur Sst

Namur Sst consists of white to fine to coarse-grained sandstone with minor interbedded siltstone and mudstone. Conglomeratic interbeds consist of lithic and quartz pebbles, carbonaceous mudstone intraclasts, and carbonised plant fragments. A low-sinuosity fluvial environment similar to that of the Algebuckina and Hutton sandstones is interpreted.

2.4.11 Murta FM

The unit consists of thinly interbedded siltstone, shale, very fine to fine-grained sandstone and minor medium and coarse-grained sandstone. Fine-grained lacustrine turbidites indicate deposition on a slope by density currents. Slope instability is indicated by spectacular slumps. Water-escape, ball, and pillow structures and bioturbation (burrows and trails) also disrupt bedding. Minor storm wave reworking of sandy beds has produced hummocky cross-bedding.

2.4.12 Cadna-owie FM

Cadna-owie FM in the subsurface is a siltstone with very fine to fine-grained sandstone interbeds and minor carbonaceous claystone. Cadna-owie FM was deposited at the interface between terrestrial and marine environments as the Early Cretaceous transgression peaked towards the end of the Neocomian. Winters were cold enough to allow rivers and shorelines to freeze and lonestones may have been ice-rafted.

A variety of non-marine and marginal marine environments have been interpreted on the basin margin including fluvial, lagoonal, shoreface, beach, and offshore.

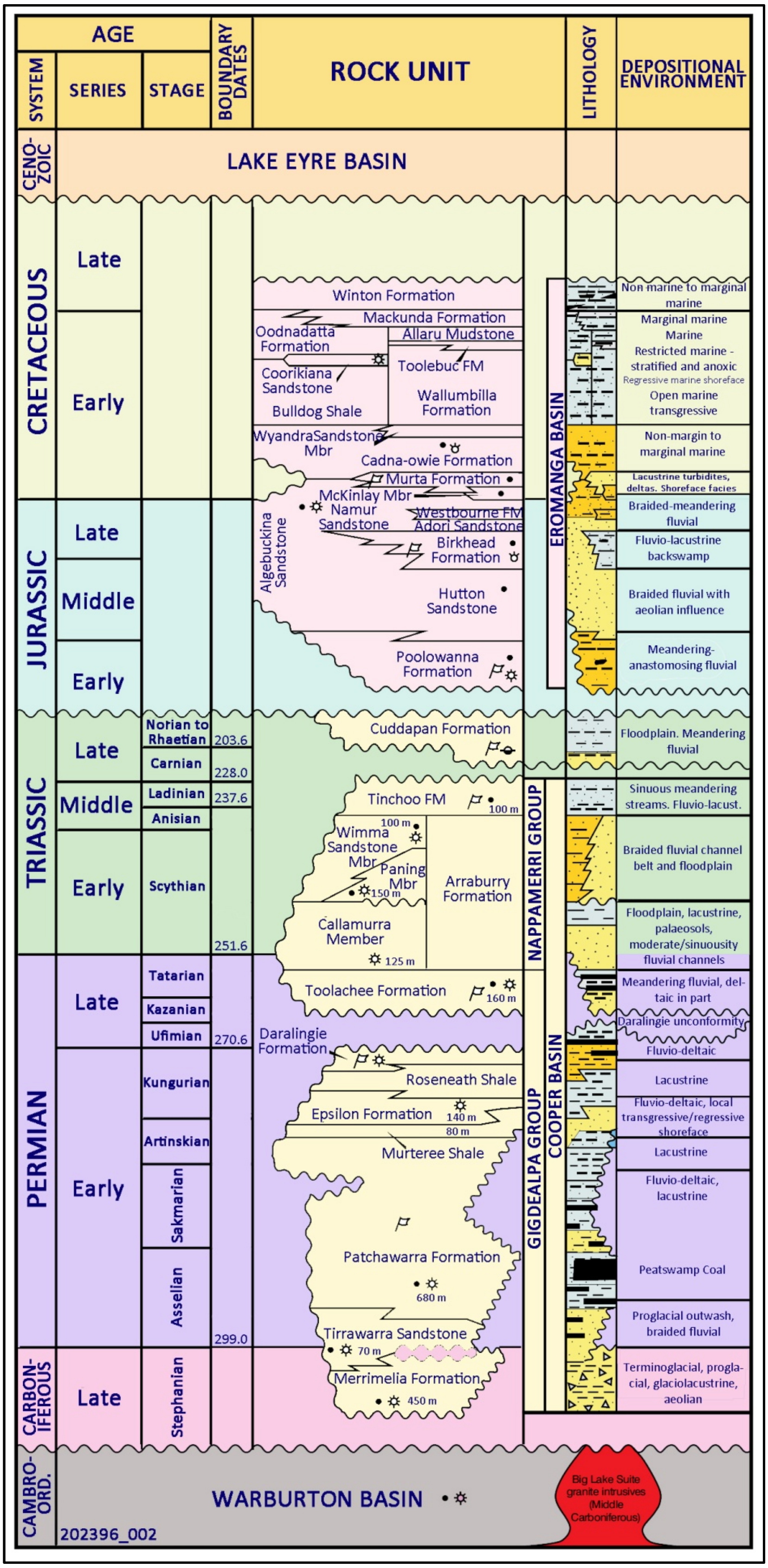


Figure 2.3 Geological summary of Cooper – Eromanga Basin (South Australia Cooper Basin Acreage Release Prepared by PIRSA, 2004).

2.5 Principles of Coalification

Coal is an organic sedimentary rock that forms from the accumulation and preservation of plant materials, usually in a swamp environment. Coal has a tremendous of surface area and can hold massive quantities of methane. Besides that, the higher gas pressures the higher its gas-adsorbing ability.

Methane is the primary gas made up by the coals (typically 95%), with varying amounts of heavier fractions and, in some cases, traces of carbon dioxide. Hence it is widely known as Coal Bed Methane or Coal Seam Gas. This is an unconventional energy along with tight sand gas, shale gas, and hydrate gas.

2.5.1 Coalification in Cooper – Eromanga Basin

Coalification starts from the Carboniferous Period (first coal period) which occur 360 – 290 mya in between. Coal forms from the accumulation of plant debris, usually in a swamp environment. When plant debris dies and falls into the swamp, the standing water of the swamp prevents it from decay. Swamp waters are usually lack of oxygen, which will allows the plant debris to persist.

Coalification requires the thick layer of plant debris with the rate of plant debris deposition greater than the rate of decay. This thick layer buried and compacted by sediment that had been washed into the swamp by a flooding river. About fifty feet of plant debris usually formed five feet of coal only, and this process would require thousands years to accumulate. During this process, the water level of the swamp must remain stable. The coalification environment diagram and process which describe how water depth, preservation conditions, plant types, and plant productivity can vary in different parts of the swamp which will yield different types of coal are illustrated in Figure 2.4.

The quality of coal depends on temperature, pressure, and the length of coalification; this is what called as organic maturity. At first, the plant debris changed into peat which will then changed into lignite or brown coal which has the lowest organic maturity. Brown coal will change into sub-bituminous coal after the influences of temperature and pressure in million years' process. This chemistry and physical changes will continue to occur until turn into the harder and darker coal named bituminous. In proper condition, the increasing organic maturity that occur will formed antrachite.

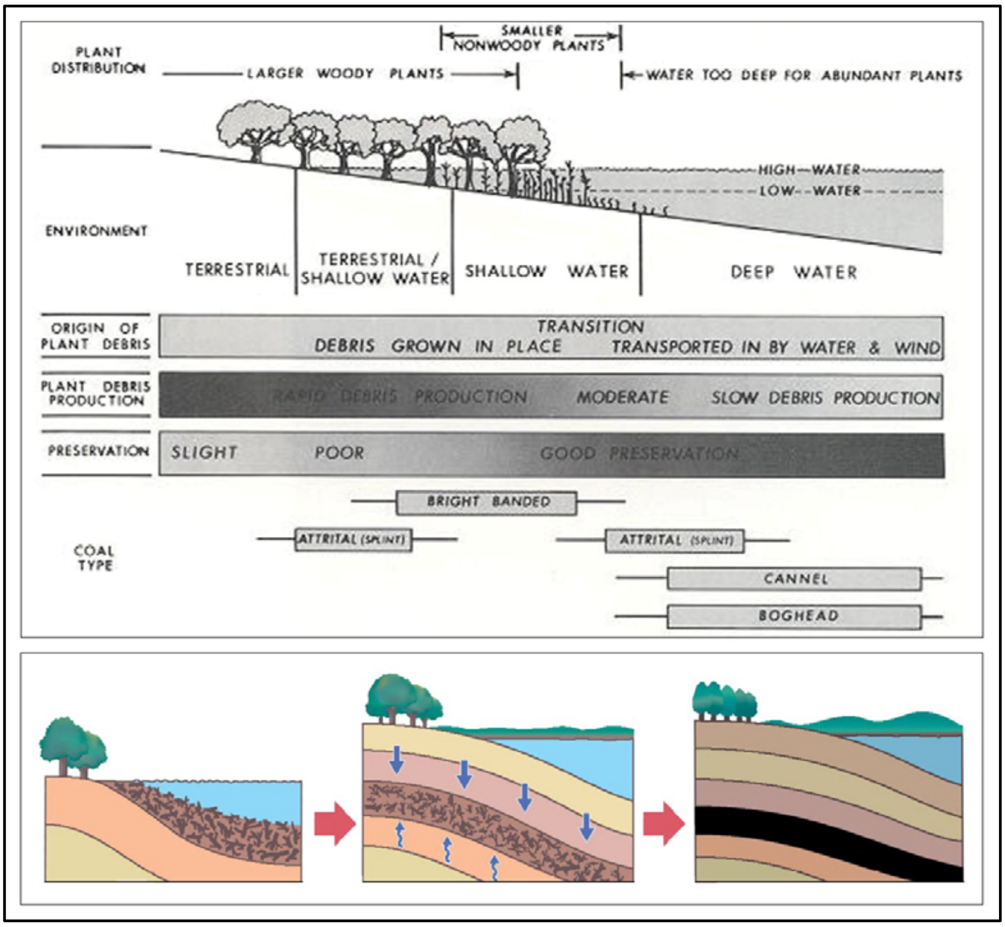


Figure 2.4 Coalification process (below) and environment diagram (above). (West Virginia Geological and Economic Survey; and Kuri-n ni Riyou Sareru Sekitan, 2004).

2.5.2 Types of Coal

Based on its organic maturity content, types of coal can define as below.

- **Peat.** A mass of recently accumulated to partially carbonized plant debris. This material is on its way to becoming coal but its plant debris source is still recognizable. It has carbon content less than 60% on a dry ash-free basis.
- **Lignite.** The lowest rank of coal is lignite. It is a peat that has been compressed, dewatered, and lithified into a rock. It often contains recognizable plant structures. It has a carbon content of between 60 – 70% on a dry ash-free basis.

- **Sub-Bituminous.** This is lignite that has been subjected to an increased level of organic metamorphism which has driven off some of the oxygen and hydrogen in the coal and produces higher carbon content coal (71 – 70% on a dry ash-free basis).
- **Bituminous.** Bituminous coal is typically a banded sedimentary rock. Bituminous coal formed when sub-bituminous coal subjected to increased levels of organic metamorphism. It has carbon content of between 77 and 87% on a dry ash-free basis. In Figure 2.5.(c) the bright and dull bands of coal material are visible horizontally across the specimen. The bright bands are well preserved woody material, such as branches or stems. The dull bands can contain: mineral material washed into the swamp by streams, charcoal produced by fires in the swamp, or degraded plant materials.
- **Antrachite.** This is the highest rank of coal. It has a bright luster and breaks with a semi-conchoidal fracture. Its carbon content over 87% on a dry ash-free basis.

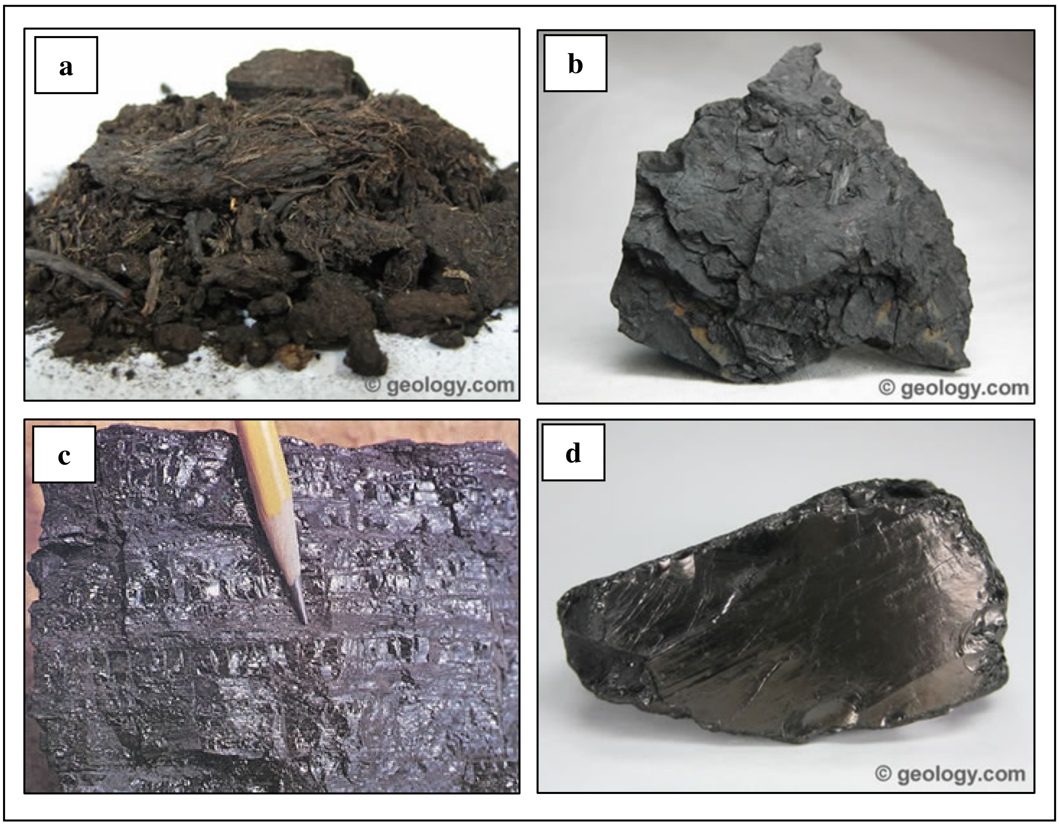


Figure 2.5 The types of coal: a) Peat, b) Lignite, c) Bituminous, and d) Antrachite (West Virginia Geological and Economic Survey).

2.5.3 Coal Seam Gas Energy

There are abundant cleat inside the coal which formed during the coalification, water and gas are flowing through this. The part of coal surrounded by those cleats known as coal matrix, the part where mostly coal seam gas sticks at the pores inside. Hence the coal in exploration acts as both reservoir and source rock.

Coal seam gas generated by 2 methods: the first, the most coal seam gas generated when chemistry reactions occurs in coal due to the heat effect in subsurface. This generation methods named thermogenesis. The second, coal seam gas also generated in brown coal zone (lignite) in depth less than 200 m. In this method, the coal seam gas generated due to the microorganism activities in anaerob environment. This generation method named biogenesis. Both of this generation method illustrated in Figure 2.6.

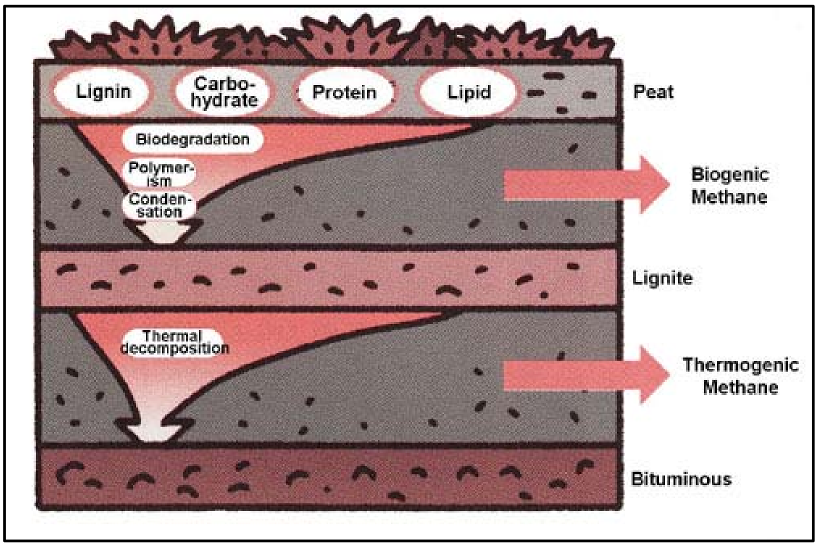


Figure 2.6 The two generation methods of Coal Seam Gas: Biogenesis (generated in shallow depth) and Thermogenesis (generated in deep). (Sekitan no hon, 2004).

There are two reasons of why Coal Seam Gas is interesting, those are:

1. If there are the conventional gas reservoir (sandstone) and Coal Seam Gas (coal) in the same depth, pressure, and rock volume; the Coal Seam Gas volume can store six to seven times more gas than the conventional gas reservoir, since coal has large internal surfaces. In another words, Coal Seam Gas has interesting quantity prospect.

2. Principally, Coal Seam Gas content generation is absorption in coal matrix, hence Coal Seam Gas has the higher success ratio since Coal Seam Gas possibly to generate in both syncline and anticline. In simply, where there is coal, there is Coal Seam Gas.

2.6 Coal Seam Gas Play of Cooper-Eromanga Basins

The most principle concept that must be remembered in exploring Coal Seam Gas is: methane (natural gas) is generated, stored, and sealed in the coal seam itself. In another words, coal seams are act as source, reservoir, and seal for the methane that produced.

2.6.1 Potential

Multi-zone high sinuosity fluvial sandstones form poor to good quality reservoirs. The main coal seam gas reservoirs occur primarily within the Patchawarra FM (porosities up to 23.8%, average 10.5% and permeability up to 2500 mD) and Toolachee FM (porosities up to 25.3%, average 12.4% and permeability up to 1995 mD) (PIRSA, 1998). Towards the margin of the Cooper Basin, oil is also produced from the Patchawarra FM. This research focused on the coal seam gas reservoir within the Patchawarra FM due to its numerous coal seam gas allocated on it.

The Patchawarra FM contains the most significant gas condensate reservoirs in the Cooper basin and has produced almost 45.1 x 10^9 m^3 (1.6 tcf) of raw gas to date (PIRSA, 2004). The Patchawarra is the thickest formation of the Gidgealpa Group and one of the most variable in thickness (Battersby, 1976), having been initially deposited in valleys before thinning by onlap of bounding ridges. Uplift at the end of the early Permian led to truncation of the Patchawarra on structural crest and at the basin margins, thus also creating structurally thinned areas.

Permian Patchawarra FM coal measure is dominated by Type III kerogens derived from higher plant assemblages. Gas composition is closely related to maturity/depth with drier gas occurring towards basin depocentres although there is strong geological control on hydrocarbon composition.

Abundant coal seams of the Toolachee and Patchawarra FM, are present throughout the Cooper Basin. The formations are multistory fluvial channel, point bar, and crevasse splay sandstone ranging from 1800 to 3500 m below the present datum.

2.6.2 Tectonics

In the Cooper Basin, the emphasis of exploration is largely directed towards the assessment of 4-way dip closures and traps associated with faults. Several stratigraphic prospects have also been drilled and a stratigraphic component of the hydrocarbon trapping mechanism has been recognised in the development phase of some gas fields.

Most anticlinal structures are partially fault-controlled which were in part rejuvenated by further fault movement, mainly in the Triassic and Tertiary. Exploration for the latter type is favoured because such traps are less likely to have suffered hydrocarbon leakage as fault penetration through to present-day surface is minimal.

2.6.3 System

The lipid-rich material associated with inertinite in Permian coals is interpreted to have originated from algal mats that covered the surface of the peat (Taylor *et al.,* 1988). In addition, as there is no evidence of botanical structure within inertinite from Patchawarra Formation coals, Taylor *et al.* proposed that it formed from the seasonal desiccation (freeze-drying) of a homogeneous gelified peat precursor. Leaf cuticles are often densely packed in Gondwanan coals and are interpreted as autumn leaf falls from the Glossopterid flora (Diessel, 1992).

Patchawarra coal seams are thinner on average than those in the Toolachee, however they are more numerous. Patchawarra FM is usually considerably thicker than the Toolachee FM, and thus total coal thickness is comparable in both formations. The chief difference between the two formations is the distribution of areas with thick coal deposits. The Patchawarra Trough was an area of thick peat accumulation, preserved Patchawarra coals are thickest in the southwestern part (the formation has been eroded to the northeast) and Toolachee coals in the northeastern part. In contrast the Nappamerri Trough is dominated by overbank siltstone and channel sandstone rather than peat, as shown by Thornton (1979).

The Tenappera Trough was also a site of peat accumulation in both formations, however Patchawarra coals thicken southwards into the Weena Trough where the Toolachee FM was either eroded or not deposited.

Hobday (1987) noted that the lowermost seams pinch out on the flanks of basement highs because oxidation would have destroyed peat in updip areas. The optimal location for peat accumulation was on the flanks of topographic highs, on sloping basement, where a stable platform for peat accumulation occurred.

The relatively thick Patchawarra coals possible that raised swamps accumulated near the western depositional edge of the Cooper Basin adjacent to the Birdsville Track Ridge in Early Permian time and in the northern Patchawarra Trough during the Early and Late Permian.

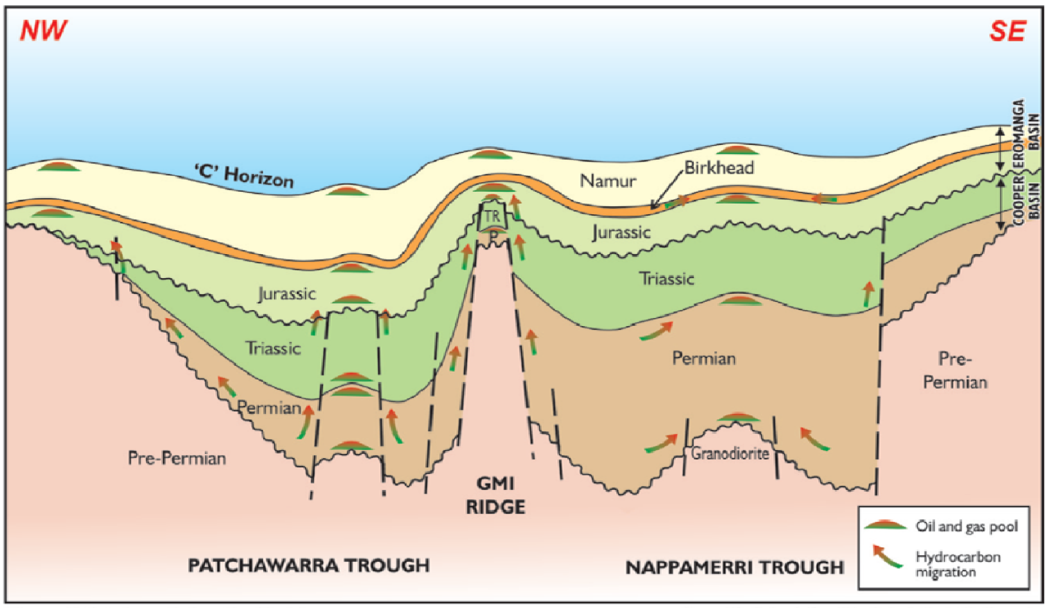


Figure 2.7 Hydrocarbon play exploration model (Prepared by Mulready Consulting for inclusion in this Prospectus, 1998).

CHAPTER 3
THEORETICAL REVIEW

3.1 Basic Concept of Seismic Reflection

Seismic method is one of exploration methods which based on seismic waves response sent from the source to the subsurface and reflected back to the surface after met the lithological boundaries with different physical properties. Basically, seismic data recorded on the specific record length and represent as traces.

The technique gives a two or three dimensional picture of the structure of rocks at depth by generating shock or seismic wave at the surface, analogous to a sound wave in fluids, and recording its reflections of those rocks by means of a linear array of geophones, then recorded as travel time (two way time) which will give us the information about velocity of p-wave of the reflection surface. The waves were originally generated by using explosives or vibroseis, the mechanical vibrators give a sharper signal with better depth penetration.

The reflections are the result of differences in the acoustic impedance of rocks formation. Different lithology will give the different seismic response, it depends on its rocks properties such as porosity, density, resistivity, and fluid content.

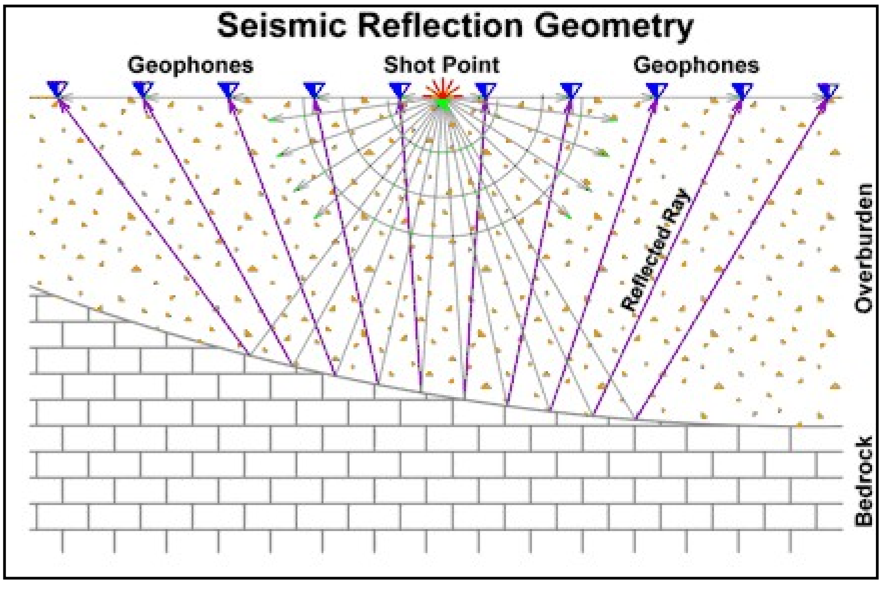


Figure 3.1 Seismic reflection raypath geometry (Enviroscan, Inc., 2003)

Field and data processing procedures of seismic reflection are employed to maximize the energy reflected along near vertical ray paths by subsurface density contrast. Reflected seismic energy is never a first arrival, and therefore must be identified in a generally complex set of overlapping seismic arrivals – generally by collecting and filtering multi-fold or highly redundant data from numerous shot points per geophone placement.

Information in seismic wavelet contains some seismic components such as amplitude, peak, trough, zero crossing, and wavelet length. These components then generate other components such as acoustic impedance, reflection coefficient, polarity, phase, vertical resolution, wavelet, and synthetic seismogram.

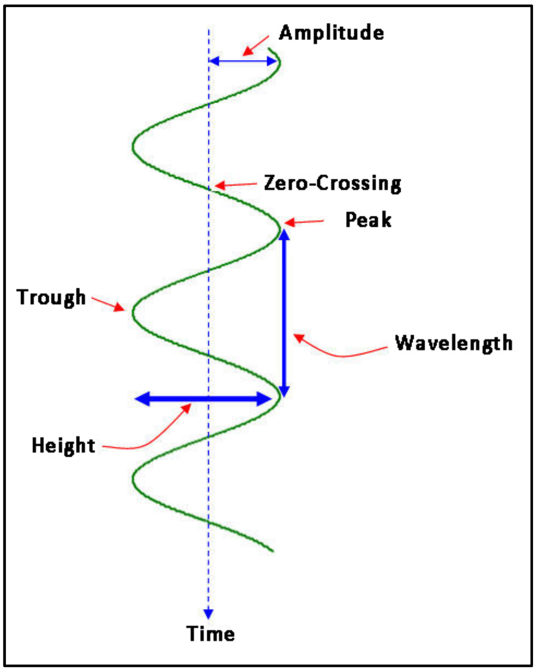


Figure 3.2 Seismic wavelet components. (Agus Abdullah, Ensiklopedi Seismik, 2007)

The further explanation of those components will define below.

3.1.1 Acoustic Impedance

Acoustic impedance (AI) could be defined as the ability of rocks of passing the seismic wave through those rocks. Physically, acoustic impedance is the convolution product of compression wave velocity (v) and rocks density (ρ). The higher rocks density the higher its acoustic impedance. In example, the compact sandstone has the higher acoustic impedance compare to shale or claystone. Mathematically, acoustic impedance (Z) could define as below:

$$Z = V.\rho\ ms^{-1}kgm^{-3} \qquad (3.1)$$

$$AI = \rho.V \qquad (3.2)$$

3.1.2 Reflection Coefficient

Lithological boundaries of two medium which has different acoustic impedance represents as reflection coefficient (RC). It can be well-define as:

$$RC = \frac{AI_1 - AI_2}{AI_1 + AI_2} \qquad (3.3)$$

The reflected wave energy value depends on the reflection coefficient value, the higher reflection coefficient (RC) the stronger its reflection.

3.1.3 Wavelet and Polarity

Seismic wavelet is the mini wave which has amplitude, wavelet length, frequency, and phase. In practical terminology, wavelet known as the wave which represents one reflector recorded in one geophone.

Basically, recorded seismic wave has specific polarity which describes positive or negative value of reflection coefficient (RC). This value will give different seismic wavelet either peak or trough. There are three convention of polarity nowadays: SEG normal and reverse polarity, European normal and reverse polarity, and American normal and reverse polarity.

Oftentimes, those polarity conventions leave peoples in confusing. In such ways, it can be simply described in two ways: increasing acoustic impedance means peak (and vice versa) or increasing acoustic impedance means trough (and vice versa).

3.1.4 Phase

Basically, there are 2 types of seismic phase: zero phase and mixed phase, and the mixed phase wavelet consists of minimum phase and maximum phase. The difference between them is their phase degree on the first break which will represents its lithological boundaries. Another difference between them is where their highest amplitude located in the wavelet, the zero phase wavelet has maximum amplitude symmetrically centered, the minimum phase wavelet has maximum amplitude in the beginning, and the maximum phase wavelet has maximum amplitude in the end of the wavelet. The definition could well-described on the picture below.

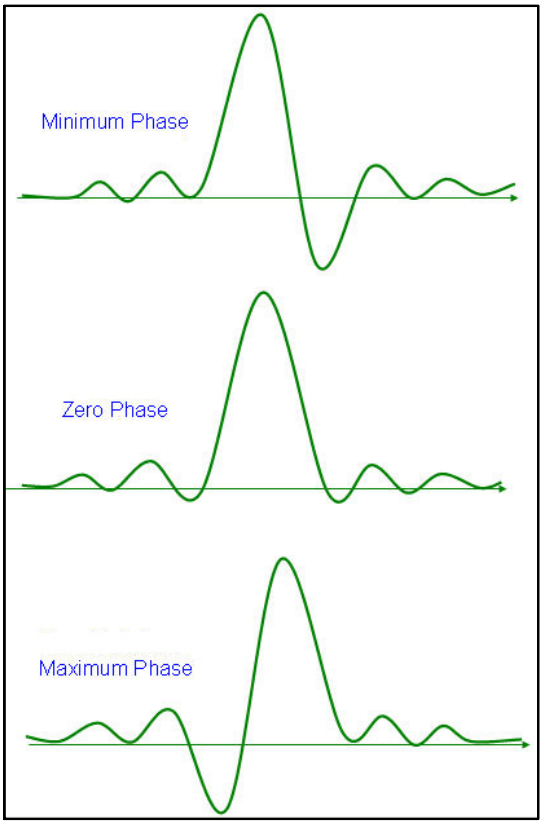


Figure 3.3 Three types of seismic wavelet phase which generally used: minimum phase, zero phase, and maximum phase. (Agus Abdullah, Ensiklopedi Seismik Online, 2007)

3.1.5 Vertical Resolution of Seismic

Vertical resolution of seismic is the ability of seismic to separate two neighboring reflector surface, this ability represents as tuning thickness. The value of tuning thickness is ¼ of wavelet length (λ), where $\lambda = v/f$ where v defines as p-wave velocity and f defines as frequency. Increasing depth will resulted in increasing velocity and decreasing frequency, in such ways its tuning thickness is increasing.

This resolution enables us to know whether we can determine the top and bottom of reservoir or not. If the reservoir thickness is above the vertical resolution, then the top and bottom of reservoir could be determined.

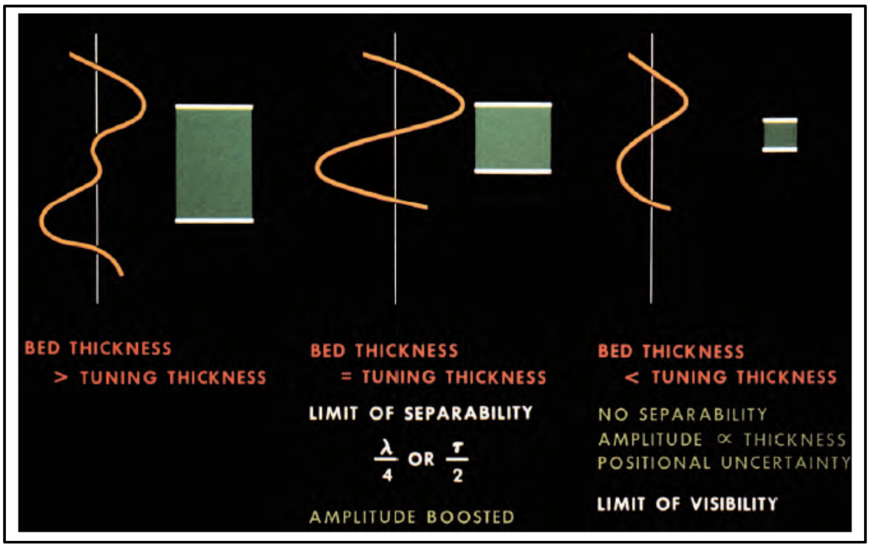


Figure 3.4 Vertical seismic resolution of the top and bottom of beds (Alistair Brown, Interpretation of 3D Seismic Data).

3.2 Basic Concept of Well Log Data

Briefly, log is a record of certain parameter to depth or time. In hydrocarbon exploration, log defines as a record of physical or chemical properties of rocks and fluid to borehole depth.

3.2.1 Caliper Log

Caliper log used to measure the diameter and shape of borehole, usually placed in the same panel as the bit size log in order to make lithology identification in borehole easier. If the size of caliper log and bit size are both in the same measurement, it will said as on gauge condition, usually occurs on impermeable or very compact lithology (i.e. big sandstone, limey shalestone, igneous rocks, and metamorphic rocks).

The condition where caliper log size greater than bit size will indicates the formation which able to dissolve in bore fluid or possibly weak and porous (i.e.

salt formation with water as bore fluid, less compact sandstone, gravels, and brittle siltstone).

If caliper log size smaller than bit size, it usually indicates the swollen and collapse formation into the borehole, or possibly the occurrence of mudcake in the porous and permeable formation (i.e. swelling shales, or porous and permeable sandstone).

3.2.2 Gamma Ray Log (GR)

Gamma ray log measures gamma ray radiation produced by radioactive element in rocks formation throughout the borehole. Radioactive elements that usually contains in rocks formation are Uranium, Thorium, Potassium, Radium, etc. Mostly, radioactive elements contains in siltstone or shale mineral, so it will give the higher gamma ray response comparing to other rocks.

Rocks radioactivity is direct function from shale mineral content in rocks, therefore could indicating grain size of sedimentary particles. Gamma ray log usually used to identify the increasing shale mineral content then could identify the decreasing depositional energy.

In basin with depositional environment like fluvio-deltaic or channel system has strata which consist of sandstone or siltstone (sandstone – siltstone interbedded). Coarse grain sandstone which contains small amount of mud will has low gamma ray; meanwhile fine mud will has high gamma ray.

Nevertheless, there are several exceptions. Uranium in rich organic material siltstone or uranium precipitates in certain sediment after deposited might cause positive anomaly in radioactivity rocks record. It means, radioactivity of that rock is high although less shale mineral content. Positive anomaly as explained before may cause by large amount of feldspar inside arkose sandstone or heavy mineral content (monazite and thorit) inside residue. Most of those effects could be detected using spectral gamma ray log.

Gamma ray log has API (American Petroleum Institute) unit and typically range between 0 – 150 and up to 200 API for rich organic material siltstone.

3.2.2 Spontaneous Potential Log (SP)

SP log measures the electrical potential between subsurface rocks and surface rocks. This log is sensitive to permeability change so it uses to differentiate sandstone (generally permeable) and siltstone (generally impermeable). SP log will works well when there are high enough resistivity contrast between borehole fluid and formation water.

In the impermeable siltstone zone, SP log will shows as straight line, it said as shale base line. The differences between siltstone types could be well-differentiated by looking the gamma ray log. SP log depends on the hydrocarbon content, cementation, and salinity of formation water change.

3.2.3 Resistivity Log

Resistivity log measures bulk resistivity in formation throughout borehole where resistivity as function of porosity and fluid in rocks. Porous rocks which contain high salinity fluid have low resistivity. Meanwhile, the non-porous rocks or rocks with hydrocarbon content will have high resistivity. If the fluid content in certain formation is constant (i.e. oil leg or water leg), resistivity trend might be good lithology indicator. Resistivity log oftentimes uses to correlate siltstone package or net sandstone package which will not show in gamma ray log.

3.2.4 Density Log (RHOB) and Neutron-Porosity Log (NPHI)

Density – neutron logs are best log series in identifying lithology so can be used to correlate lithology and depositional trend. Density log measures electron density inside formation by catching the reflected gamma ray then converting into real bulk density. Meanwhile, neutron-porosity log measures formation porosity based on the interactions of neutrons detached by the instrument and neutrons inside formation.

Neutron log calibrated to limestone. Linear porosity unit of limestone calibrated using API Neutron pit on 19 % porosity, limestone which contains water defines as 1000 API units.

Lithology difference could be determined using density log based on returned density. For example, pure quartz has bulk density up to 2.65 gg/cm^3, coal up to 1.2 – 1.8 gg/cm^3, limestone up to 2.75 gg/cm^3, dolomite up to 2.87 gg/cm^3, and anhydrate up to 2.98 gg/cm^3.

Log scale of these logs placed together and will overlap in limestone zone. In sandstone zone, logs will show separation, starts from relatively small separation (in mostly sandstone) until the relatively big separation (in mostly feldspatic sandstone). The increasing siltstone content will causes the increasing the measurement neutron content of the hydrogen tied in shale mineral. Meanwhile, density log relatively not changing. In such way, the overlapping and separation of both curves could be used as sensitive indicator of grain size. Besides that, coal could be easy to identify from density – neutron log.

The collapse and erosion of borehole wall and also the occurrence of heavy minerals (pirit and siderite) will affected the density log because the borehole will measures the greater size. The present of gas also will cause the higher neutron log as the increasing hydrogen atom proportion in methane.

3.2.5 Sonic/Acoustic Log (DT)

Sonic log measures travel time of wave which traveling through the rocks. This travel time is function of porosity and lithology. Wave in siltstone will moves relatively slow compare to the wave through sandstone in the same porosity. In another words, the time travel of siltstone is slower than travel time of sandstone in the same porosity.

This phenomenon enables us to use sonic log as grain size indicator. High organic material content inside coal and black siltstone will cause the high travel time inside those rocks. That is why sonic log might be used to identify condensed section with rich organic material content.

Besides affected the factors as explained above, sonic log also depends of the cementation and compaction of rocks, and also depends on the rocks' fracture.

3.3 Well to Seismic Tie

Well to seismic tie is the process of tying the well log into the seismic data, this is important process before doing further interpretation since both of them has different parameter: well log data is in depth domain (metres) and seismic data is in time domain (two way time travel time).

Well log data which important to be used are sonic log (DT, DT long spacing, or sonic velocity), density (RHOB), and time to depth relationship (checkshot, VSP, or corridor stack).

The first thing to do in well to seismic tie is converting well log data in depth domain into time domain, in such way log curve which will be used is sonic log and time to depth relationship (checkshot, VSP, or corridor stack).

Sonic log is susceptible to local change around borehole such as washout zone, lithological snap change, and only able to measure the rock formation in 1 – 2 ft. In the other hand, chekshot unable to measure more details than sonic log. Because of these weaknesses, it is necessary to create sonic corrected checkshot, and the value of this checkshot correction known as drift.

The next step is creating reflectivity log which generated from sonic log and density log, then creating synthetic seismogram by performing convolution between reflectivity log and wavelet.

Wavelet selection itself is the important thing to do, because seismic phase will change by increasing depth. In example, in Seismic Reference Datum (SRD) wavelet which used is zero phase wavelet (after processing technique applied) but in certain depth its phase might be changed.

In creating synthetic seismogram, simple wavelet such as zero phase ricker wavelet 25 Hz might be used. By comparing the synthetic trace and seismic trace around borehole, the adjustment could be applied whether the wavelet frequency too high or too low. Besides that, phase wavelet around area of interest also necessary to estimate. After that, bulk time shifting could be applied and possible applying stretching and squeezing only if it is necessary.

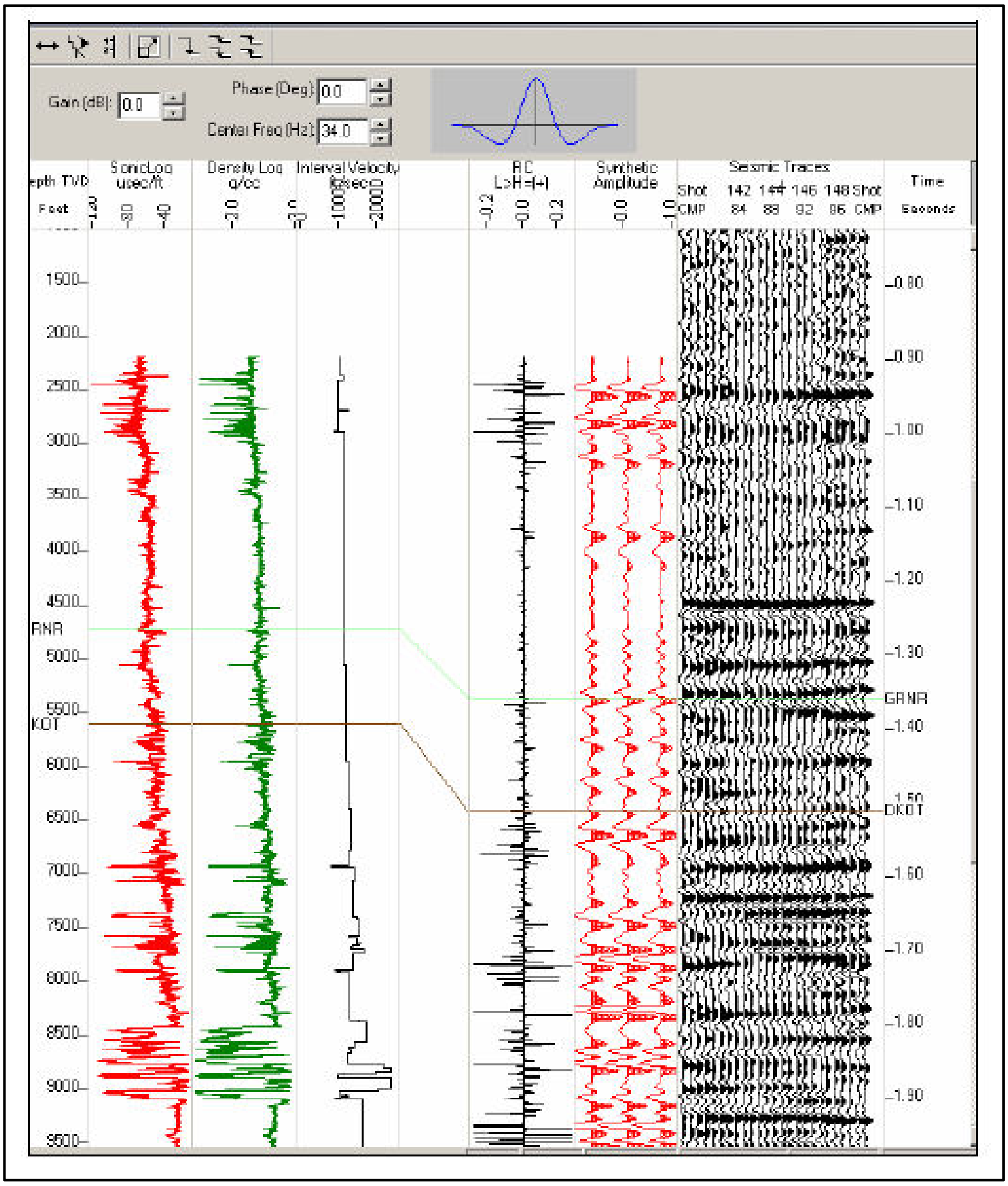


Figure 3.5 Well to seismic tie process using Landmark Graphic. (Courtesy Dutch Thompson, Landmark Graphics Corporation, 2003)

Besides that, phase wavelet around area of interest also necessary to estimate. After that, bulk time shifting could be applied and possible applying stretching and squeezing only if it is necessary.

3.4 Rocks Physics Analysis

Basically, lithological crossplot used as the parameter which will shows whether rocks in target zone could be differentiated each other or not. The crossplot that might be used are Acoustic Impedance, Gamma Ray, Neutron Porosity, Density, and Resistivity. But this basic lithology crossplot not design to characterize the physical properties of rocks and fluid.

In order to understand the character and physical properties of rocks and fluid, rocks physics analysis is needed. The main purpose is finding the physical properties which could differ and separate the prospect and non-prospect zone. Physical properties as define here are P-wave velocity (Vp), S-wave velocity (Vs), Poisson's Ration, Acoustic Impedance, Lambda-Rho, Mu-Rho, etc.

The picture below is the example which represents rocks physics analysis in order to separate the non-pay, gas-pay, wet-shally, etc. Shown data usually generated from well log data or seismic inversion result.

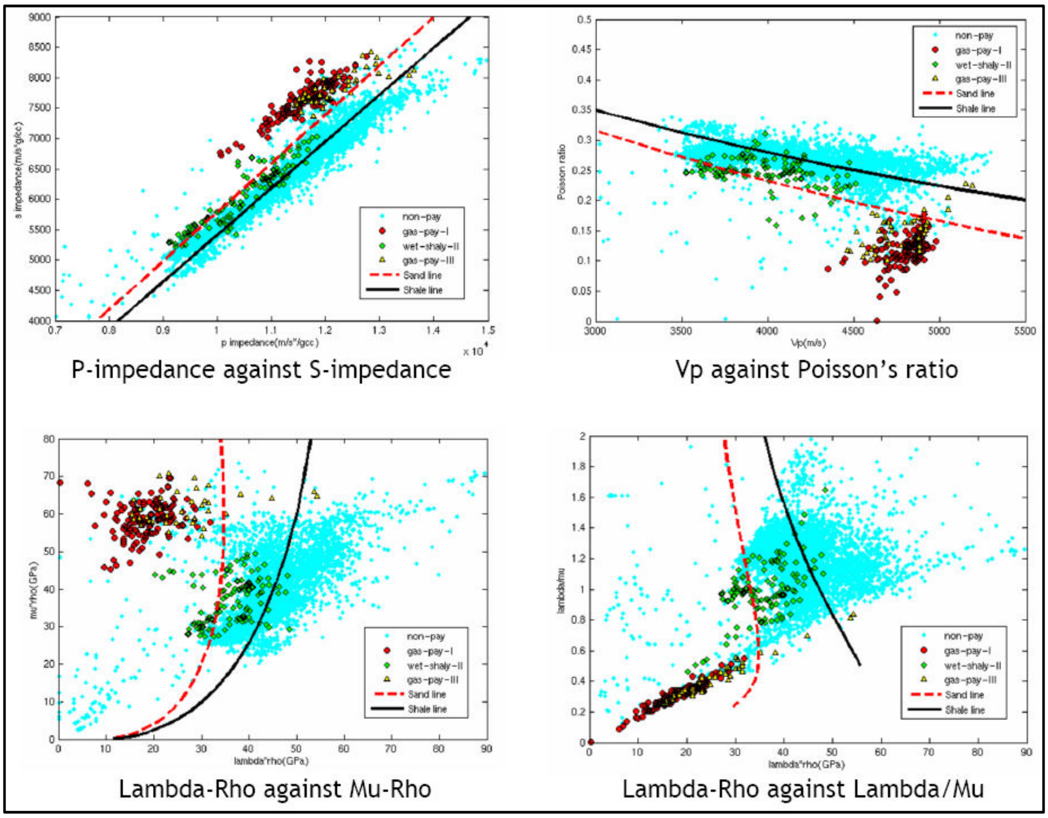


Figure 3.6 Crossplot for rocks physics analysis (Courtesy Chopra, CSEG, 2006)

Crossplot as shown above is very useful, for example to convert certain physical properties map into another physical properties map.

3.5 Model-Based Acoustic Impedance Inversion

Seismic inversion is the process of geophysical modeling which performed to estimate physical properties information of the subsurface based on seismic record information. Mathematically, acoustic impedance (Zp, Z, or AI) is defined as the product of compresional wave velocity (Vp) and density (ρ) as written below:

$$Z = Vp \times \rho \tag{3.4}$$

Both velocity and density are indicators of lithology, fluid content, porosity, and other petrophysical properties, hence the quantitative estimation of acoustic impedance from seismic data can be used to characterize petrophysical properties of the subsurface. If we treat seismic trace as a band-limited estimate of the earth layered normal incidence reflectivity, then the trace only gives information about the boundary between layers, not the layers themselves.

Inversion itself is the inverse of seismic acquisition (forward modeling), while the forward modeling is the process of convolution between wavelet source and acoustic impedance contrast (reflection coefficient). In such way, inversion process is division process of seismic record to predicted wavelet source. Figure 3.7. as shown in previous page might give the illustration.

There are several advantages of applying acoustic impedance inversion over interpretation of the stacked traces themselves (Latimer et al., 2000; Veeken and Da Silva, 2004), which are:

- Acoustic impedance inversions incorporate well log information into the parameter estimate which includes low frequency information that is not available in the seismic data alone.
- In estimating acoustic impedance of a layer, an attempt to remove the wavelet is made which can reduce wavelet side lobe and tuning effects.
- Seismic data is a band-limited estimation of the reflectivity at the interface between layers, while an acoustic impedance estimate, although also band-limited, is a property of the rock layers themselves.

- The layer based acoustic impedance rock property is more easily correlated with well data which is also layer based information (as opposed to layer interface information)
- Because acoustic impedance is a rock property, it can be more easily related to other petrophysical properties such as fluid content and porosity.

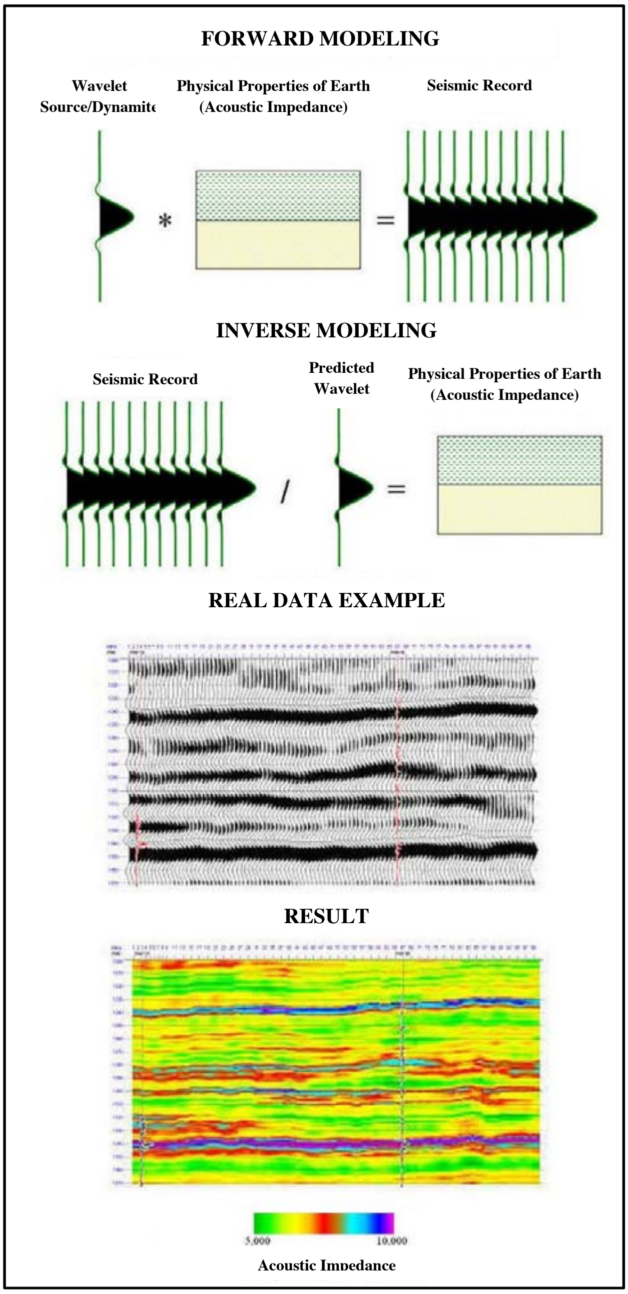


Figure 3.7 Post-stack seismic inversion concept. (Agus Abdullah, Ensiklopedi Seismik Online, 2007).

Predicted wavelet selection of the inversion process is very important procedure, the predicted wavelet must be represented the horizon of the target zone. Wavelet extraction on the inversion target zone might be the solution for selecting the right wavelet. But the error of extracting the inappropriate wavelet on the target zone is still possible to happen, because it also depends on the sonic log quality and well to seismic tie process (if extreme stretch and squeeze are applied on).

Seismic inversion that would be used in this research project is the post-stack seismic inversion only. There are several types of this post-stack inversion, but the methodology applied to this research is model based inversion.

Generally, model based inversion uses an initial guess model of the impedance which is used in an objective function that includes consideration of the extracted wavelet. The initial model relates frequency information from local wells. The objective function is minimized by iterative perturbation of the model which results in a reasonable solution if the initial guess is within the region of global convergence of the objective function.

Basically, this method creating initial guess geological model and compare it to the real seismic data. This comparison then used to rebuild the model, adjusted to the real seismic data. The benefit of using model-based inversion is this method not directly inverted the seismic data, but inverted the initial guess model.

However, the components of the initial guess model those are not resolved by the data tend to be carried through from the initial guess model. The high frequencies above the seismic band are carried trough if they are not filtered away from the model prior to the inversion. Sparseness in the inversion can achieve by the assumption of a finite number of discrete layers within the inversion window.

Since this method inversed the initial model that built at first, it is necessary to remember that the appropriate initial model must be made first. Principally, the initial model made using the wavelet, so the most appropriate wavelet must be extracted. The wavelet extraction is the most crucial thing to do here, because when the wrong wavelet applied to initial model then it will cause the inappropriate result of inversion.

3.6 Subsurface Responses of Coal Seam Gas

Laterally, CSG (Coal Seam Gas) also known as CBM (Coal Bed Methane) become the new alternative fossil energy. Gas produced from the coal seams which act as both the source rock and the reservoir. Methane gas (CH_4) can be sourced by thermogenic alterations of coal or by biogenic action of indigenous microbes on the coal.

CSG plays also provide a very good means of CO_2 sequestration because CO_2 molecules displace CH_4 methane molecules on the face of the coal, generating greater methane production while sequestering the CO_2 in the coal seams. CSG potentials in usually located in shallow depth (hundreds metres) in Indonesia, while in Australia its potential more likely in deep (thousands metres).

3.6.1 Log Responses of Coal Seam Gas

Physically, coal could be identified in log data by its extreme low density and P-wave velocity, also its extreme high porosity and sonic log; comparing to the overburden rocks. The physical properties which made up the anomaly of coal have been explained in the previous chapter.

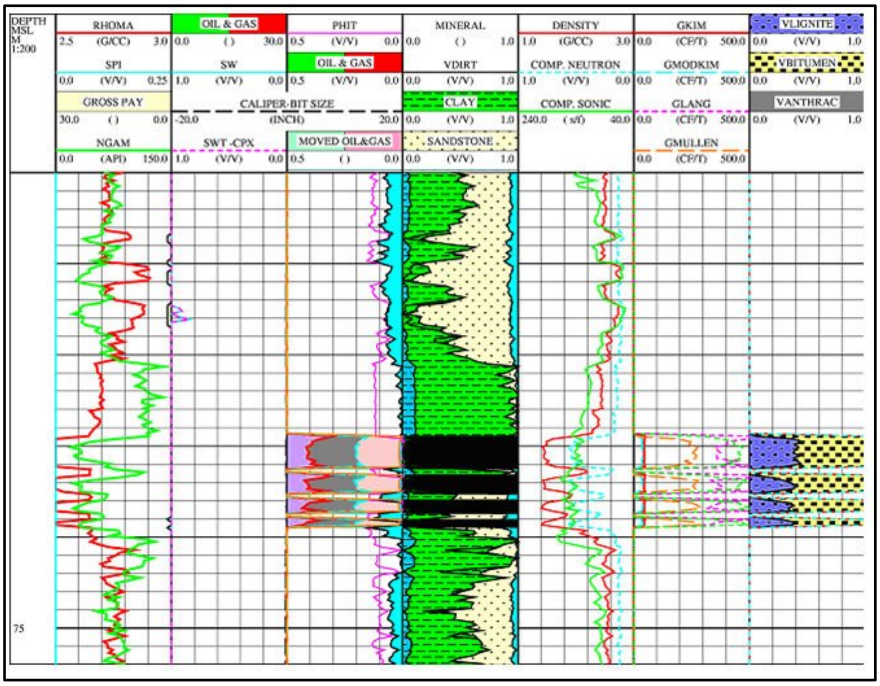


Figure 3.8 Well log curves which show the response of Coal Seam Gas (Courtesy Petrolog).

Figure 3.8 show some log responses of coal and rocks surround. The picture shows that coal has low density, Vp, and Gamma Ray compare to the shale.

3.6.2 Seismic Response of Coal Seam Gas

Because of coal's extreme low density and P-wave velocity, CSG will give the apparent amplitude response in seismic record. It becomes the reasons of why the not-so-thick or almost thin CSG thickness still able to identify in seismic, because the vertical resolution is no more $\lambda/4$ but change into $\lambda/8$ (Gochioco, 1991), where λ represents wavelength.

Actually, the vertical resolution of seismic itself did not change into $\lambda/8$ but still in $\lambda/4$ value. But the occurrence of CSG will enhance the seismic visibility coal, it is important to remember that the seismic response of other rocks will remain the same, not change into $\lambda/8$.

The picture below shows the example of high amplitude response in seismic data which given by CSG. For shallow CSG exploration, High Resolution Seismic might be the appropriate method to use to, where dominant frequency range between 50 – 150 Hz. The next picture below shows the result of High Resolution Seismic for CSG in 150 metres in depth with dominant frequency 120 Hz.

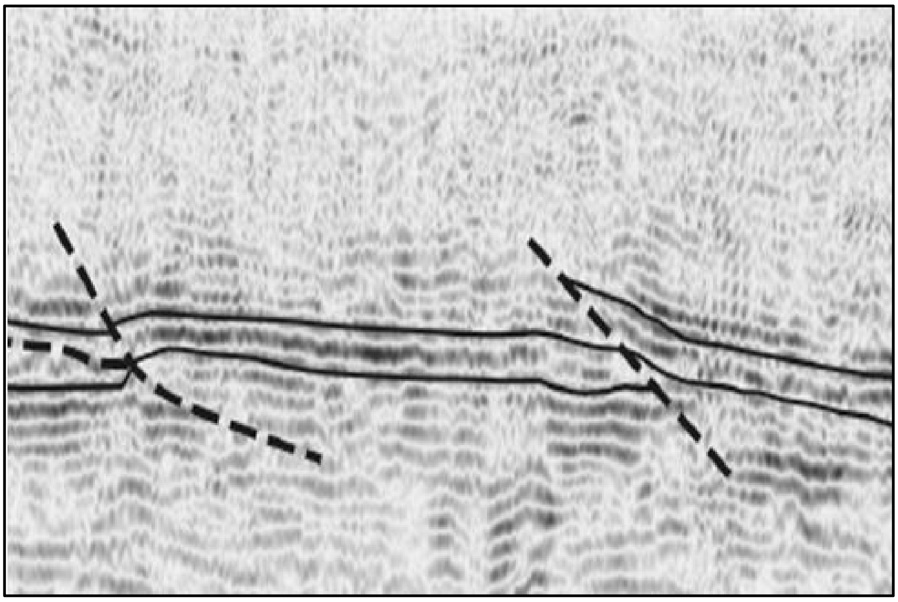


Figure 3.9 Seismic response of Coal Seam Gas (Courtesy Troy Peters and Natasha Hendrick, Velseis Pty Ltd)

CHAPTER 4
METHODOLOGY

This research used the model based acoustic impedance inversion which intended to image the existence of coal seams gas in Patchawarra FM. The method itself has a workflow to follow to, as explained in this chapter. The work presented in this research was created using Hampson-Russell Software and Geographix Discovery Software.

4.1 Data Support

Data required to perform seismic acoustic impedance inversion are seismic data, well log data, and checkshot survey as time to depth conversion between seismic and well log data. This research gets the additional data, which is formation tops, which could help the interpretation.

4.1.1 Seismic Data Description

Seismic data which has been used for this research is Spinel field, seismic field operations conducted by Great Artesian Oil and Gas consists of recording of 495 km^2 during December 2006 – April 2007. Record length of this seismic data is approximately 30004 ms which consists of 1000 inlines and 950 crosslines. The geometry of the seismic data shows in Figure 4.1.

Government of South Australia, Primary Industries and Resources SA, has been released this post-stack time migration zero phase with 4 ms sample interval seismic data of Spinel field as open file for public research. Unfortunately, the pre-stack data are not available in the public dataset.

Polarity of this data is normal polarity, with assumption increasing impedance will shown as peak and vice versa. This polarity might be checked by investigating the seismic response of coal seams, which present in this research data.

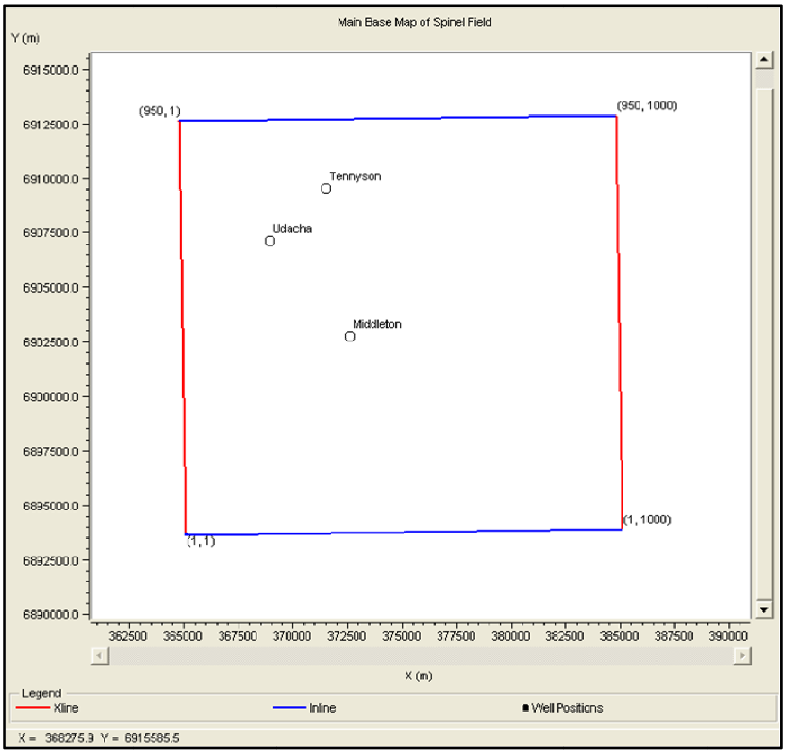


Figure 4.1. Main base map of 3D seismic data along 3 complete wells within (STRATA, Hampson-Russell Software)

4.1.2 Well Log Data

Actually, there are 6 wells which located within the seismic data area, 4 of them belong to Beach Petroleum (Beach Energy nowadays), one of them belongs to Great Artesian Oil and Gas, and the rest belongs to Santos. However only 3 wells that could be used in this research. It caused by the incompleteness of another 4 wells that provide Gamma Ray log data only. Nevertheless, these 4 wells still used to help the well log correlation in the further. The location of these 3 complete wells within seismic area shows in Figure 4.1.

Table 4.1 Well database within the research area.

Well Name	CAL	GR	SP	RLD	RLS	LLD	LLS	RHOB	DT	DTL	Sonic	NPHI	PEFZ	Checkshot
Udacha	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Middleton	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Tennyson	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Smegsy		√												
Carrickalinga		√												
Aratna		√												

The three wells which fulfill the requirements for seismic inversion process provide 3 sonic logs and 2 density logs (exception for the Tennyson which only provide 1 density logs but still 3 sonic logs). The sonic logs that available are DT, DT long spacing, and Sonic Velocity; while the density logs that available are RHOB (high resolution density logs) and RHOZ (standard density logs).

The density logs that preferably to be used is the high resolution density log one (RHOB), but the Tennyson well still using RHOZ since no RHOB available in this well. Meanwhile, the 3 sonic logs curve must be overlap plotted in order to see which sonic log that provide the better measurement, hence the DT long spacing chose to be used in the further research.

4.1.3 Checkshot Survey

Since both well log and seismic data has different domain, well log in depth domain while seismic data in time domain, the time to depth conversion is needed. Checkshot survey is the time to depth conversion that used in this research.

Although the checkshot survey is available for all 3 wells, these checkshot surveys are preferably not used. It caused by the bulk time shift of this checkshot survey are too high, approaching 0.5 s. In such way, the checkshot survey that preferable to use is checkshot survey that derived from sonic log (DT long spacing).

4.2 Well Log Correlation and Basic Log Interpretation

Generally, geological marker or formation tops are picked and correlated to each well, in exception for coal marker. In this research, the formation tops for all wells are already provided; hence the next thing to do is investigating those formations in order to do the basic log interpretation and determining the area of interest by using the quick look method.

The well log correlation for 3 wells is shown in Figure 4.2.

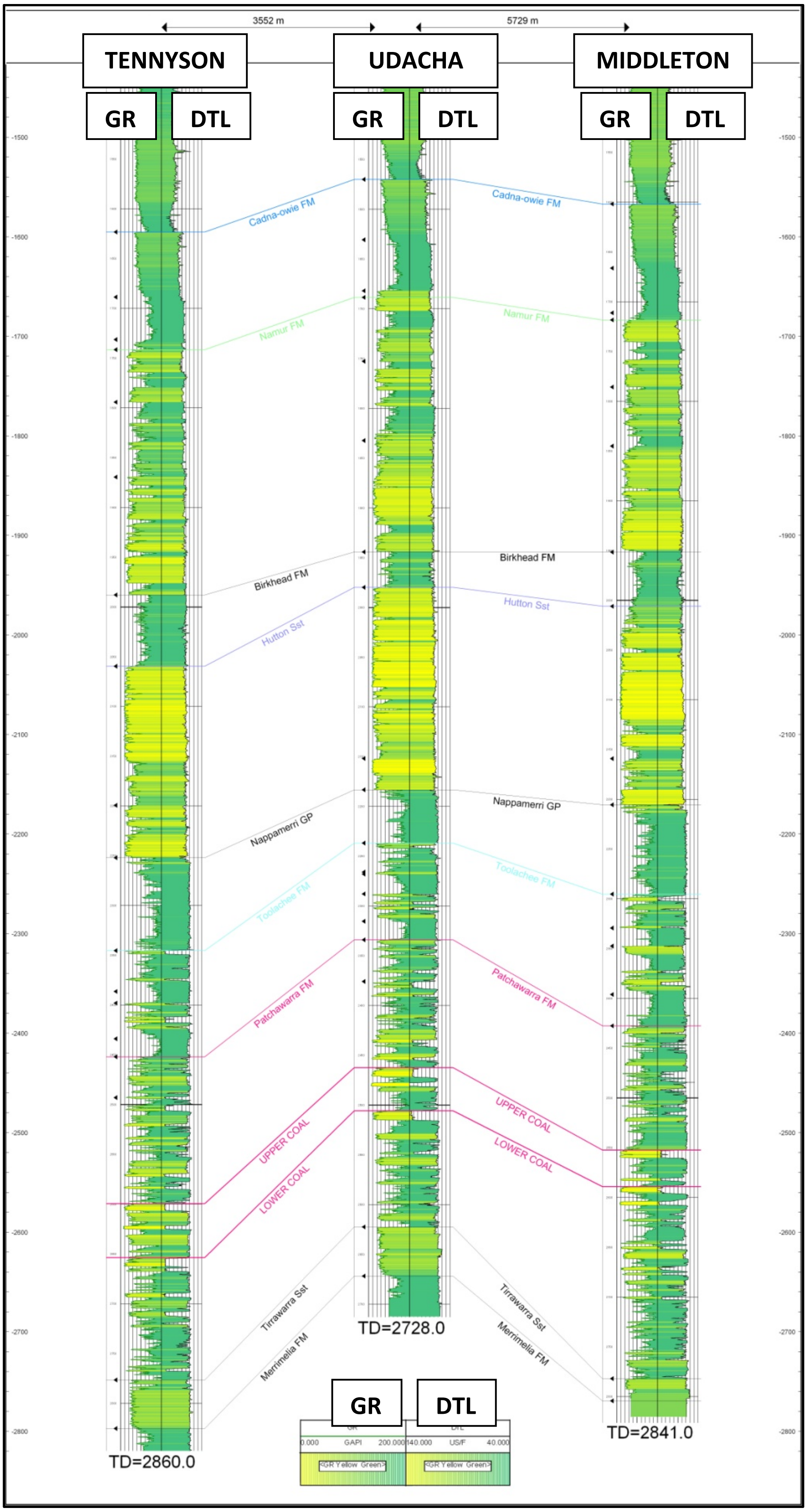


Figure 4.2 Well log correlation starts from Cadna-owie FM between 3 main wells: Tennyson, Udacha, and Middleton (XSection – Geographix, Landmark Discovery Software)

As explained in the chapter 3, coal has unique characteristics which are extremely low density and P-wave velocity, high neutron-porosity and sonic logs, and low gamma ray. Thereby the identification of coal seams gas by using this quick look method can easily determine, hence the prospect coal seams gas could be marked.

This basic log interpretation also shows that there is no conventional hydrocarbon prospect besides coal seam gas although the regional geological stratigraphy said there are some oil prospects in several formations.

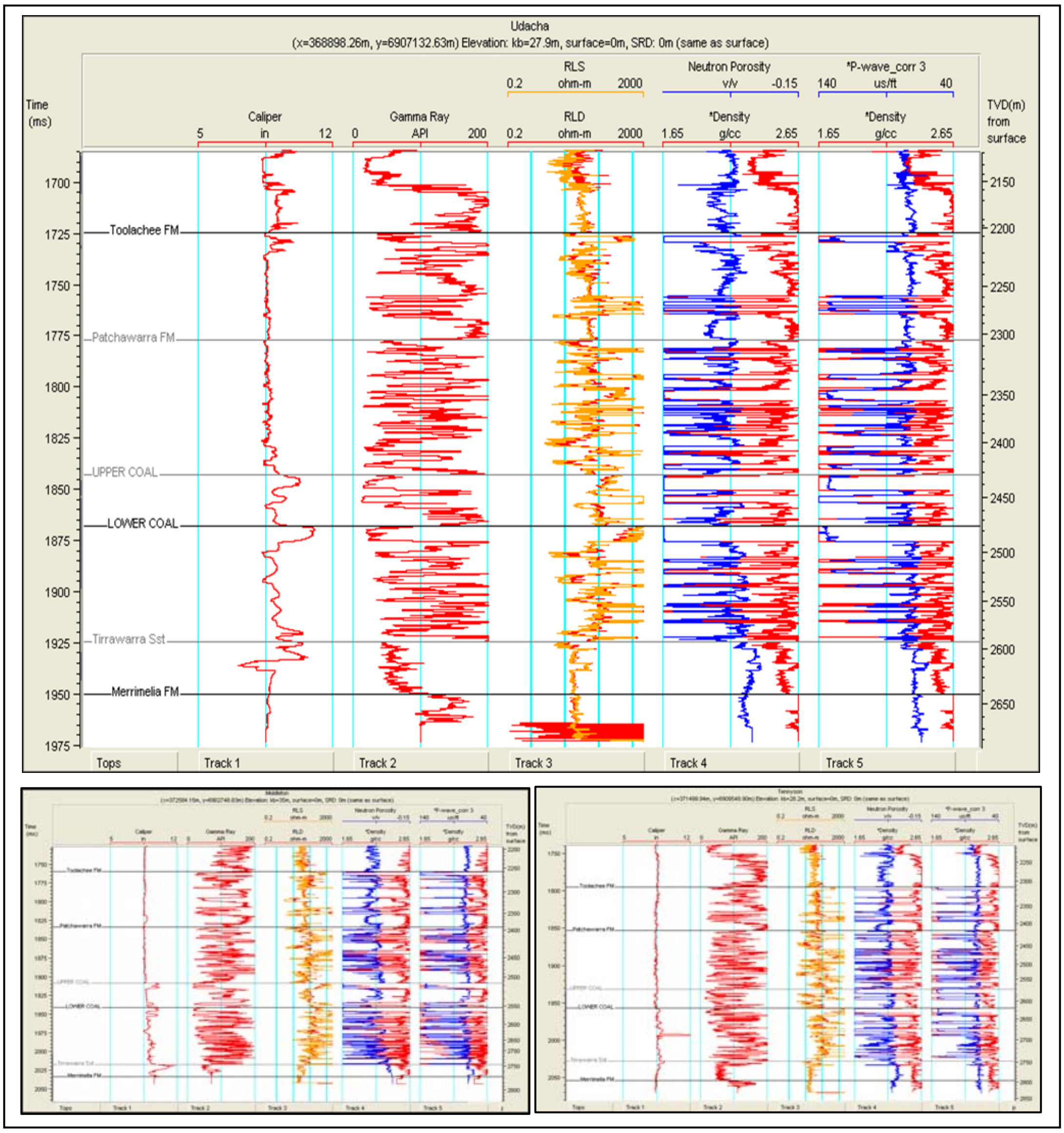


Figure 4.3. Quick look basic log interpretation of Udacha (2150 – 2650 m), Middleton (2200 – 2800 m), and Tennyson (2250 – 2850 m). Coal Seam Gas noted in almost along the Patchawarra FM and easily noticed by the low RHOB and GR, also the high NPHI and DTL (ELOG, Hampson – Russell Software).

4.3 Rocks Physics Analysis

Notwithstanding the basic log interpretation could give the prospect zone, further rocks physics analysis should be performed. Besides able to enhance the basic log interpretation in determining prospect zone, it is also necessary to investigate whether there is lithological separation or not because it will represents lithological sensitivity.

The investigation performed by creating several lithological crossplot such as Acoustic Impedance vs Gamma Ray, Acoustic Impedance vs Density, Acoustic Impedance vs Neutron-Porosity.

Data used in rocks physics analysis are generated and derived from well log data with the data range the prospect zone only as determined before by using basic log interpretation. Figure 4.4 shows the rocks physics analysis of the Udacha well and its cross section.

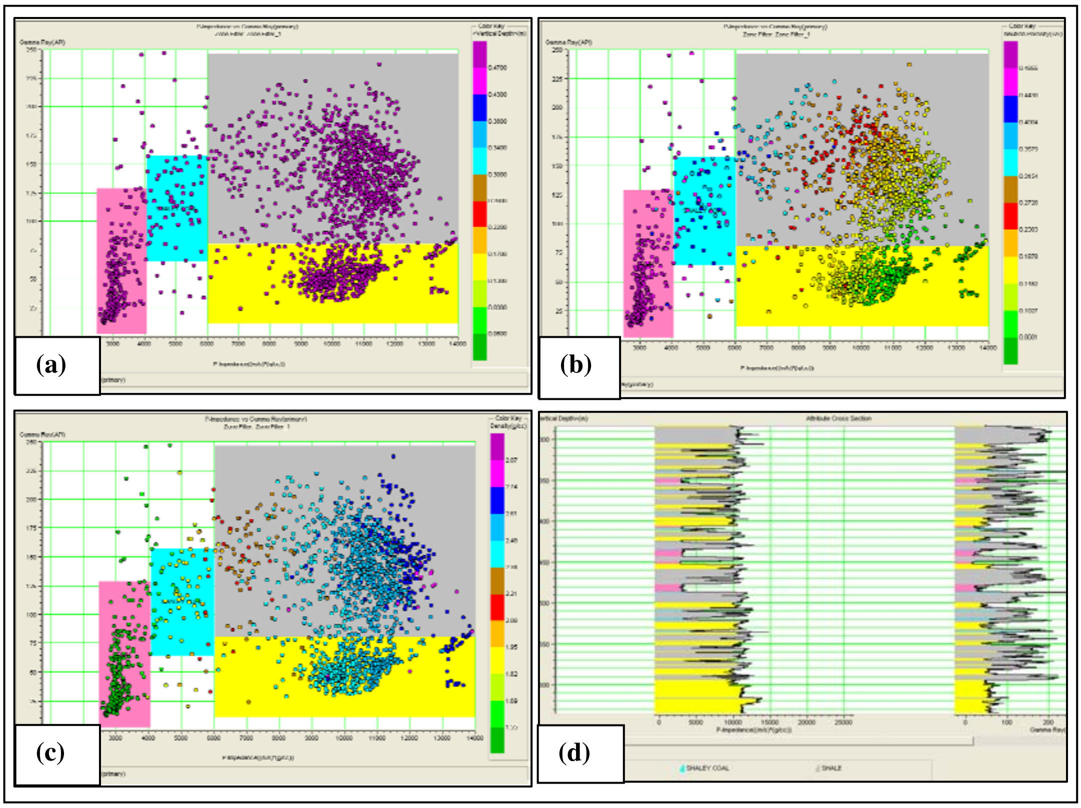


Figure 4.4 Lithological crossplot of Udacha well for AI vs GR using color key: (a) Vertical Depth, (b) Neutron Porosity, and (c) Density; also its cross section. Coal marked in the pink zone, shaley coal in the blue zone, shale in the grey zone, and sandstone in the yellow zone. (ELOG, Hampson – Russell Software).

4.4. Wavelet Extraction and Well to Seismic Tie

Both basic seismic interpretation and seismic inversion algorithms require information about the seismic wavelet, first it is needed to perform well to seismic time, and later it is needed to perform inversion.

In tying the well log data to seismic data, checkshot velocity survey must be applied first. By doing this, bulk time shift will be showed, if the bulk time shifts relatively small (< 20 ms) therefore the well seismic tie process might be continued. But when bulk time shifts relatively big (> 20 ms), the checkshot survey must be edited first by summation or reduction factor of bulk time shift.

After the checkshot survey looks reasonable, the well seismic tie process might be continued first by wavelet extraction using statistical, then continue to wavelet extraction using well. There are three categories of wavelet extraction methods: deterministic, statistical, and using well. This research using two methods only those are statistical and using well.

Actually, when well to seismic tie performed, the first wavelet used is ricker wavelet 30 Hz. Because the wavelet extraction before well to seismic tie might cause the inappropriate extracted wavelet.

After using the ricker wavelet, we get the more reliable correlation between well and seismic. Then the wavelet extraction might performed, the first method to use first is statistical method which is estimating the wavelet from the seismic data individually. In using this method, the seismic phase must be known first, then setting it up after determining the extraction window length. In this research, the seismic phase known as zero and so do the statistical method set up. Other parameters to set are also the extraction window length, wavelet length, and algorithm used.

This research sets the extraction window length throughout the target zone, 1850 ms – 1950 ms, and wavelet length 128 ms. Whereas the algorithm used is roy white algorithm, because it can produce the better extracted wavelet compare to the full wavelet algorithm). Figure 4.7 (above). shows the extracted wavelet using statistical method.

Well to seismic tie then continued applying the extracted wavelet using statistical until the maximum correlation between well and seismic is reach. Then the wavelet extraction using well is performed. This method combines the well log and seismic information. Theoretically, it could provide exact phase information at the well locations. However, this method depends critically on the depth to time conversion and mis-ties might degrade the result significantly. Hence this extraction method preferably performs after well to seismic tie reach the maximum correlation when statistical extracted wavelet applied.

Figure 4.7. below shows the extracted wavelet using statistical for Udacha well with parameter setting roy white algorithm, extraction window length 1700 – 2000 ms, wavelet length 128 ms, and time shift removed. This extracted wavelet using well then used to make the better well to seismic tie.

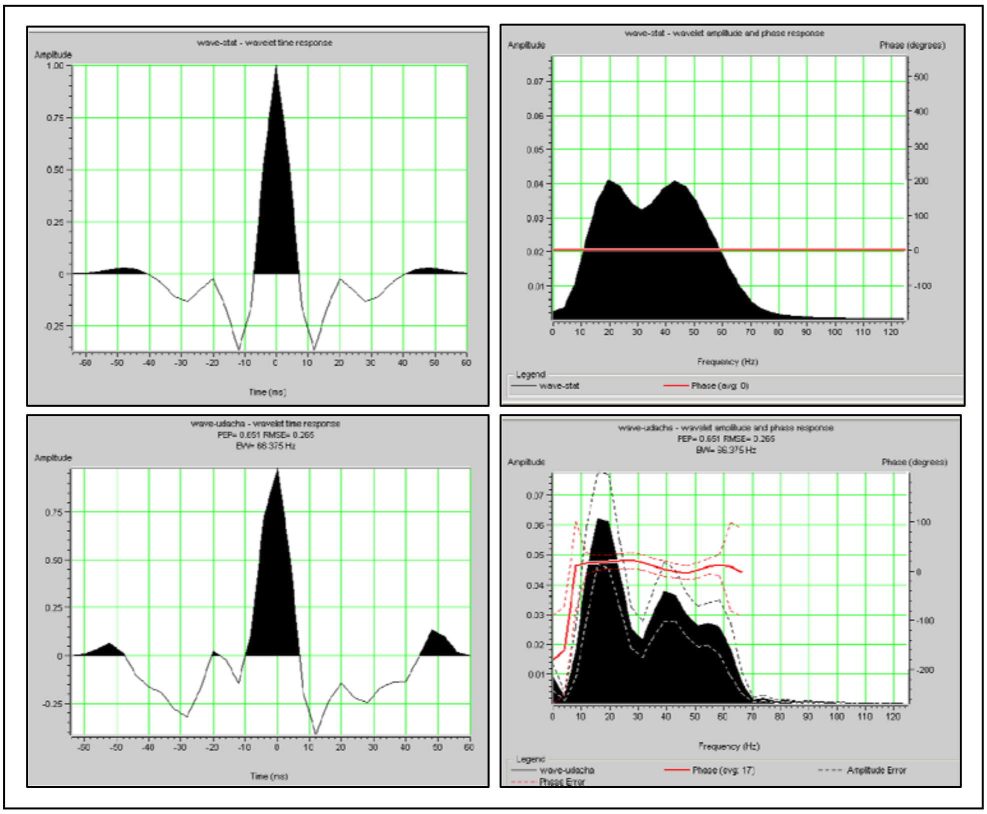


Figure 4.5 Extracted wavelet and its frequency using statistical (above) and using Udacha well (below) (ELOG, Hampson – Russell Software).

Figure 4.6 shows the final well to seismic tie process of the three wells where Udacha reach the good correlation coefficient 0.710 in correlation window 1350 – 2000 ms (650 ms). Tennyson and Middleton also reach the fine correlation coefficient those are 0.629 and 0.647.

To get the more reliable extracted wavelet, the wavelet extraction using well might performed once again. But there is no guarantee that the extracted wavelet using well might be better to use in seismic inversion compare to statistical extracted wavelet. To determine which preferably wavelet for seismic inversion, the inversion analysis might be help. This analysis will explain in the further sub-chapter.

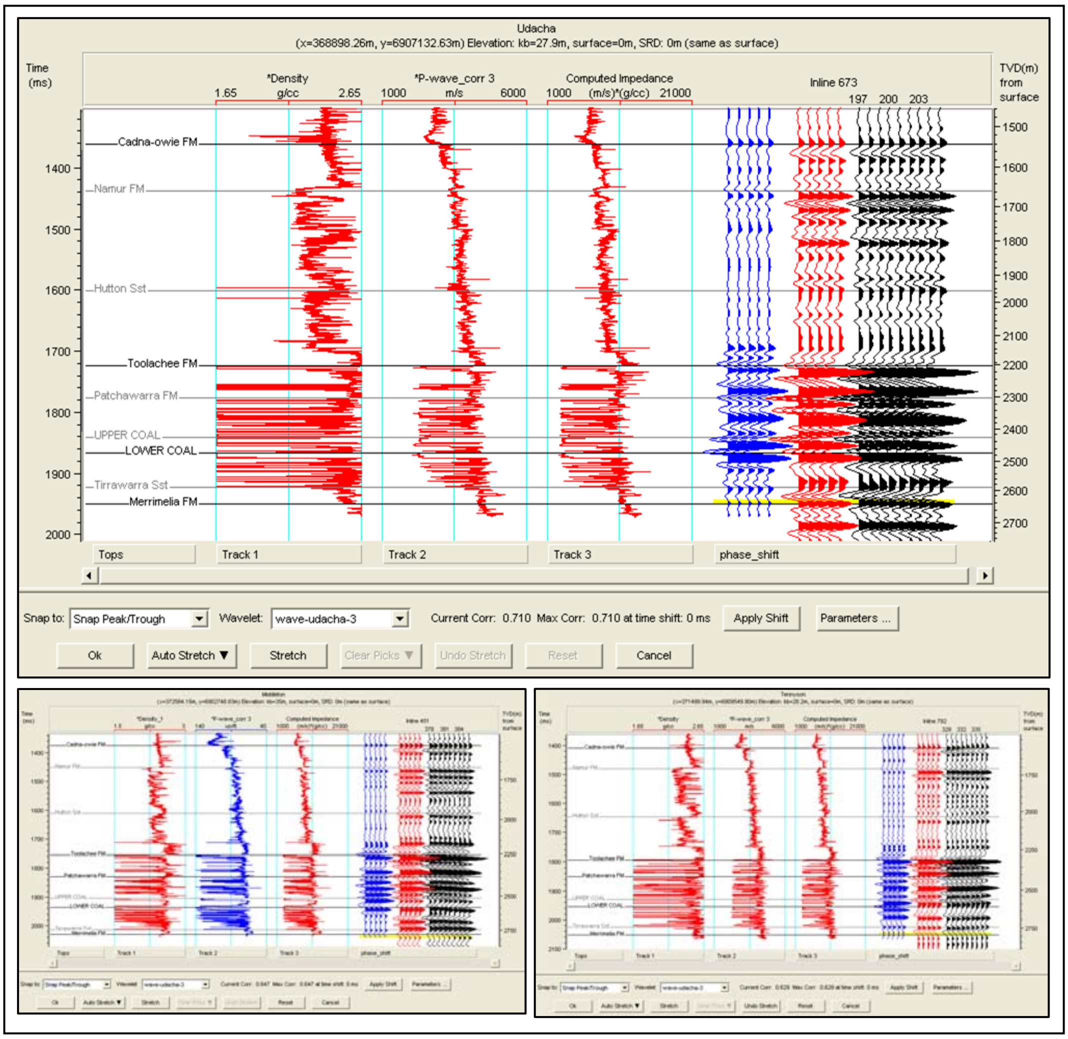


Figure 4.6. Well to seismic tie process on Udacha well gives good correlation coefficient, 0.710. The other wells also gives fine correlation coefficient: Middleton (0.647) and Tennyson (0.629). (ELOG, Hampson – Russel Software).

4.5 Basic Seismic Interpretation

Basic seismic interpretation is still needed as guidance for further research, in this case acoustic impedance inversion. The first thing to do in basic seismic interpretation is plotting the well log data which had been tied before and approaching fine to good correlation coefficient between synthetic seismogram and seismic traces around borehole.

4.5.1 Structural Picking

Spinel field is located in Patchawarra Trough, one of the main depocentre in South Australia. As seen in the seismic section, there is no major structure besides faulted anticlinal structure on the western margin of the Patchawarra Trough. This major structure cannot be seen clearly in the inlines, but clearly identify in crosslines because it is perpendicular to the fault plane.

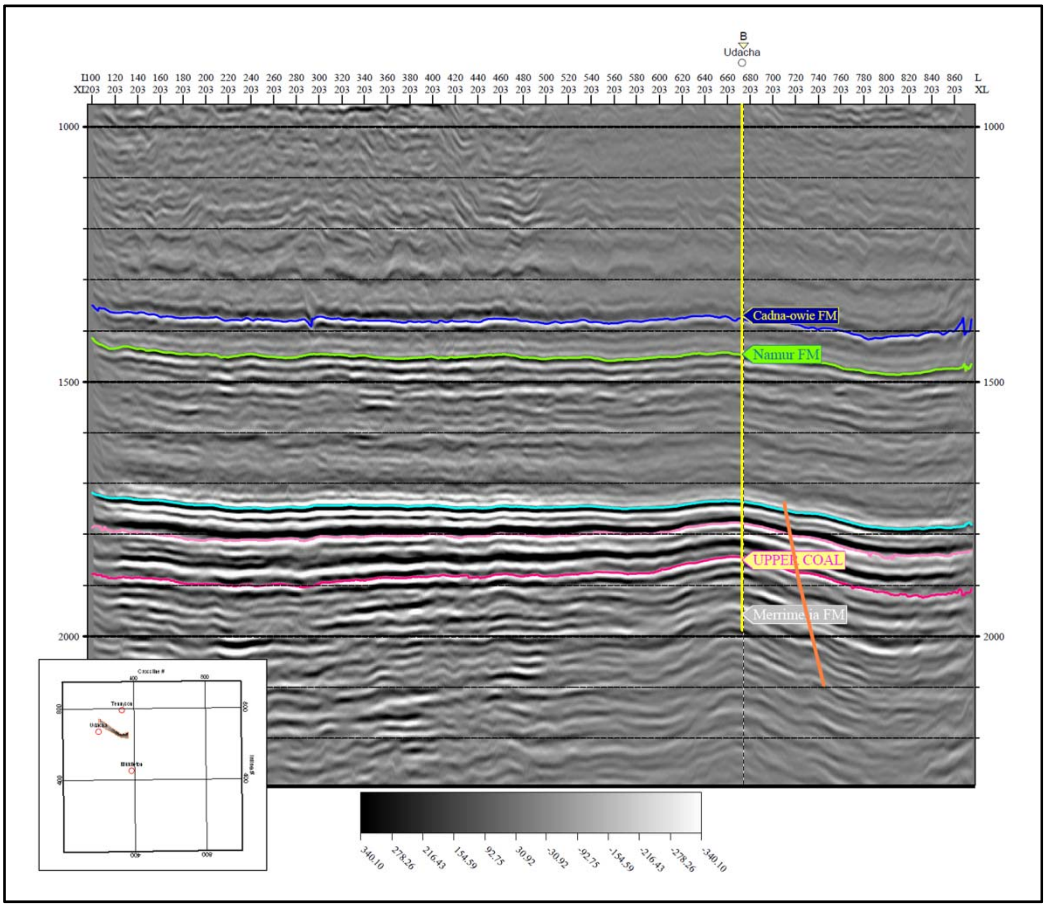


Figure 4.7 Faulted Anticlinal Structure identified in Crossline 203. Map index in the bottom left shows the small fault plane. (SeisVision – Geographix, Landmark Discovery Software).

4.5.2 Horizon Picking

Horizon picking starts from the seismic lines which has much marker from the well, the alternate way is picking the horizon throughout arbitrary line with increment 10 lines.

After the horizon pick seems continues and reasonable, horizon picking continues throughout inline and crossline with increment 5 lines. And after the horizon looks more reasonable, the details horizon could be picked by using increment 1 line.

Not all formation tops are picked as horizon in this research, only the formation tops in the non-marine succession are picked as horizon. The horizons picked are Cadna-owie FM as the boundary between non-marine and marine succession, Namur FM, Toolache FM, and Patchawarra FM. Upper Coal and Lower Coal, which become the target zone, are located in Patchawarra FM.

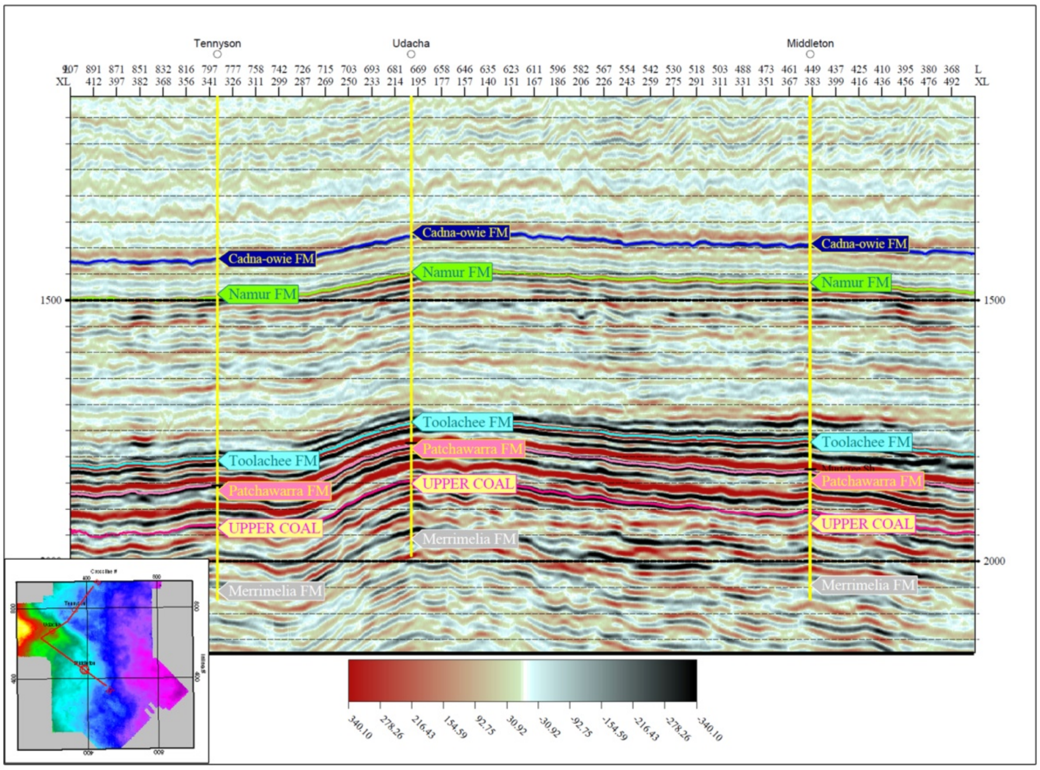


Figure 4.8 Horizon picking displayed in arbitrary line throughout 3 main wells: Tennyson, Udacha, and Middleton (SeisVision – Geographix, Landmark Discovery Software)

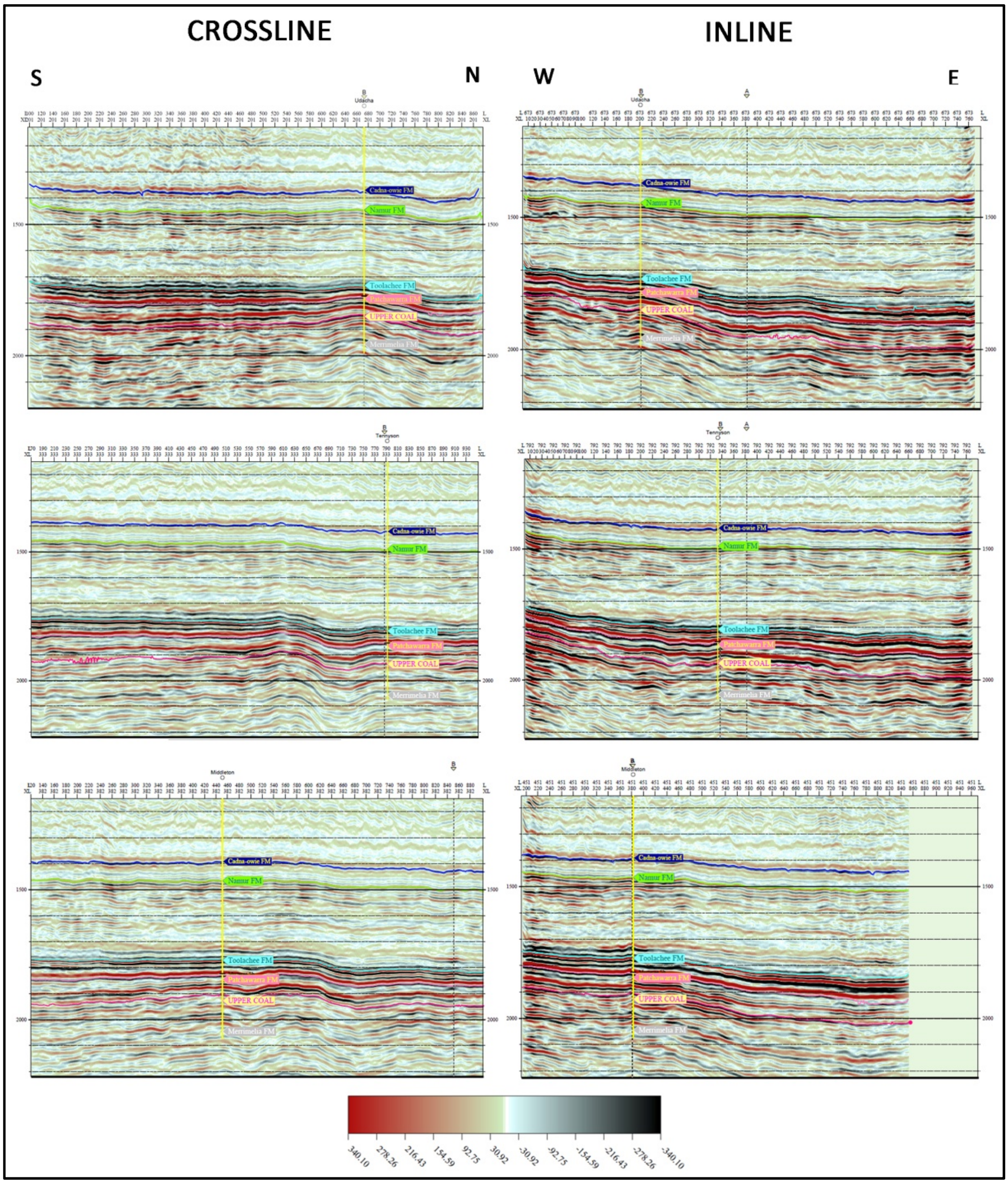


Figure 4.9 The seismic section which cross over the 3 main wells. (SeisVision – Geographix, Landmark Discovery Software)

Picture in the above shows how the horizon picked throughout the three wells, both in crossline and inline. In slight-seeing, the deposition environment in the target zone is relatively flat, exclude in the northwest of the research area. The interpreted anticlinal faulted zone is the only dominant structure in the research area.

4.6 Seismic Inversion

Seismic inversion can be described as "a procedure for obtaining models which adequately describe a dataset" (Treitel et al., 1988). In the case of seismic exploration, our recorded seismic traces show the effects of the rock physical properties on elastic waves propagating through the earth. Inversion process allows us to estimate these physical properties.

Inversion process often relies on forward modeling, which uses a mathematical relationship to generate the earth's response for a given set of model parameters. For example, we can generate a synthetic seismogram using the elastic wave equation and a model containing the wave velocity and density parameters. Inversion process can be seen as a "reverse" of the forward modeling: for a given dataset, find a model, which reproduces the observations.

4.6.1 Acoustic Impedance Earth Model

Before performing any post-stack inversion, the earth model must be generated by using the 3 wells. The initial guess model built by 3D interpolation of the impedance logs, which is the multiplication of the sonic and density logs. Picked seismic horizons are used to introduce structural information in the interpolation. Model might be generated whether applied high cut filter, running average 5 samples, or without any filter.

The model that will be used in the model-based inversion is the model which has the better the inversion analysis, in this case the better correlation coefficient of the inversion. Figure 4.10 shows the initial guess model using high cut filter. Both with or without filter model might be used in the seismic inversion, but will give the different result. No filter initial guess model will give the more details acoustic impedance within the model.

4.6.2 Acoustic Impedance Inversion Analysis

Before performing the model based inversion, it is preferably if performing the inversion analysis first. It is necessary to choose the most appropriate wavelet for using in model based inversion.

The inversion analysis showed that the most appropriate wavelet that might be used in the further is extracted wavelet using Udacha well. It is well-matched even in another wells.

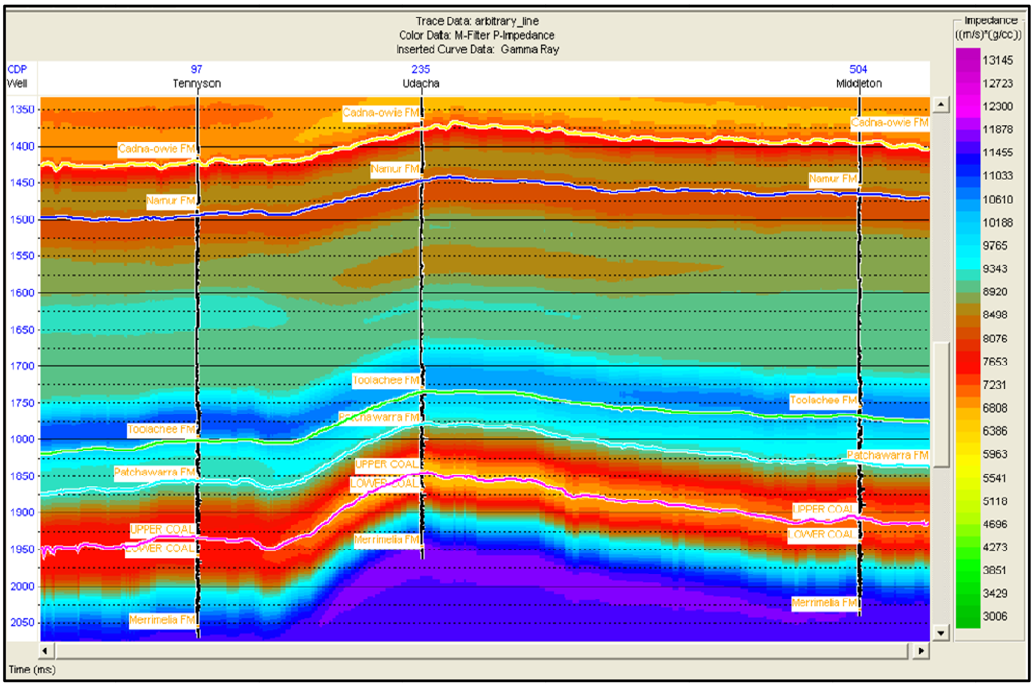


Figure 4.10 Initial model of the research area throughout arbitrary line if high cut frequency filter applied (STRATA, Hampson-Russel Software)

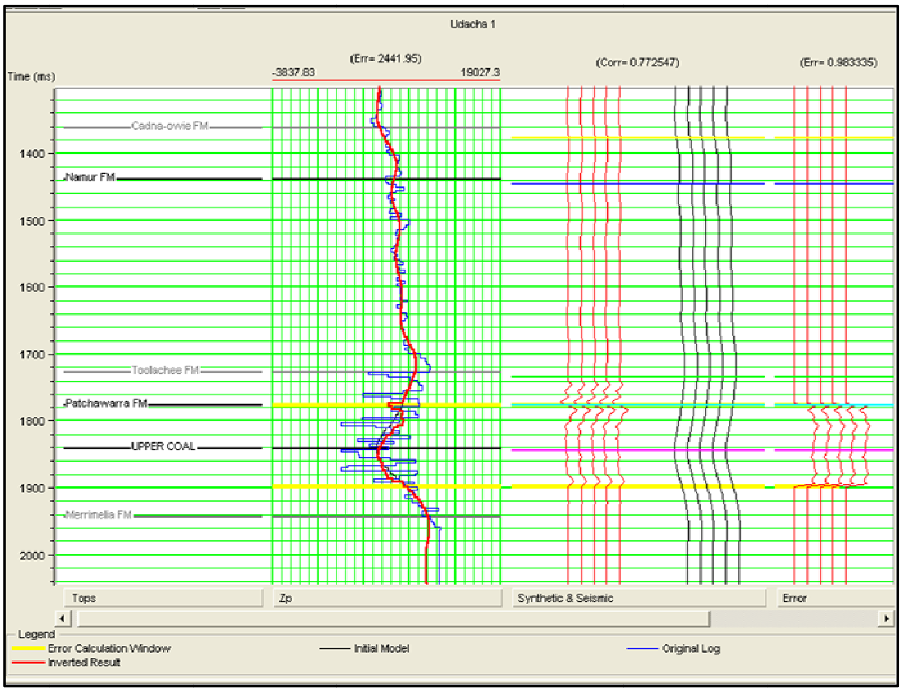


Figure 4.11 Model-based acoustic impedance inversion analysis of Udacha well shows correlation approach 0.77 (STRATA, Hampson-Russel Software).

4.6.3 Model Based Acoustic Impedance Inversion

Figure 4.12 is an arbitrary line of the model-based inversion result. The wells that are known to produce hydrocarbon including coal seam gas are associated with low-impedance values. Meanwhile, Udacha well is located in a low-impedance area as shown as the yellow color surround by the higher impedance.

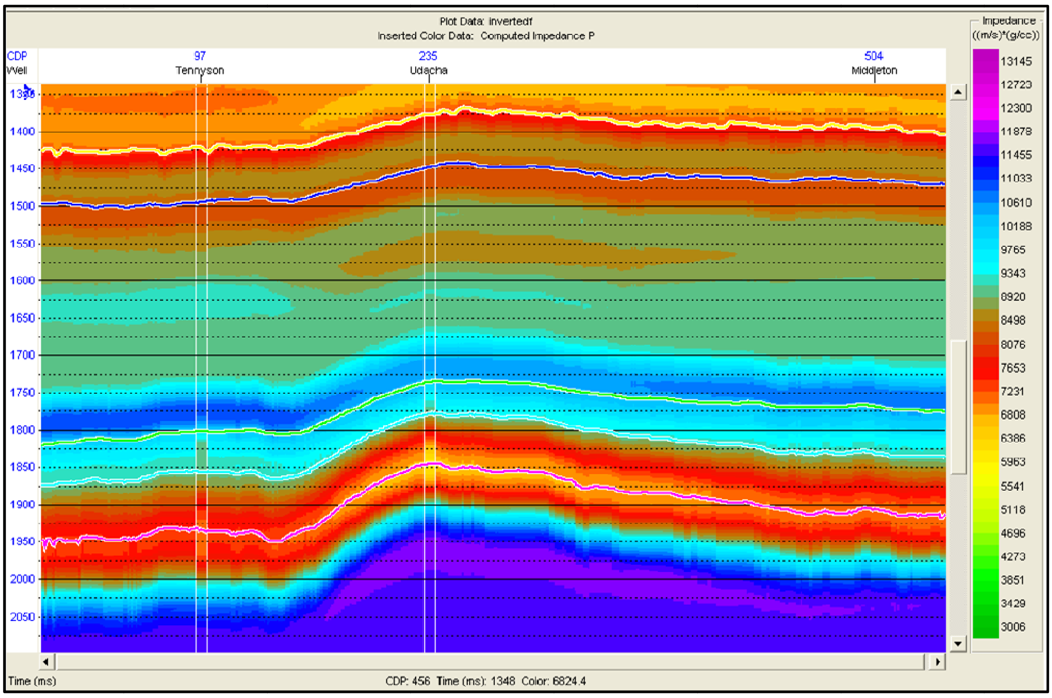


Figure 4.12 Model-based acoustic impedance inversion result of the research area throughout arbitrary line (STRATA, Hampson-Russel Software).

CHAPTER 5
RESULTS AND ANALYSIS

The integrated analysis based on the result of basic log interpretation, rock physics analysis, basic seismic interpretation, and seismic inversion. Every analysis will complete each others.

5.1 Basic Log Interpretation

Basically, the three complete wells (Udacha, Middleton, and Tennyson) are show numerous coal seams appearance in Patchawarra FM. Basic log interpretation in all wells are able to show those coal seams easily because of the uniqueness and easy-to-identify coal characteristics.

Figure 5.1. shows the basic log interpretation from Cadna-owie FM to the bottom of Patchawarra FM. By looking to these half-depth logs, the characteristics of coal seams are identified below the Toolache FM and numerically found within the Patchawarra FM. The significant low value of density (RHOB) follows with the significant high value of sonic (DTL) and neutron porosity (NPHI). All of these values are set in such a manner so they all aimed and touched at the left boundaries of the track curves.

The zoomed in display Patchawarra FM logs are shown in Figure 5.2. The thickest coal seams in all wells only reach 12 metres in maximum in Udacha well. It is clearly shown that the coals are not deposited as thick coal or coal bed, but deposited as numerous coal seams which interbedded with sandstone and carboniferous siltstone.

These numerous coal seams appear as the middle assemblages in Patchawarra FM in 2250 m – 2600 m in Udacha, 2250 m – 2750 m in Middleton, and 2300 m – 2750 m in Tennyson. These are became the target zone of the research, but it needs to be strengthen by analysing the rock physics of each well.

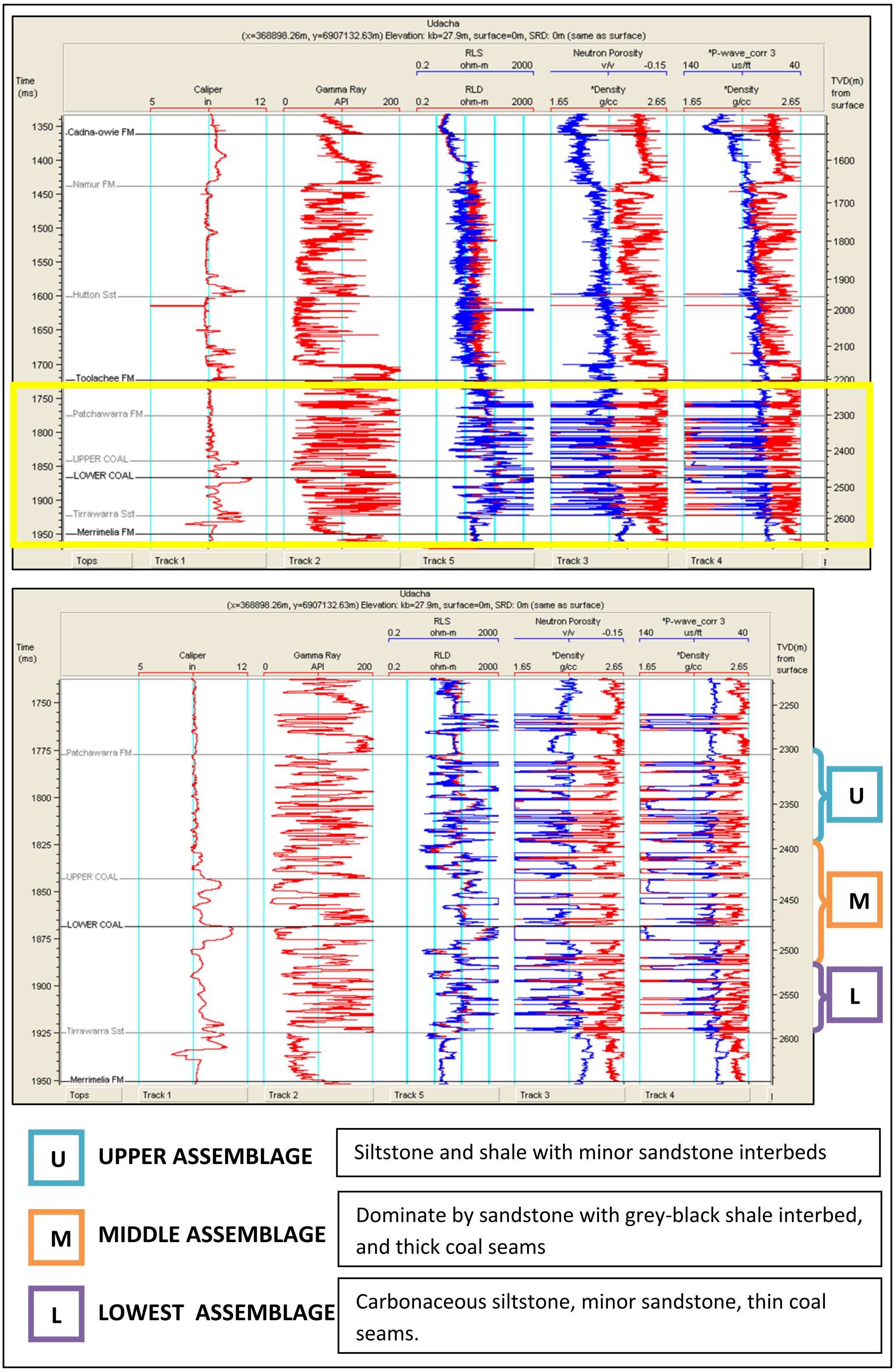


Figure 5.1 The summary of basic log interpretation of Udacha. The yellow area noted as the appearance of numerous coal seams gas which will be the target zone, and the formation itself could be defined into 3 assemblages. (ELOG, Hampson – Russell Software).

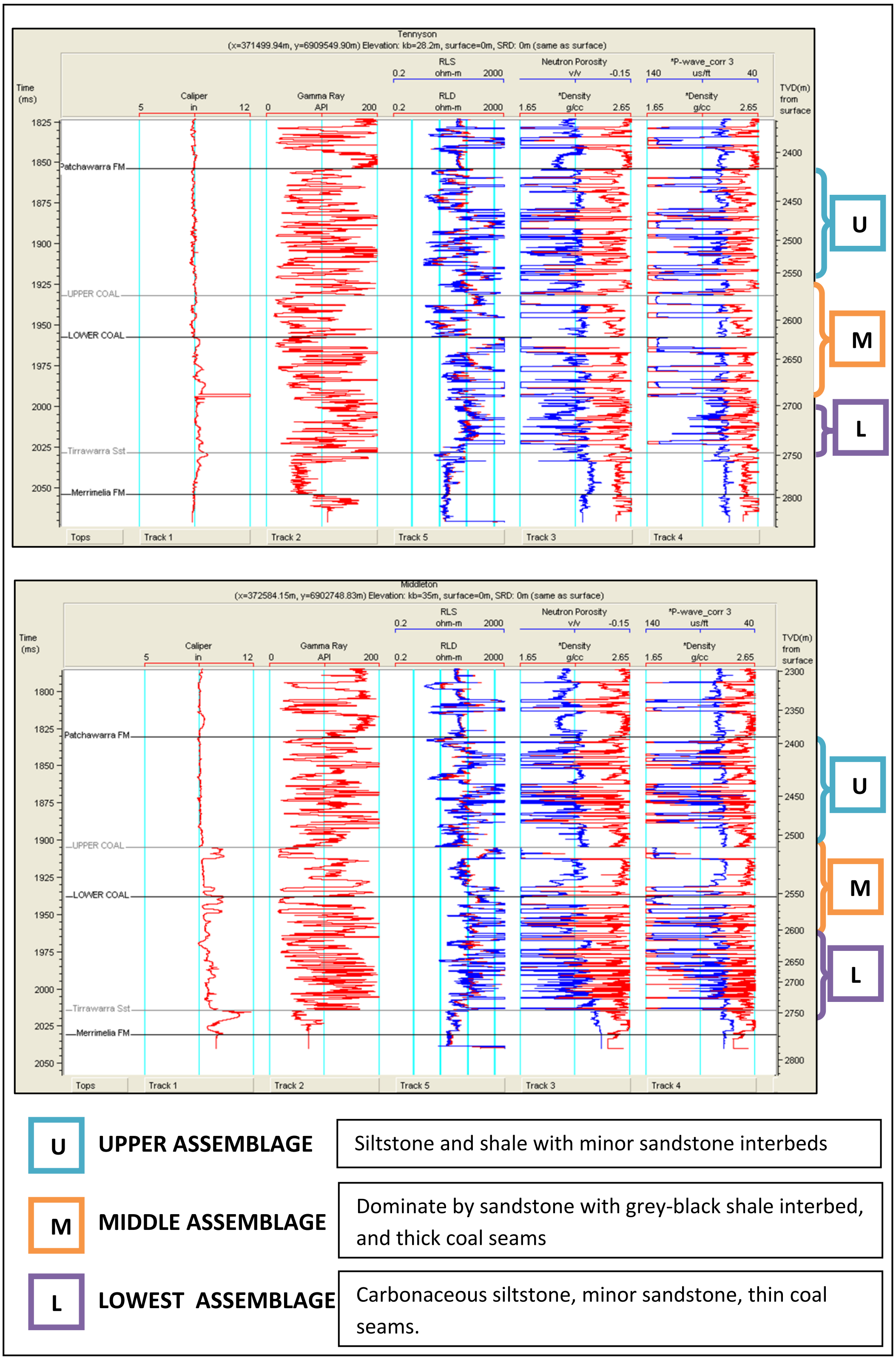


Figure 5.2 Three assemblages of Middleton and Tennyson in Patchawarra FM. (ELOG, Hampson – Russell Software).

5.2 Rock Physics Analysis

Target zone also identified by analysing the rock physics. Coal seams can be seen in general lithological crossplot: acoustic impedance vs gamma ray, acoustic impedance vs neutron porosity, and acoustic impedance vs density. Figure 5.3. shows lithological crossplot of acoustic impedance vs gamma ray using color key vertical depth. This crossplot then applied using another colour key such as neutron porosity and density as shown in Figure 5.4.

Coal identified as the low gamma ray and low acoustic impedance, high neutron porosity and low density. The crossplot below shows that there are some points that far separated from another points then identified as coal zone due to the low gamma ray, low In Figure 5.3 and Figure 5.4., the black coloured zone noted as coal, while the grey coloured zone noted as shaley coal.

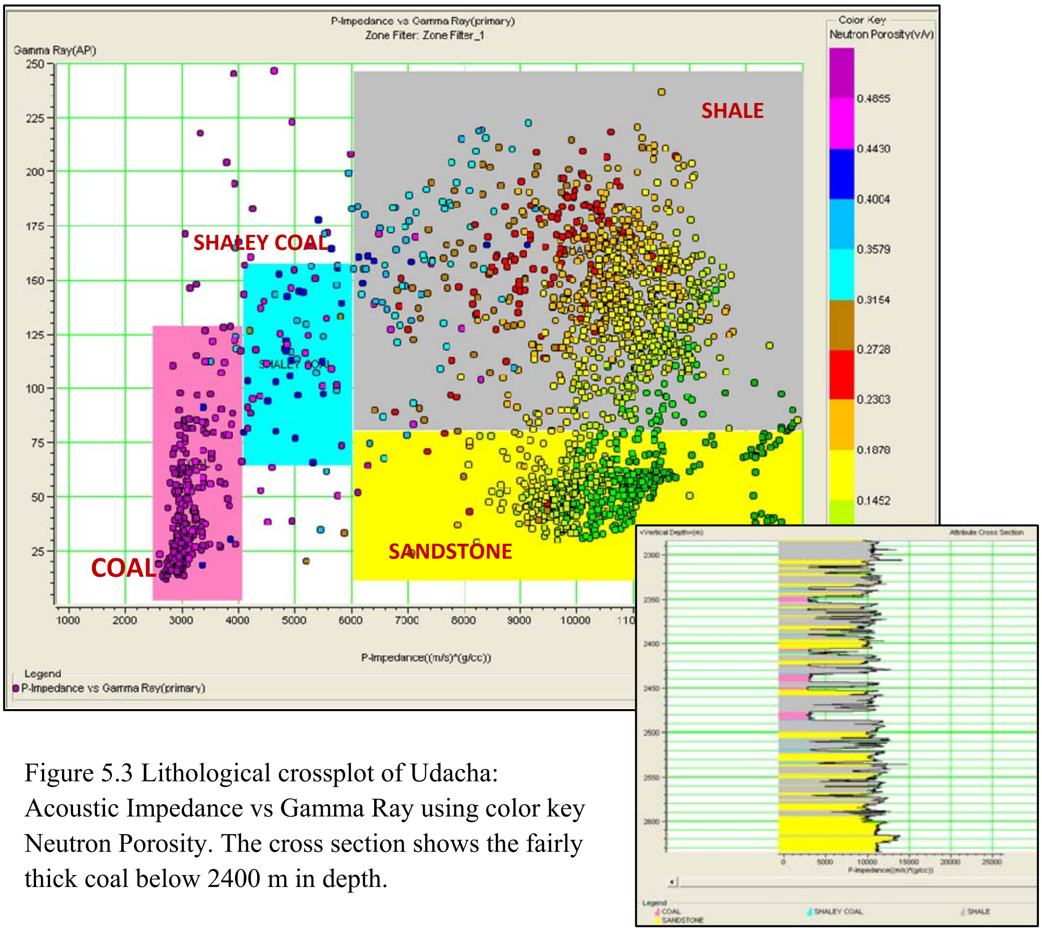


Figure 5.3 Lithological crossplot of Udacha: Acoustic Impedance vs Gamma Ray using color key Neutron Porosity. The cross section shows the fairly thick coal below 2400 m in depth.

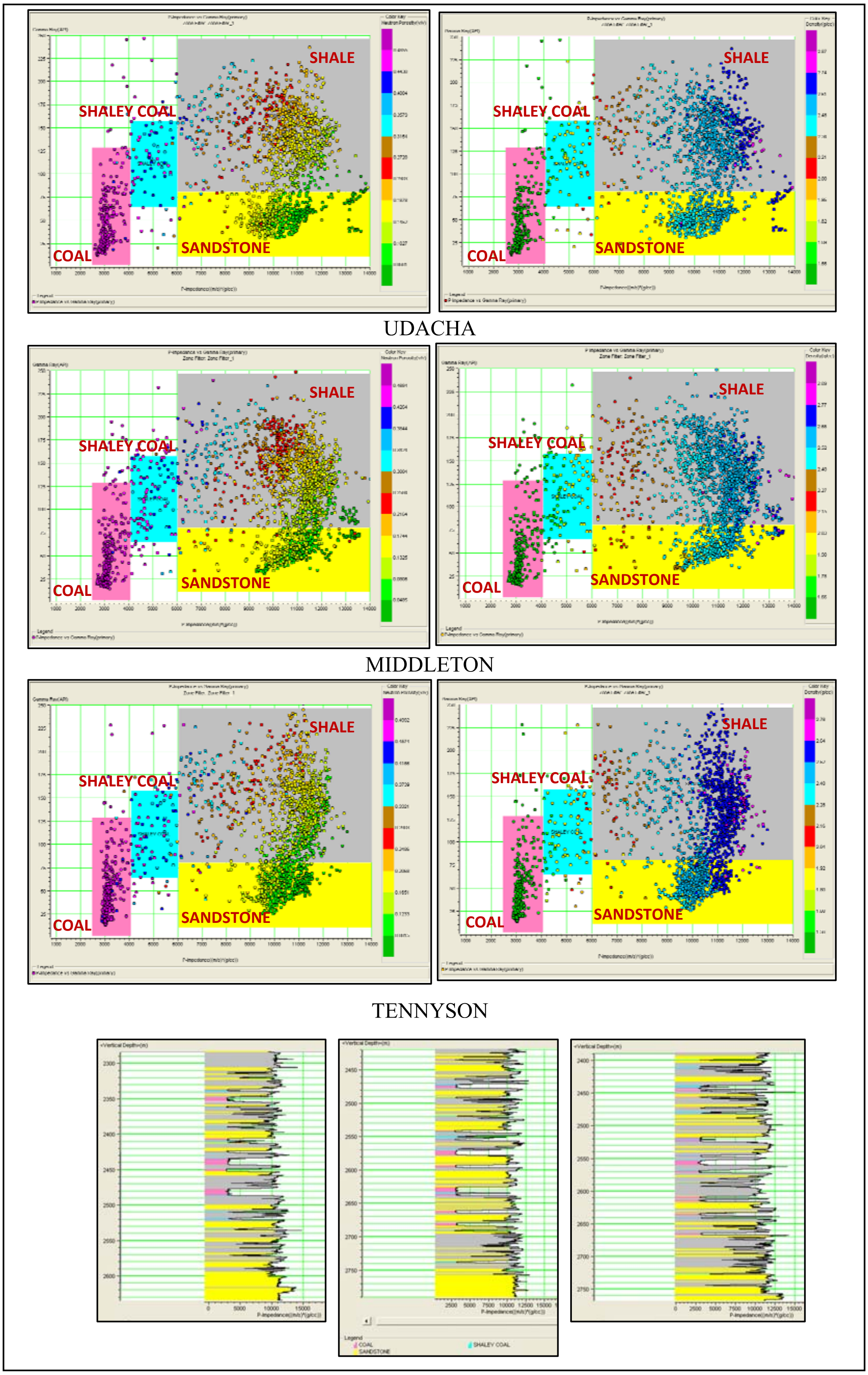


Figure 5.4 The summary of the crossplot and cross section of AI vs GR using color key Neutron Porosity (left) and Density (right). (ELOG, Hampson – Russell Software).

In Figure 5.4 the purple colour in colour key neutron porosity noted as the highest neutron porosity, while the green colour in colour key density noted as the smallest density. Both colours are allocated in the coal zone and shaley coal zone.

The well log data used in lithological crossplot are data in target zone only because the objective of performing crossplot is to see whether the target can be differentiated from the rocks around them or not. It is necessary to perform lithological crossplot because acoustic impedance inversion can be well-performed only if there are differentiated lithology.

Rocks which points are allocated in the right of the crossplot curves are sandstone and shale and difficult to differentiate each other. But, since the target zone is coal seams gas, the model based acoustic impedance inversion still can be performed. It is because coal seams gas can be differentiated with sandstone and shale.

5.3 Basic Seismic Interpretation

The result of basic seismic interpretation is time structure map of the target zone which is Patchawarra FM, the formation where the most numerous coal seam gas is located as interpreted in well log and rock physics analysis. Basic seismic interpretation is still necessary to bolster up the seismic inversion result later.

5.3.1 Structural Interpretation

Spinel field is located in Patchawarra Trough, one of the main depocentre in South Australia. As seen in the seismic section, there is no major structure besides faulted anticlinal structure on the western margin of the Patchawarra Trough. As explained in the chapter 2, Patchawarra Trough is a depocentre with generally northwest trending structures interpreted to reflect the wrench fault system.

This major structure cannot be seen clearly in the inlines, but clearly identify in crosslines because it is perpendicular to the fault plane. This faulted anticlinal structure starts to identify from crossline 203, crossline 220, until crossline 367. Actually this structure even starts from crossline 43.

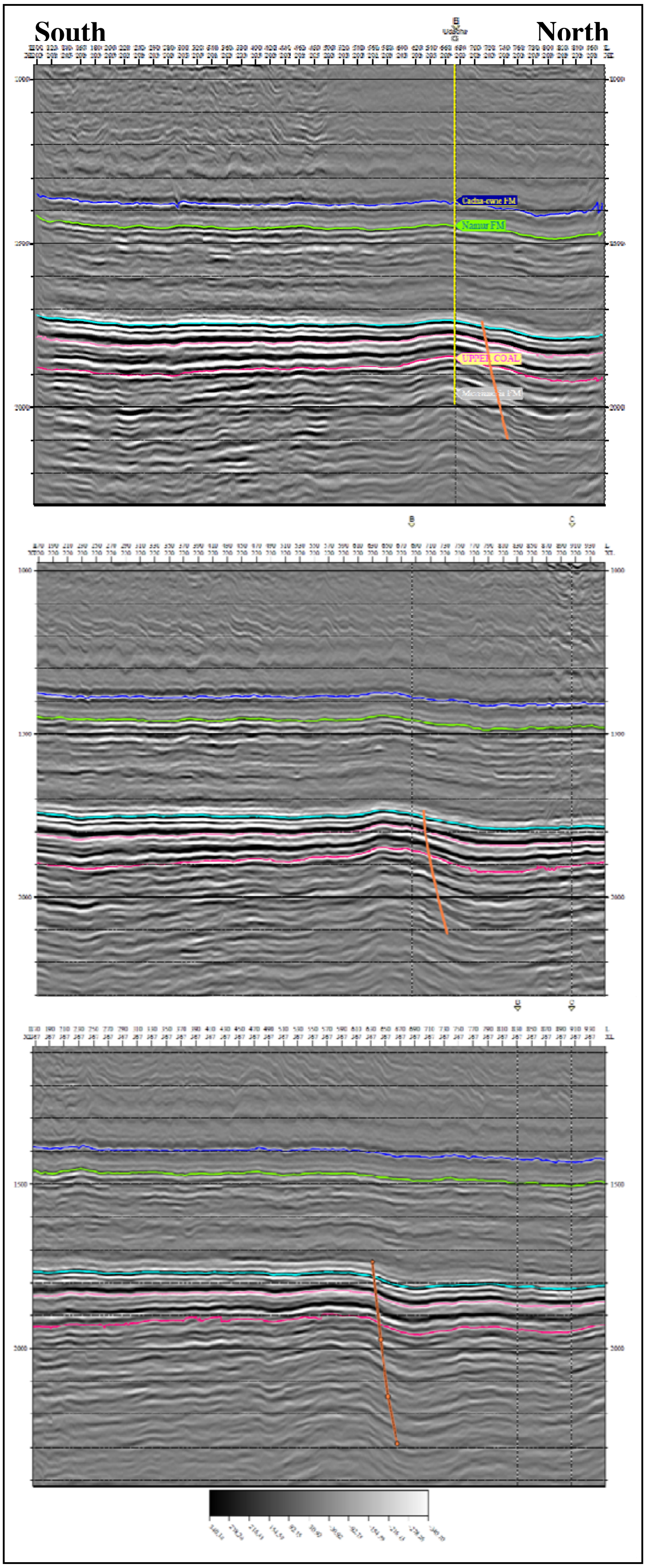


Figure 5.5 Faulted Anticlinal Structure identified from crossline 203, 220, until 367.

5.3.2 Horizon Interpretation

Patchawarra Trough, where the research area located, consists of numbers of formations, but only 5 formations picked in this research. These formations picked due to their depositional environment. Since coal seams are deposited in non-marine succession, the 5 formations picked are the formations which located in the non-marine succession.

The horizons picked in this research are Cadna-owie FM as the boundary between marine and non-marine succession, Namur FM as one of the formation that usually interpreted as prospect zone in another field, Toolachee FM as the second area of interest which also contains coal seams as seen in well log, Patchawarra FM as the first area of interest which contains numerous coal seams, and Merrimelia FM as the bedrock.

By understanding each main formation and its seismic responses, the research area could be defined into two successions: marine and non-marine, where Cadna-owie FM as the boundary between these successions. Since Coal Seam Gas only possible to occur in non-marine succession, then the marine succession could be ignored. The marine succession also can easily determined by looking the seismic reflection. As we can see, the seismic reflection gave the unclear reflection right above the Cadna-owie FM due to its depositional environment, which has been defined as transgression period.

Another interesting thing in the research area is we can describe the non-marine succession itself into two depositional environments: rapid accommodation and low accommodation. The environment said has a rapid accommodation when the sediment accumulated in rapidly in such short time, hence the seismic will gave the non-continues reflection as shown below the Namur FM.

Coal Seam Gas needs the stability of water table and quiescence tectonic to occur, hence the Coal Seam Gas is impossible to occur in rapid accommodation period. In such way, the interesting area is the formations which deposited in low accommodation period.

Actually there are some potential in the formations which are deposited in low accommodation period, but prior to the basic well log interpretation and simple rock physics analysis, the potential of Coal Seam Gas shown in the Patchawarra FM.

Theoretically, Coal Seam Gas will occur almost spread evenly in such formation, but, there is still the discontinuity of the Coal Seam Gas in this research. The UPPER COAL horizon, which interpreted as the thickest Coal Seam Gas in Patchawarra FM, actually disappears in some locations, especially in the southeastern of the research area, as shown in the Figure 5.8. However, the LOWER COAL as another thick Coal Seam Gas, which situated right below the UPPER COAL, is still continues in those areas

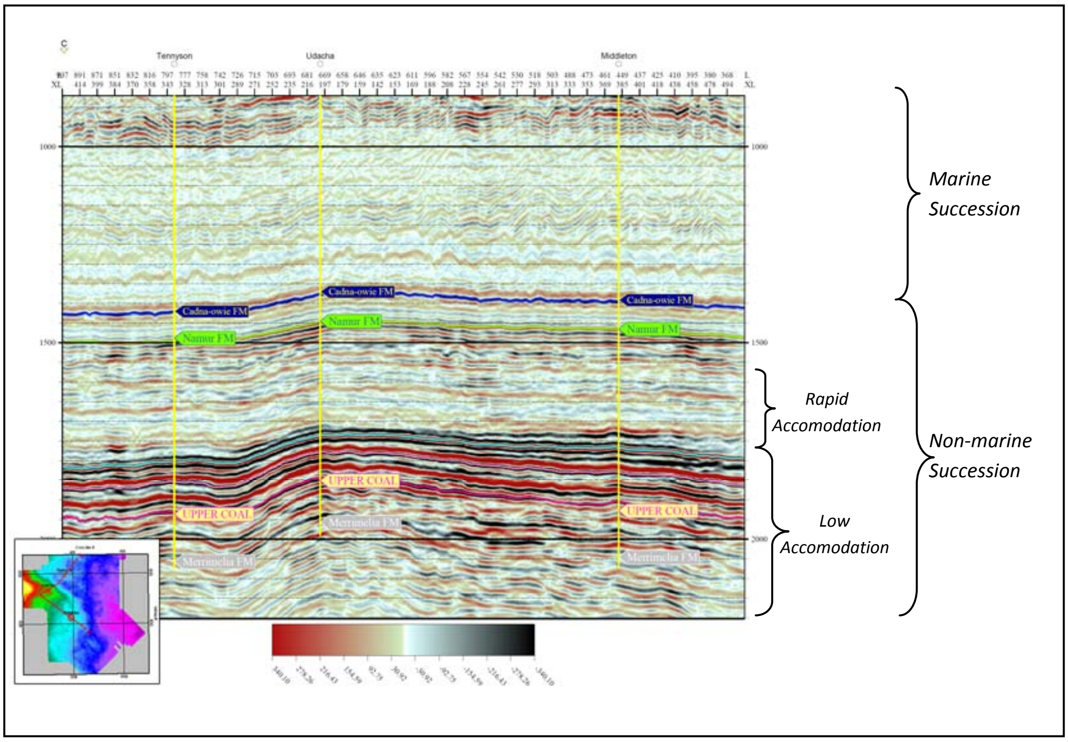


Figure 5.6 Horizon picked in the arbitrary line throughout Tennyson, Udacha, and Middleton. These are non-marine succession member. (Seisvision – Geographix, Landmark Discovery Software)

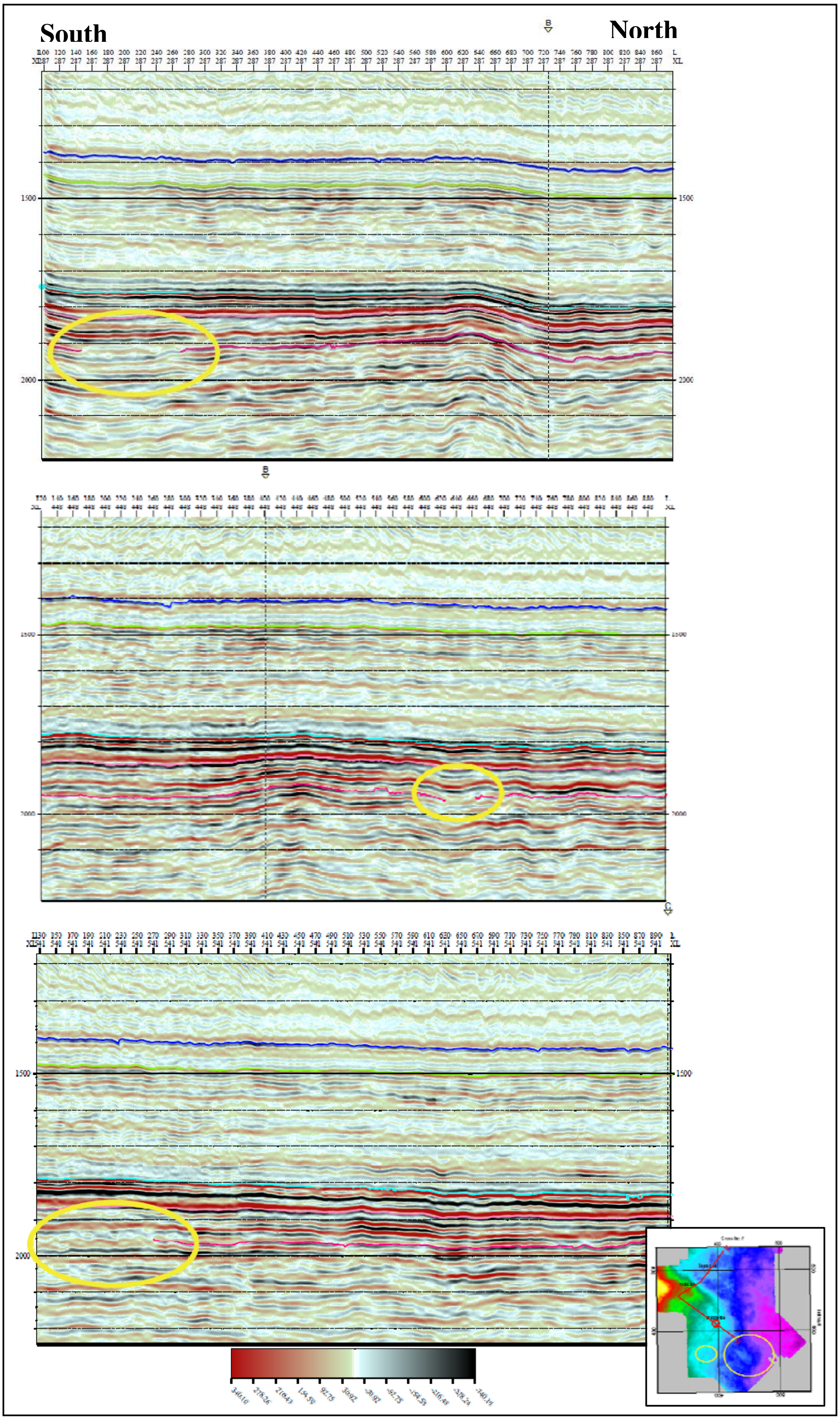


Figure 5.7 The discontinuity of UPPER COAL horizon occurrence shown by the yellow circle in the southern of the research area . (SeisVision – Geographix, Landmark Discovery Software)

As seen in the seismic section and structural interpretation, the research area lying in the relatively flat depocentre. The highest area which interpreted as faulted anticlinal is located where the Udacha well is located which is in the northwest of the research are.

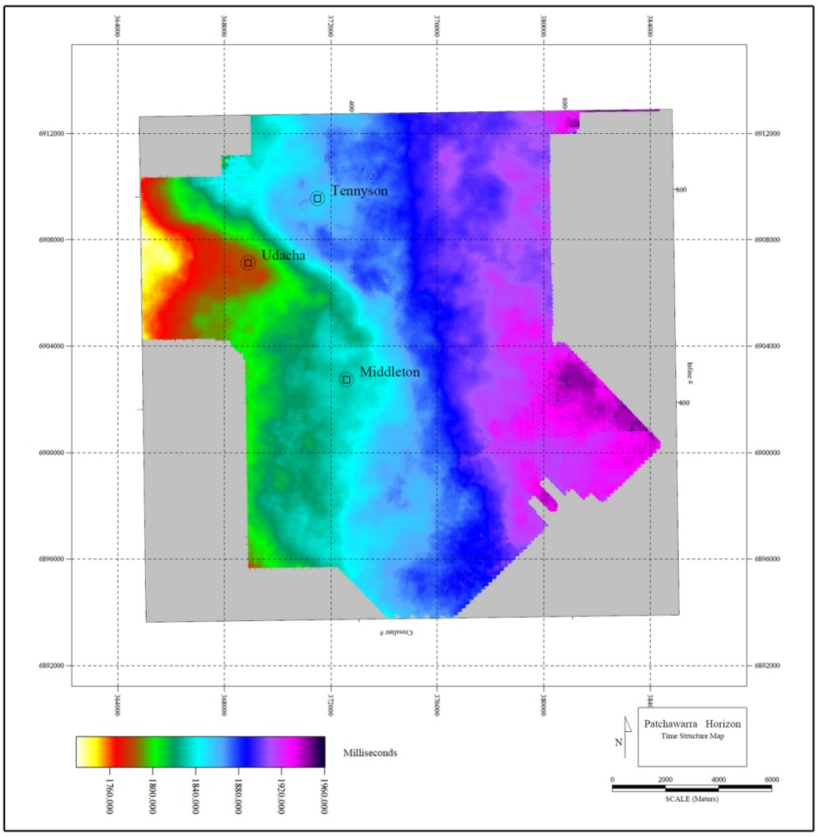
The anticlinal structure then turned into the flatter area in the south of the research area, but still not in the same height as in the anticline. This flatter area possibly interpreted as the part of the anticlinal structure. Middleton well is located in this area.

The lowest deposition area is seen in the north to northeast of the research area, where Tennyson well also located on. This area becomes the lowest area around the anticlinal structure due to the occurrence of the major fault interpreted in the northeast of the anticline.

Figure 5.8 shows the time structure map of Patchawarra FM and UPPER COAL horizon and also shows that the eastern of this research area is the lowest area. The northwest – southeast fault as the major fault is slightly noticeable from this time structure map. This fault is located near to the northwest anticline which is the only one major structure in this research area.

Based on these time structure maps, we can assume that the anticline possibly continues to the southwards of the research area.

Although the Coal Seam Gas commonly occurs and thicken in the relatively flat and stable area, actually the occurrence of the fault plane would not harm the continuity of the Coal Seam Gas, it might even create the permeability for the Coal Seam Gas. However, the fault plane possibly creates the eroded formation which possibly harm the continuity of the Coal Seam Gas.



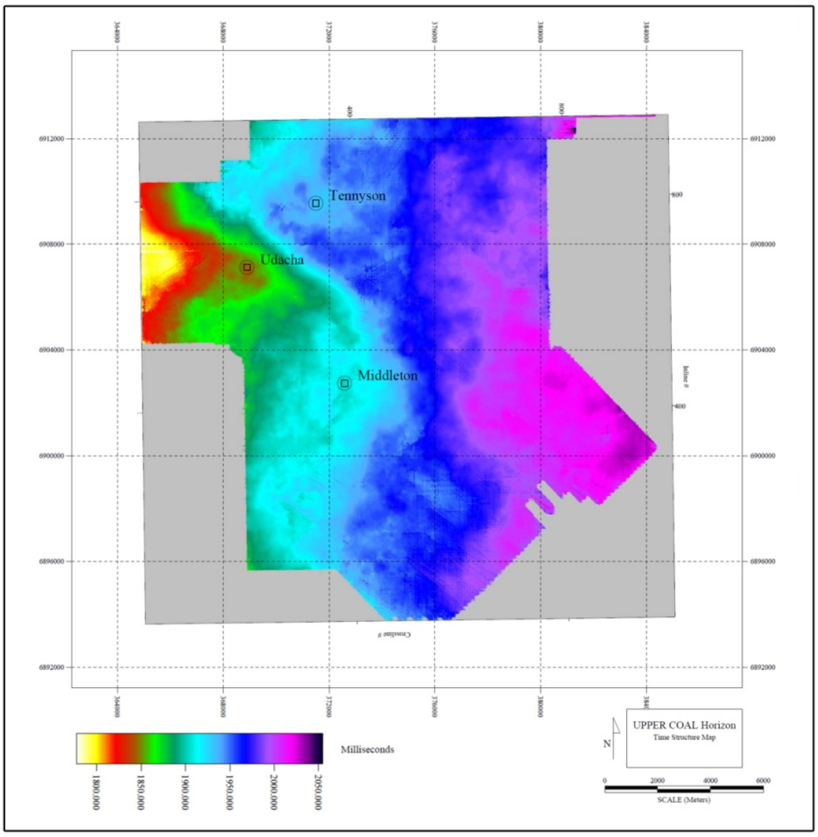


Figure 5.8 Time structure map of Patchawarra Horizon (above) and Upper Coal Horizon (below). (SeisVision, Geographix, Landmark Discovery Software)

5.3.3 Seismic Response of Coal Seam Gas

One of the important fields of application of the thin layer theory is in coal exploration where coal seams form a notable exception to the above acoustic impedance rule. Coal seams, although extremely thin with respect to wavelength (λ), can produce distinct reflections because of exceptionally large acoustic contrast with respect to roof and floor rocks with impedance ratios ranging from 0.25 to 0.38 (Gochiocho, 1991).

Due to the uniqueness characteristics of coal, it will give the significant seismic response although the coal seams relatively thin. Figure 5.10 shows the example of seismic response of the thickest coal seams in Udacha well which annotated as UPPER COAL (12 m) and LOWER COAL (8 m). Both are interbedded with another rocks whether sandstone or shale.

As explained before, coal will give the low impedance response when meet another rocks. It is not depends on what kind of rocks around coal, because coal itself has the lowest value of velocity and density which will give the low impedance response. In such way, coal will always identified as trough in seismic response, whatever kind of rocks they meet on, in assumption that the polarity is normal (increase impedance means peak and vice versa).

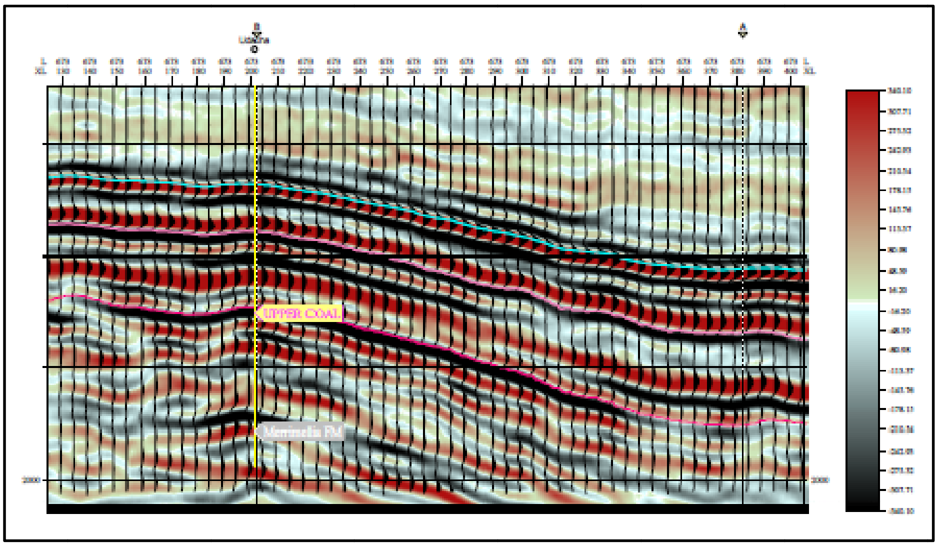


Figure 5.9 Seismic response of coal seams annotated as UPPER COAL in Udacha well, the LOWER COAL situated right below the UPPER COAL. (SeisVision – Geographix, Landmark Discovery Software).

5.4 Seismic Inversion

As explained in the previous chapter, the first step of performing model based acoustic impedance inversion is making the initial geological model, then running the inversion analysis to determine which wavelet will used in seismic inversion, then performing the seismic inversion itself. The following sub-chapter wills explain the result of those steps.

5.4.1 Initial Acoustic Impedance Earth Model

The initial guess model was based solely on the calculated impedance at log resolution from each well (Udacha, Middleton, and Tennyson). These impedance logs were extrapolated throughout the survey domain as the initial guess model. Initial model performed in this research use by applying filter, those are high cut filter and running average in 5 samples. It will caused the coal are no longer interpreted as seams but as a coal package. If no filter applied, the coal will show as seams but will give the complex display.

Components of the initial guess model that are not resolved by the seismic data are carried through the inversion algorithm. If the model at log resolution was used as the initial guess model, it would be difficult to know what detail in the inverted impedance estimate had come from the data and what had simply been carried through from the initial guess (McCrank and Lawton, CREWES, 2008). Hence, the initial guess chose to applied is low pass filtered at 10 –20 Hz (frequency band below the band of the seismic data) and running average in 5 samples.

Applying filter will give us the smoother display as shown in the Figure 5.11. But applying the high cut filter will give the best display compare to running average filter. Both models were used as the initial guess model for the conjugate gradient perturbation of the impedance model.

Both are shows the same locations of coal seams package as noted as the yellow colour inside the red one.

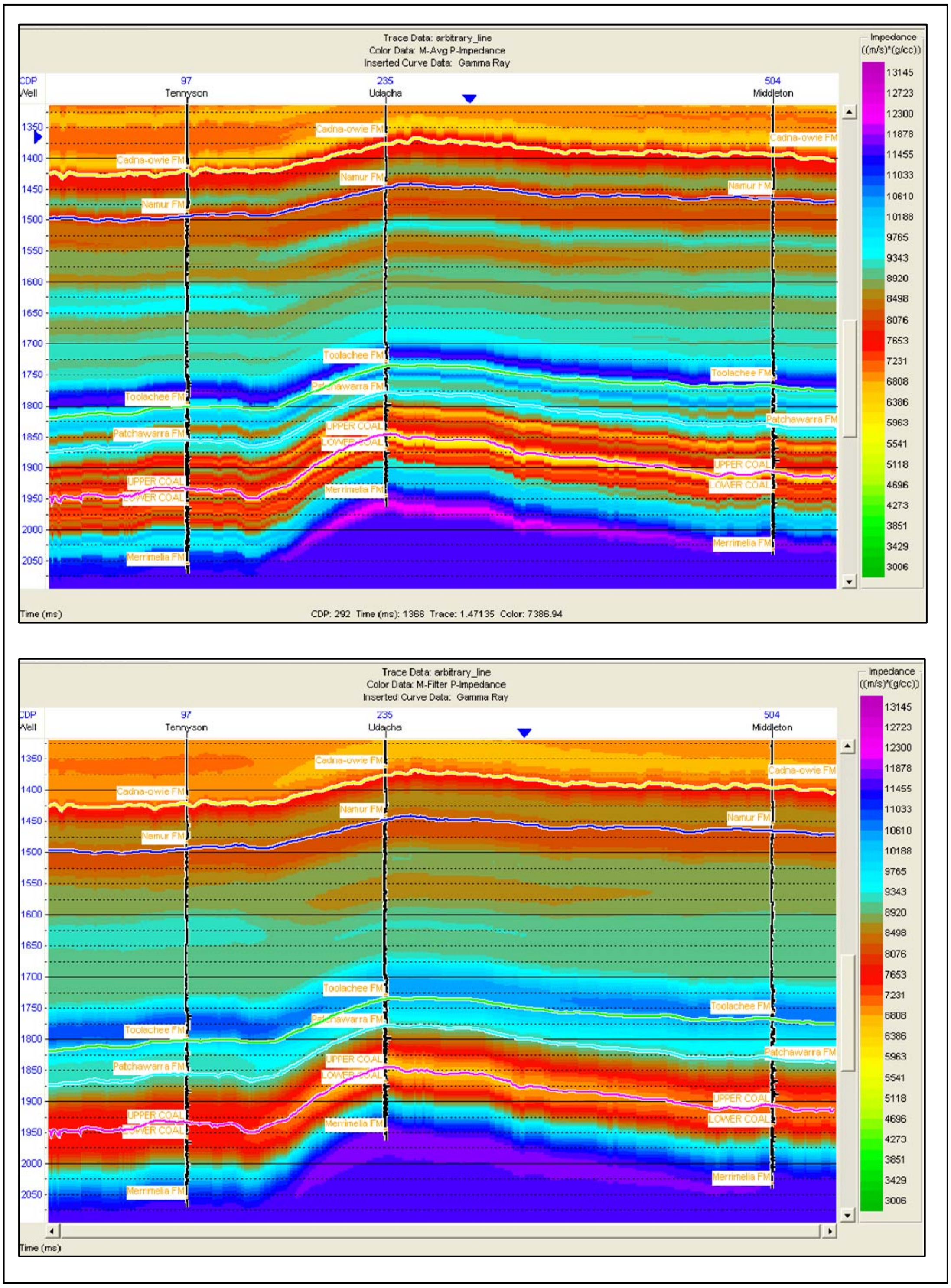


Figure 5.10 The comparison between the initial earth running average in 5 samples (above) and high cut filter (below) for arbitrary line through Tennyson, Udacha, and Middleton (STRATA, Hampson-Russell Software).

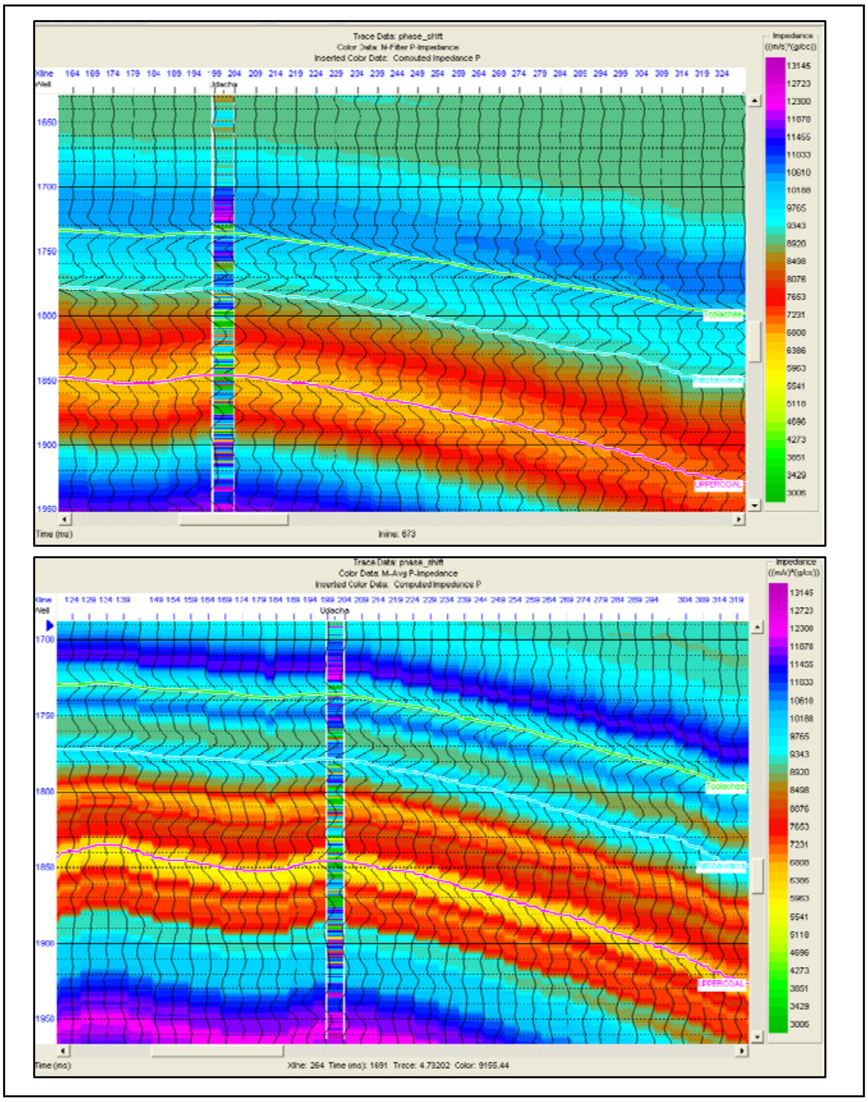


Figure 5.11 The comparison of the initial earth model using high cut filter (above) and running average in 5 samples (below) for Udacha well (STRATA, Hampson-Russell Software)

5.4.2 Acoustic Impedance Inversion Analysis

Wavelet determination is the most crucial things in performing seismic inversion. Performing acoustic impedance inversion analysis means performing seismic inversion simulation, wavelet might be choose from one to another in simulation to see which wavelet will give the best result in seismic inversion.

This analysis performed at well locations where the actual impedance values are known and might compared to the inverted impedance. Some parameters are tuned to reduce the residual difference between the logged impedance and the inverted impedance.

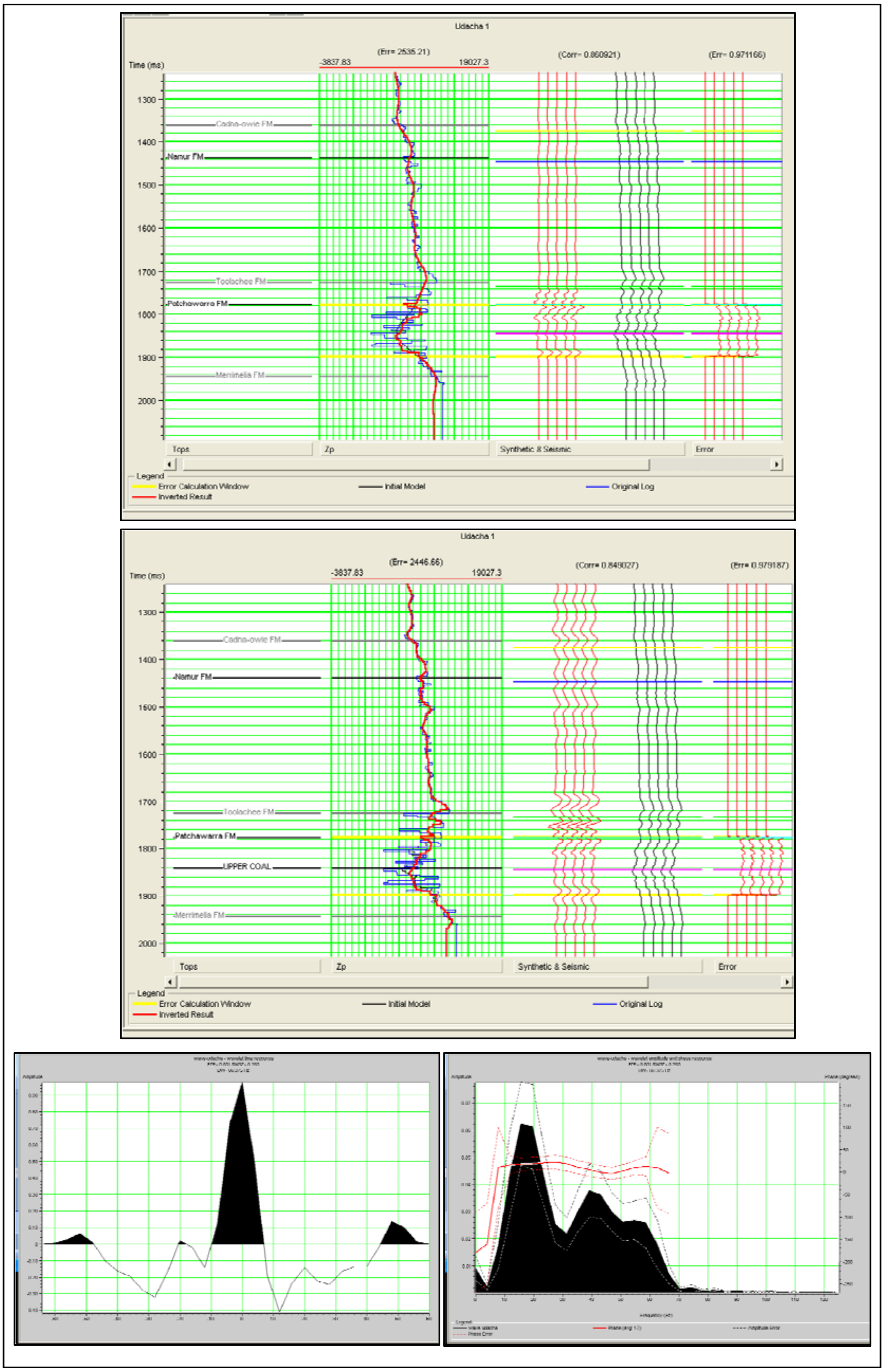


Figure 5.12 Acoustic impedance inversion analysis with high cut filter (above) and running average (below) using the udacha wavelet. (STRATA, Hampson-Russell Software).

In this research, the inversion analysis using wavelet udacha gave the best result in all wells, those are 0.86 in Udacha (error impedance 2535 (m/s)(g/cc)), 0.639 in Tennyson (error impedance 2280 (m/s)(g/cc)), and 0.831 in Middleton (error impedance 2822 (m/s)(g/cc)); if high cut filter applied.

And the inversion analysis using wavelet udacha gave 0.85 in Udacha (error impedance 2446 (m/s)(g/cc)), 0.738 in Tennyson (error impedance 2180 (m/s)(g/cc)), and 0.726 in Middleton (error impedance 2820 (m/s)(g/cc); if running average in 5 samples applied.

5.4.3 Model Based Acoustic Impedance Inversion

Figure 5.14. is an arbitrary line of the model-based inversion result. The occurrences of hydrocarbon including coal seam gas are associated with low-impedance values. Meanwhile, Udacha well is located in a low-impedance area as shown as the green to red colour (6000 – 7000 (m/s)(g/cc)).

Although there is 2400 - 2800 (m/s)/(g/cc) in between as error impedance in inversion analysis, the result of this model-based inversion is quite good by understanding that there still the different resolution between the log data and seismic data. To see whether the inversion result near to the computed impedance from log, one simple ways might be done, that is re-sampling and put the high cut filter into the related log data in order to reach the seismic resolution.

Model based inversion using high cut filter shows the coal seams located in the faulted anticline where Udacha well located. But the model based inversion using running average in 5 samples shows the coal seams also located in the Middleton wells. Then it might be interpreted that the prospect coal seams gas are allocated in the south to west of the research area.

These differences might happen due to the filter that had been applied, the high cut filter shows the regional Coal Seam Gas Package and the running average shows the more details Coal Seam Gas occurrences. Basically, both are showing the similar anomaly.

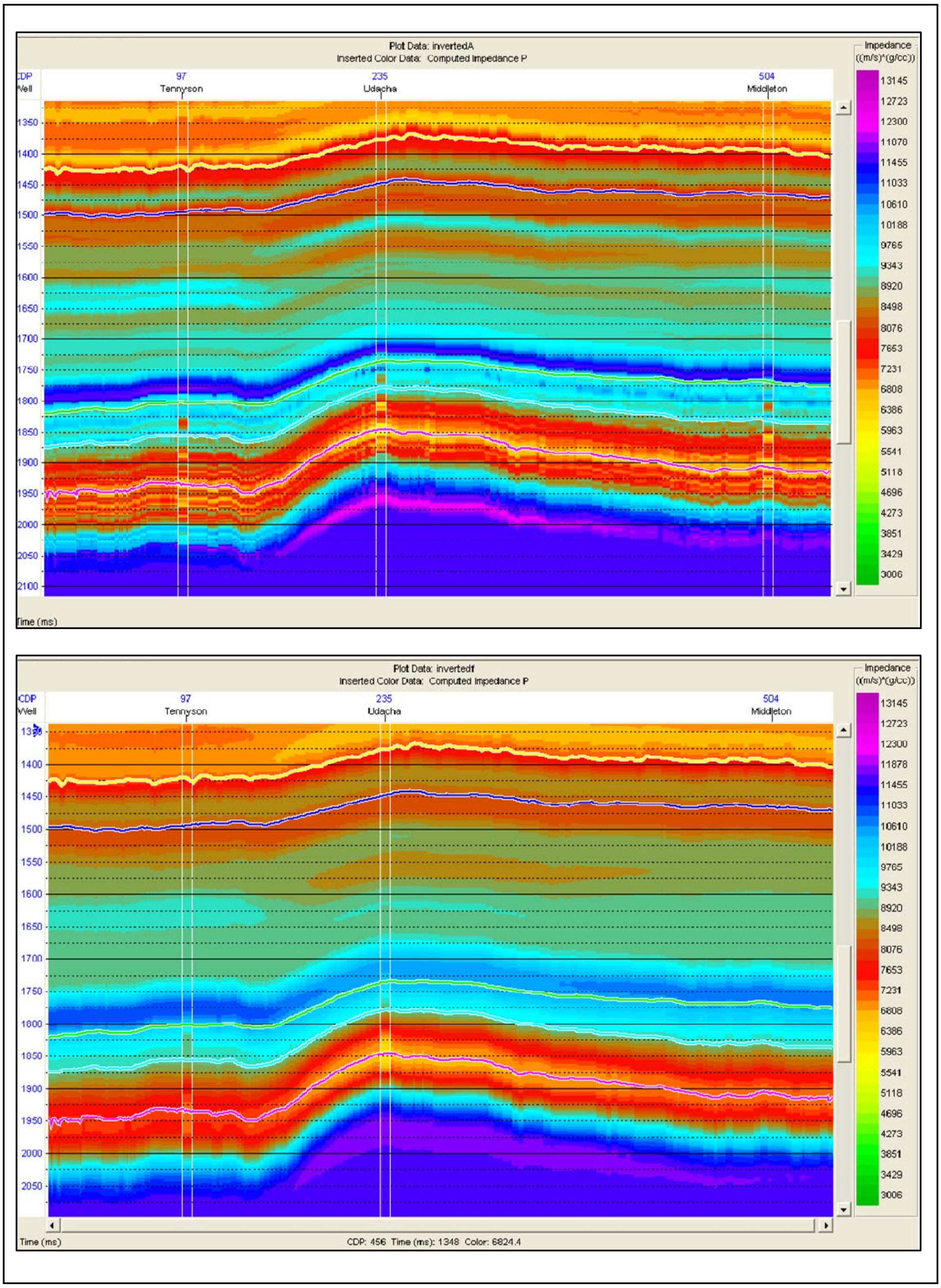


Figure 5.13 The result of acoustic impedance inversion using running average in 5 samples (above) and high cut filter (below).

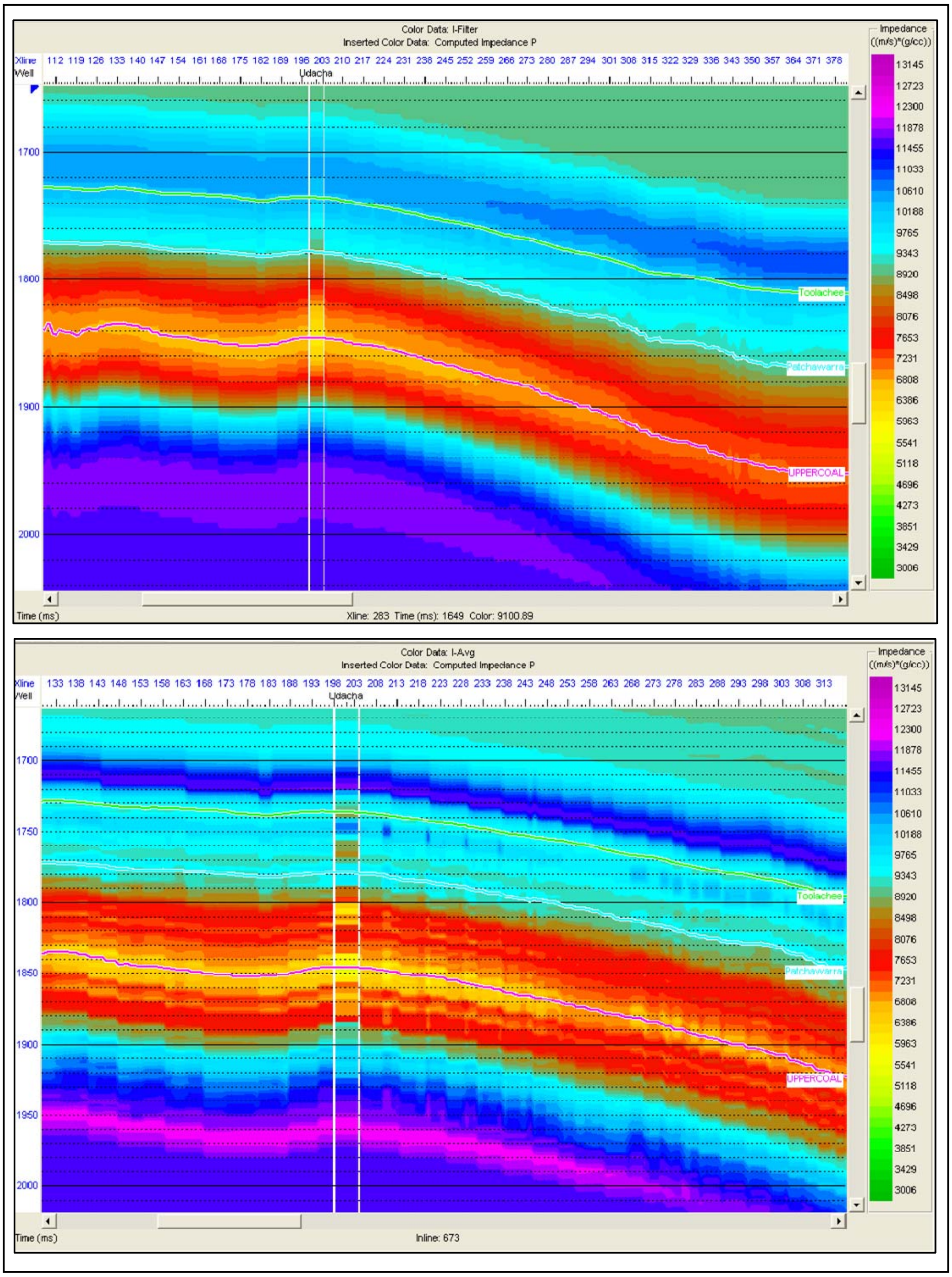


Figure 5.14 The correlation between computed impedance (log resampling) and acoustic impedance inversion using high cut frequency filter (above) and running average in 5 samples (below). Both are show the fine correlation.

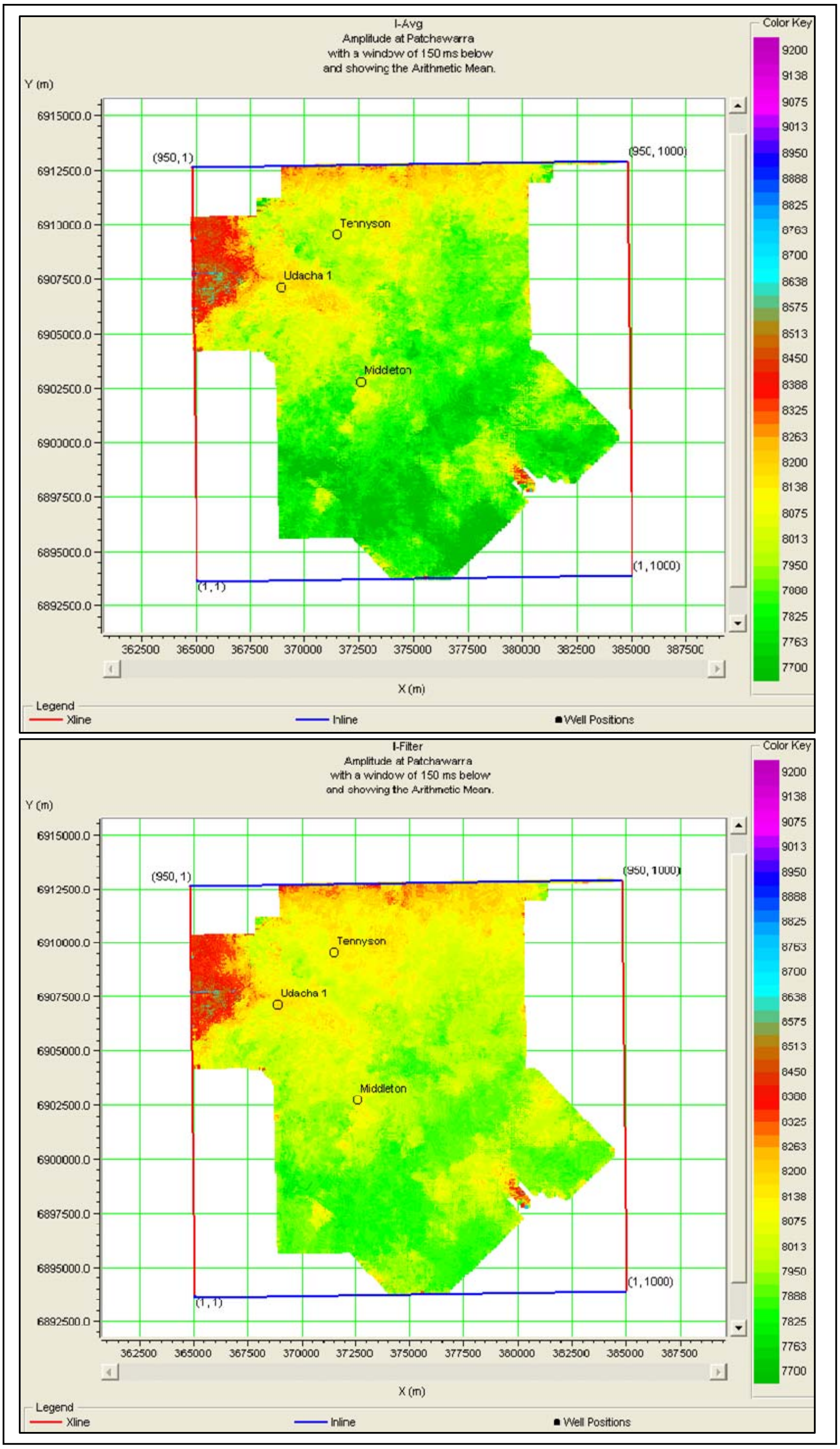


Figure 5.15 The distribution AI using model-based inversion (running average 5 ms applied in the above and high cut filter in the below). The map made by applying the arithmetic mean in the top to bottom of Patchawarra FM (STRATA, Hampson – Russell Software).

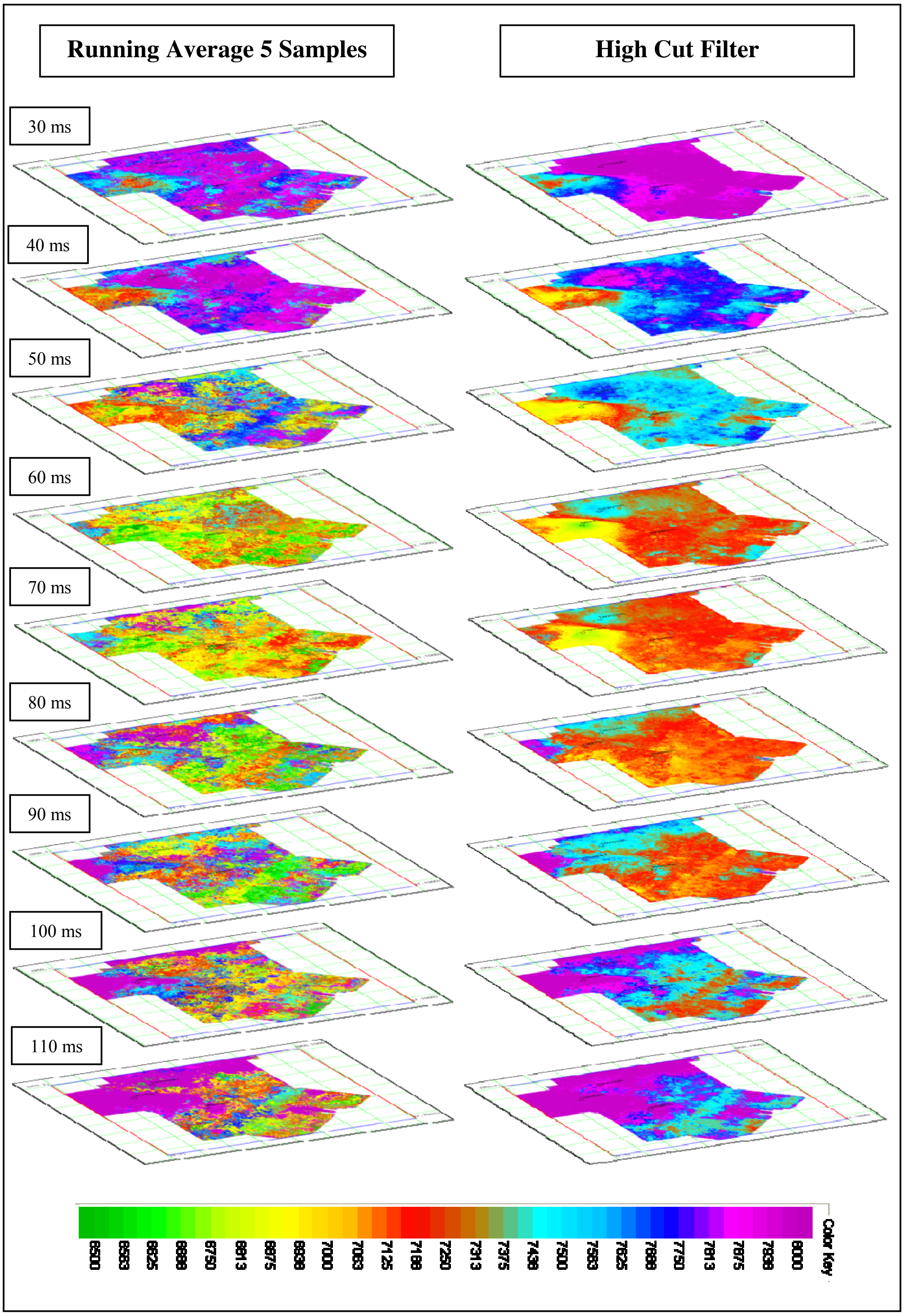


Figure 5.16 Ten ms steps through the inverted AI of the Patchawarra Coal Seam Gas from 30 ms below the Patchawarra horizon (STRATA, Hampson – Russell Software).

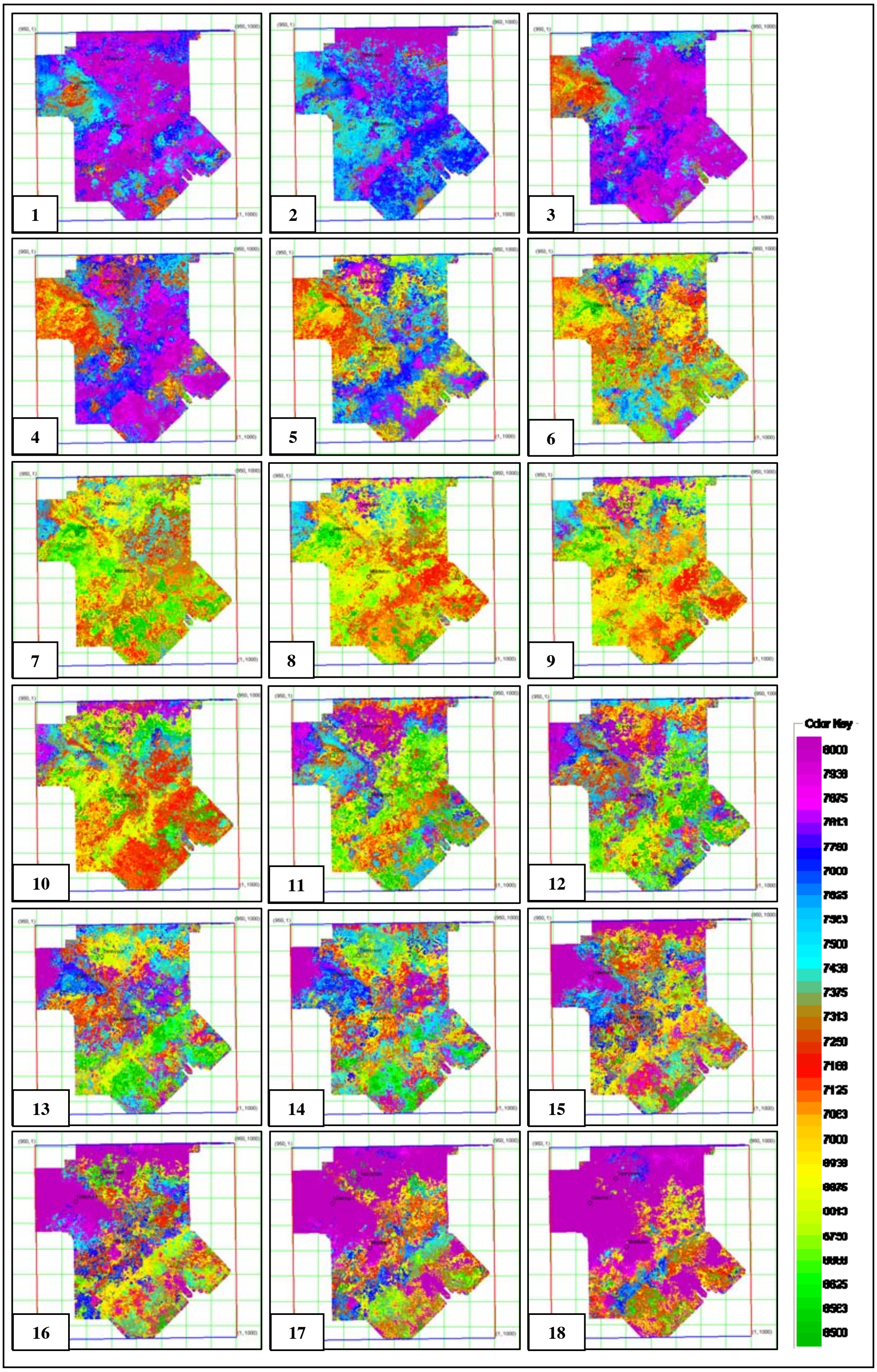


Figure 5.17 Five ms steps through the inverted AI using running average of the Patchawarra Coal Seam Gas from 30 ms below the Patchawarra horizon (STRATA, Hampson – Russell Software).

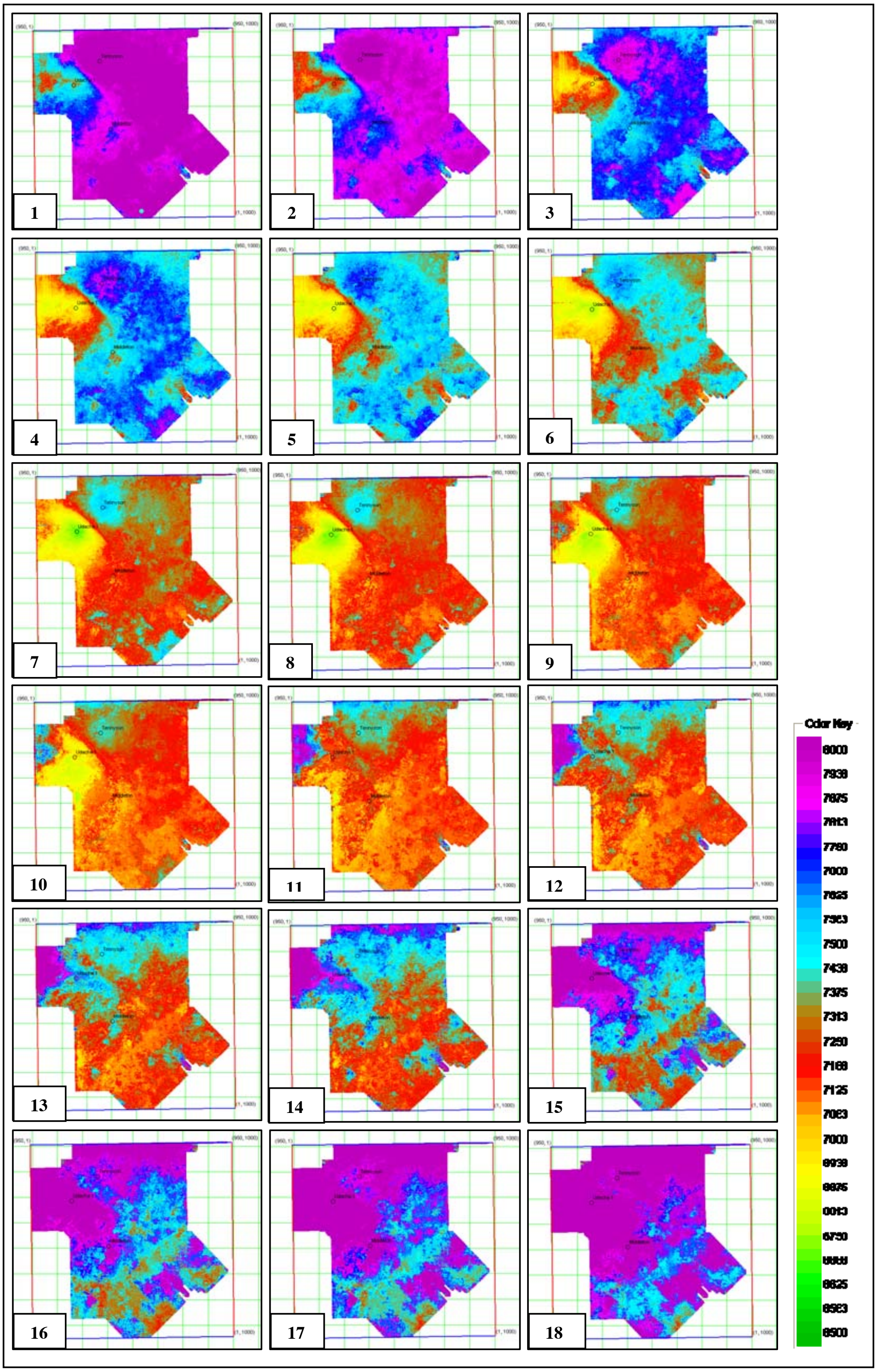


Figure 5.18 Five ms steps through the inverted AI using high cut filter of the Patchawarra Coal Seam Gas from 30 ms below the Patchawarra horizon (STRATA, Hampson – Russell Software).

Almost the whole of Patchawarra FM noted as the green and yellow colour anomaly (both in seismic section and distribution map), both in the same range of acoustic impedance, it means the whole formation actually has the low impedance. Considering the basic log interpretation and rocks physics analysis, Patchawarra FM actually consists of numerous coal seams. Hence the red anomalies might generate from those coal seams. Those coal seams did not shows the lowest impedance as shown as yellow colour possibly caused by the existence of another lithology such as sandstone and shale which interbedded with the thin coal seams.

Coal Seam Gas which deposited right in the Patchawarra horizon actually consists of numerous thin coal seams approximately 2 metres only in thickness and interbedded with another rocks. This numerous Coal seam Gas of course give the strong reflection, but possibly interfered with the strong reflection of another interbedded rocks in-between.

The absence of coal seam gas in the Tennyson wells possibly not directly related to the existence of northwest – southeast fault. Principally, coal distribution is not depends on structure. Unlike the conventional reservoir which require the traps, coal might be distributed in any structure either anticline or syncline. The existence of fault possibly not affects the continuity of coal distribution; it might probably help the Coal Seam Gas' permeability. But, the existence of fault possibly causes eroded surface which might causes the discontinuity of Coal Seam Gas or maybe it is just as simply as not deposited to the north-east of the research area.

Hence the yellow anomaly (low impedance) disappears after met the northwest – southeast fault which is the major fault in this research area. The anomaly also disappears in the slope of the anticline in the southeast which possibly caused by the local anomaly such as the unstable water table which act locally.

CHAPTER 6
CONCLUSIONS & RECOMENDATIONS

6.1 Conclusions

There are some conclusions that had been reached after doing the research of Coal Seam Gas identification in Spinel Field using model-based acoustic impedance inversion, those are:

1. Acoustic impedance inversion utilizing a model based approach has proved to be a worthwhile process for improving the Coal Seam Gas identification. The attraction of the inverted data is settled up through the inclusion of low frequency components, where the inverted results take on the appearance of a geological section.
2. This research focused on the Coal Seam Gas potential in Permian Patchawarra FM which situated in 2300 m (1770 ms) in Udacha well, 2400 m (1830 ms) in Middleton well, and 2400 m (1850 ms) in Tennyson well. This formation gross thickness is approximately 300 m, but the Coal Seam Gas interbedded with sandstone and shale.
3. In this research, the inversion analysis using wavelet Udacha gave the best result in all wells, those are 0.86 in Udacha (error impedance 2535 (m/s)(g/cc)), 0.639 in Tennyson (error impedance 2280 (m/s)(g/cc)), and 0.831 in Middleton (error impedance 2822 (m/s)(g/cc)); if high cut filter applied.
4. The inversion analysis using wavelet udacha gave 0.85 in Udacha (error impedance 2446 (m/s)(g/cc)), 0.738 in Tennyson (error impedance 2180 (m/s)(g/cc)), and 0.726 in Middleton (error impedance 2820 (m/s)(g/cc); if running average in 5 samples applied.
5. The research of Coal Seam Gas in Spinel field has been yield that the occurrences of hydrocarbon including Coal Seam Gas are associated with low-impedance values. Meanwhile, Udacha and Middleton well is located in a low-impedance area as shown as the green to yellow colour 6000 – 7000 (m/s)(g/cc)) surrounded by the higher impedance as shown as the red

colour (7000 – 8000 (m/s)(g/cc)) with error impedance range from 2400 – 2800 (m/s)(g/cc) in between. In such way, the Coal Seam Gas predicted to mainly allocated on the northwest to south of the research area.

6. The mapping of reflectors allows identification of northwest – southeast anticlinal faulted structures that might affect coal seams continuity but not in direct effect. The existence of fault plane possibly causing the eroded, hence the yellow anomaly (low impedance) disappears after met the northwest – southeast fault which is the major fault in this research area, or the Coal Seam Gas is just discontinue to deposited, possibly due to the channel existence. The anomaly also disappears in the slope of the anticline in the southeast which possibly caused by another local anomaly such as unstable water table during coalification.

6.2 Recommendations for Future Work

This current method only works for identifying Coal Seam Gas as package, not as the single layer of Coal Seam Gas. Besides that, this method only works for identifying the continuity of the Coal Seam Gas laterally. However, further study is needed to enhance the reservoir characterization, things that possibly to study is identifying the distribution of the effective permeability and determining the gas content of the Coal Seam Gas. Coal Seam Gas, although contains enormous methane, is lack of permeability which will makes the gas production more difficult or not economic due to the inability of the gas to flow from the Coal to the production well.

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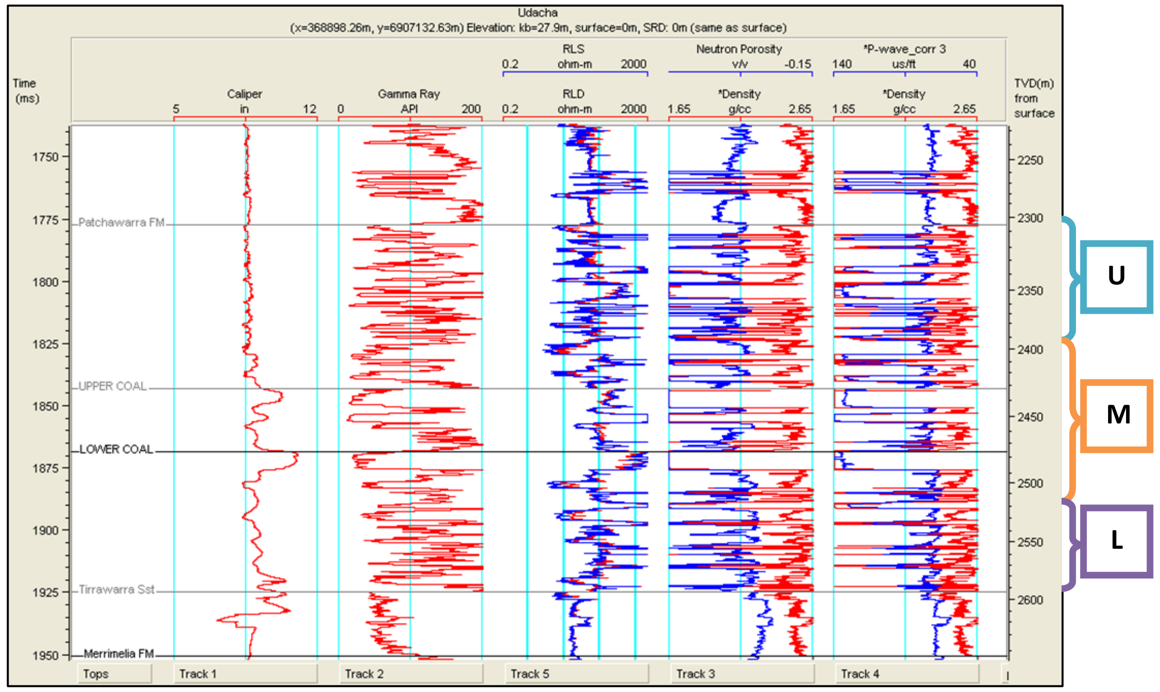
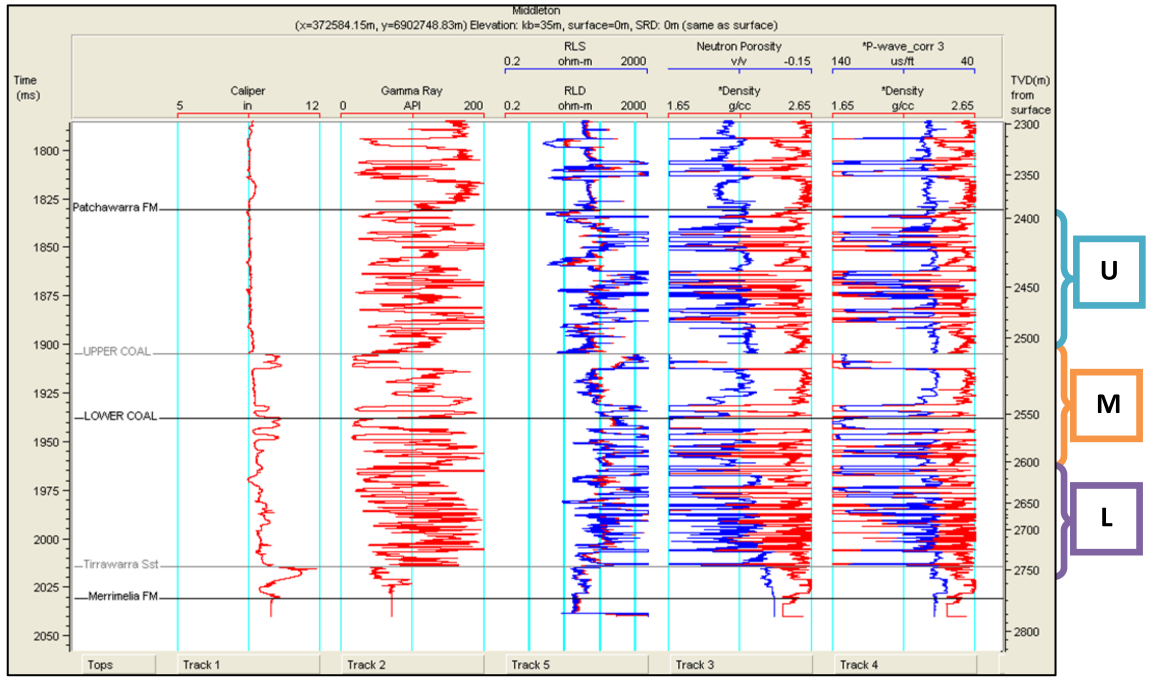
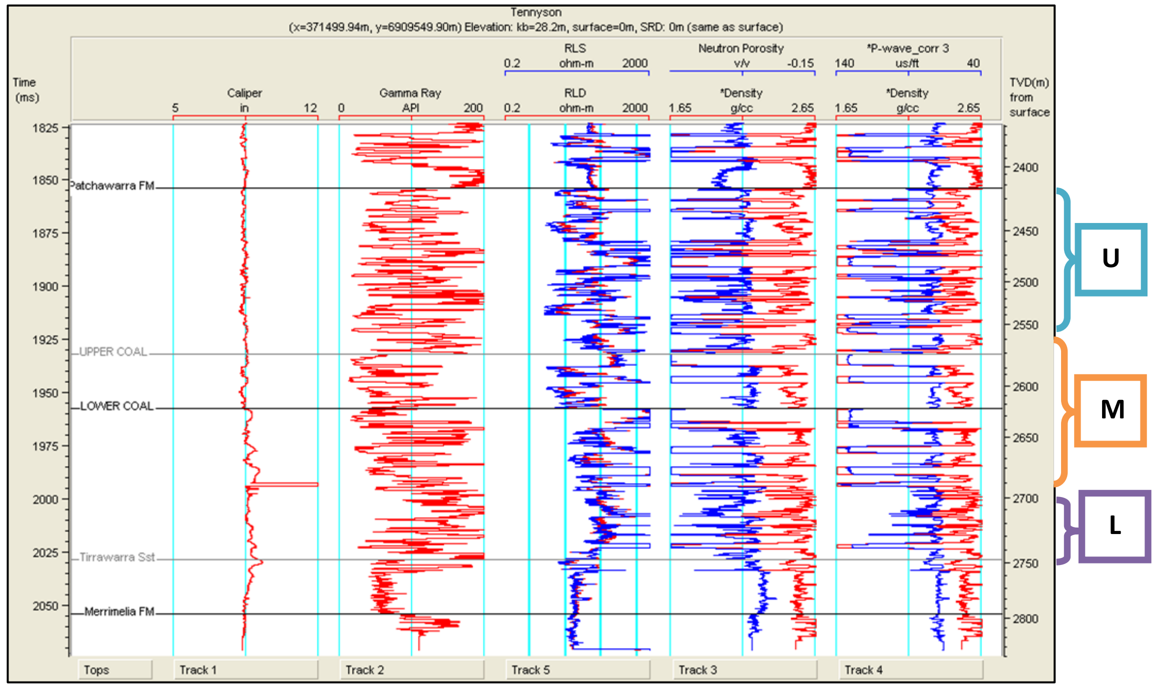
APPENDIX A
LOG INTERPRETATION AND ROCK PHYSICS

Basic Log Interpretation of Udacha Well, Middleton Well, and Tennyson Well

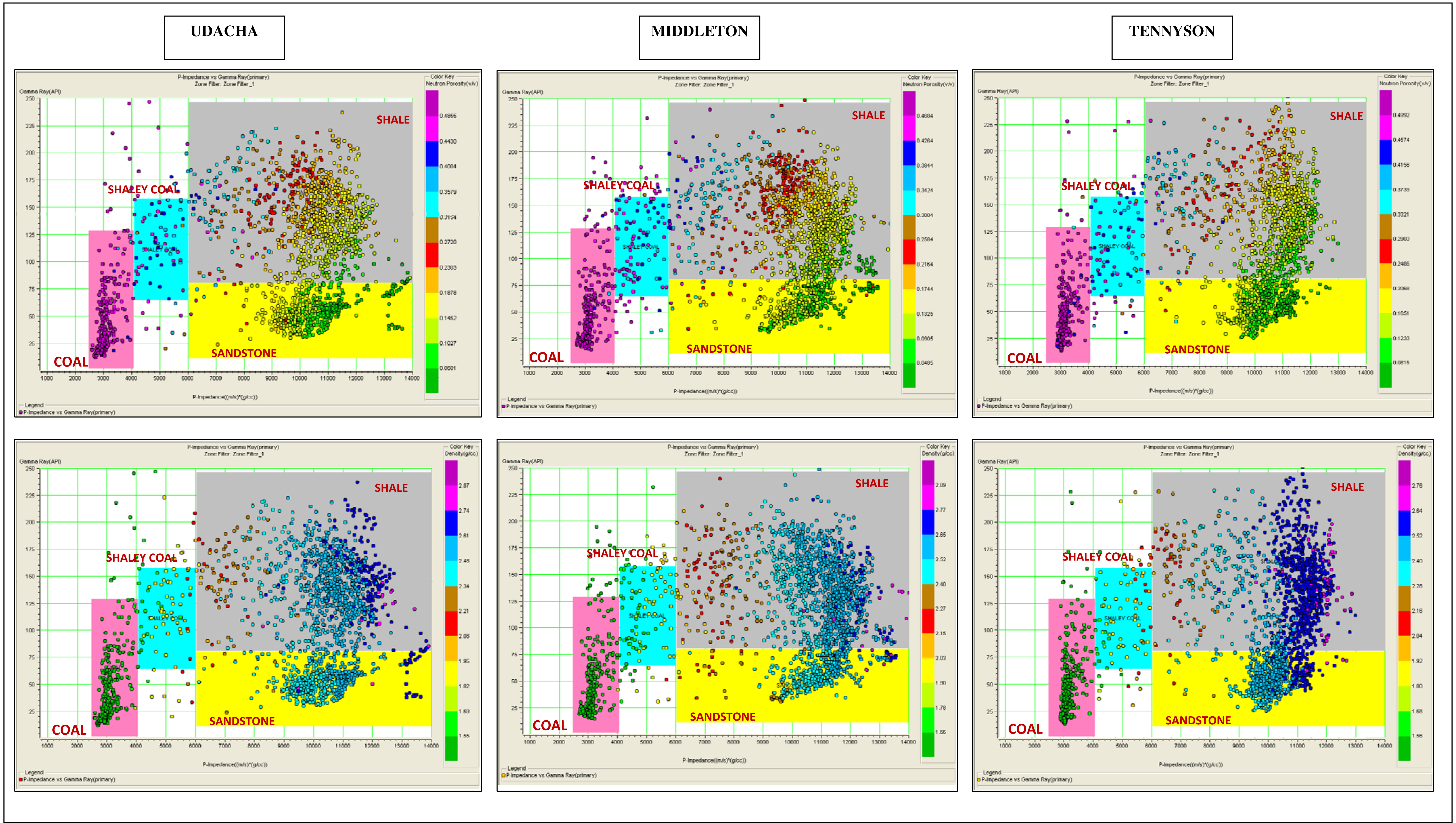






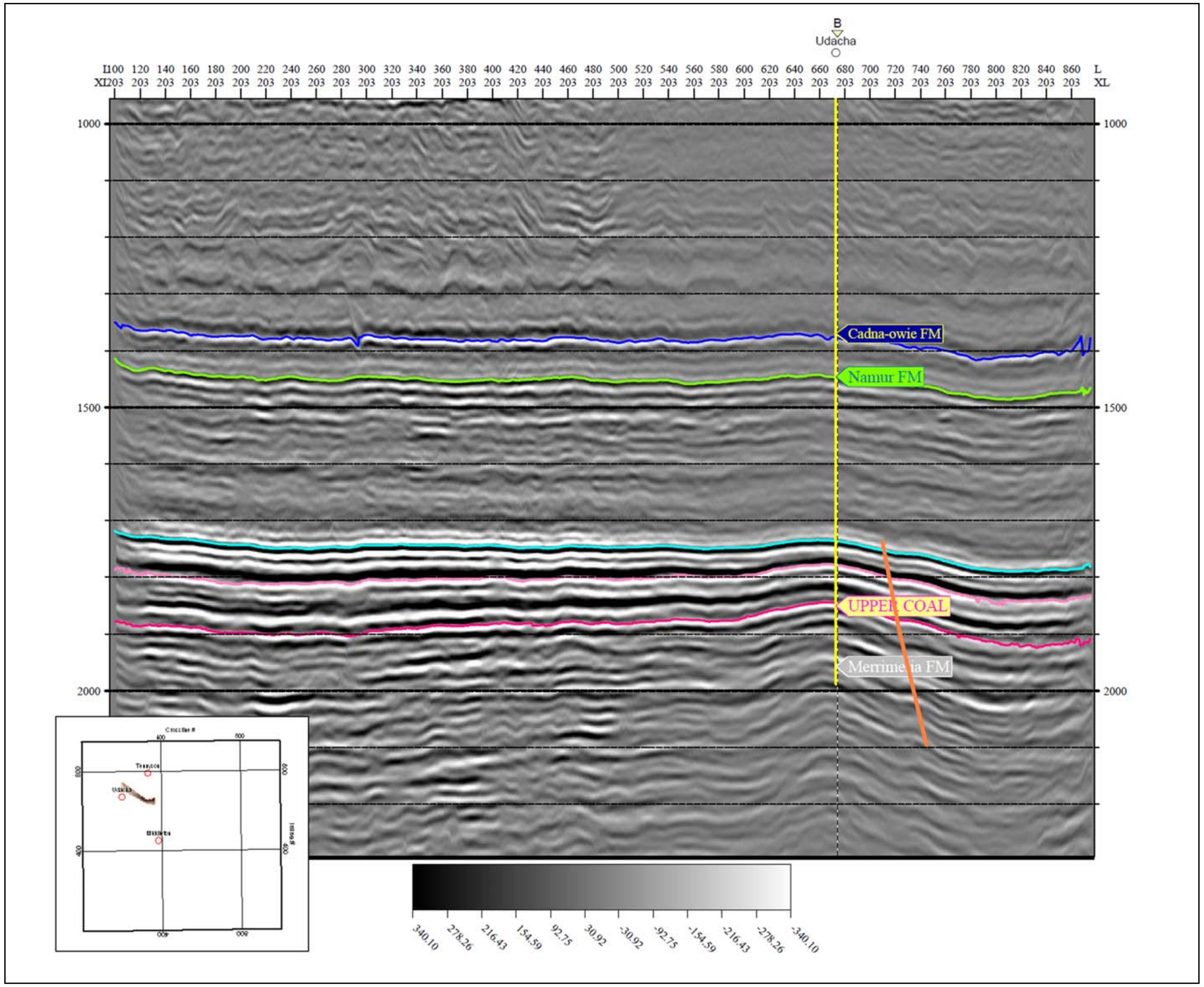
U	UPPER ASSEMBLAGE	Siltstone and shale with minor sandstone interbeds
M	MIDDLE ASSEMBLAGE	Dominate by sandstone with grey-black shale interbed, and thick coal seams
L	LOWEST ASSEMBLAGE	Carbonaceous siltstone, minor sandstone, thin coal seams.

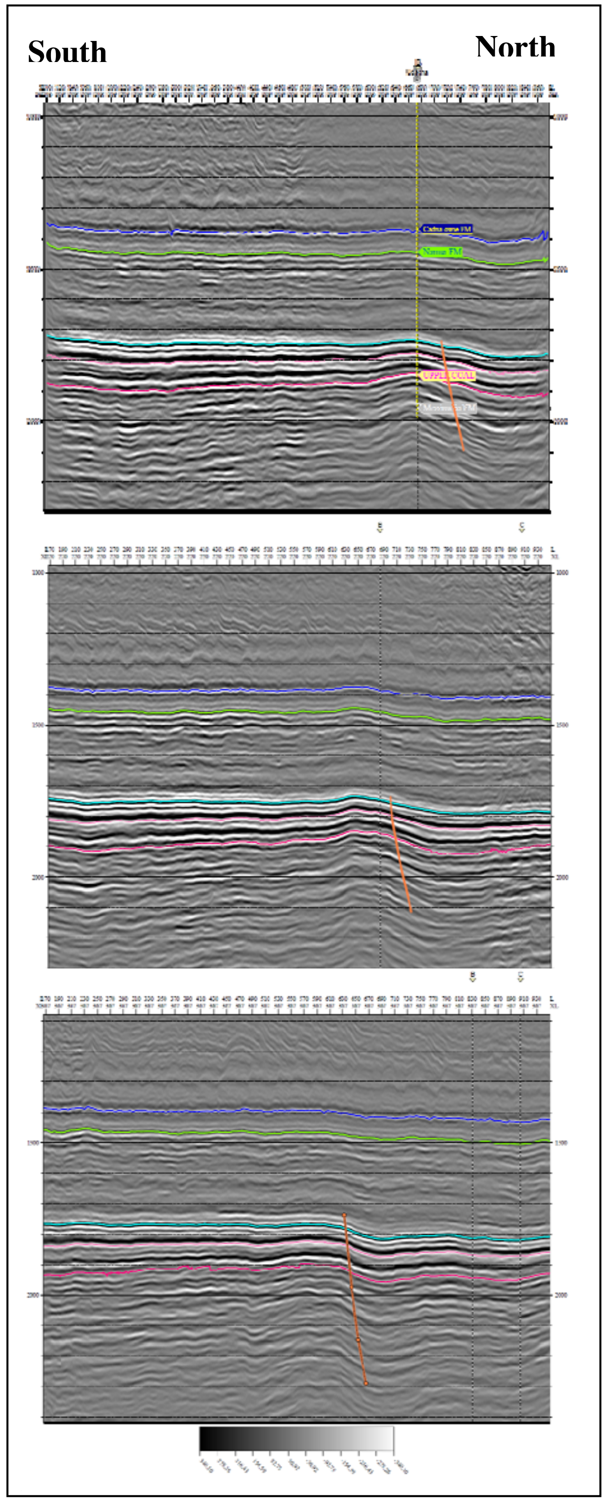
Lithological Crossplot of Udacha Well, Middleton Well, and Tennyson Well



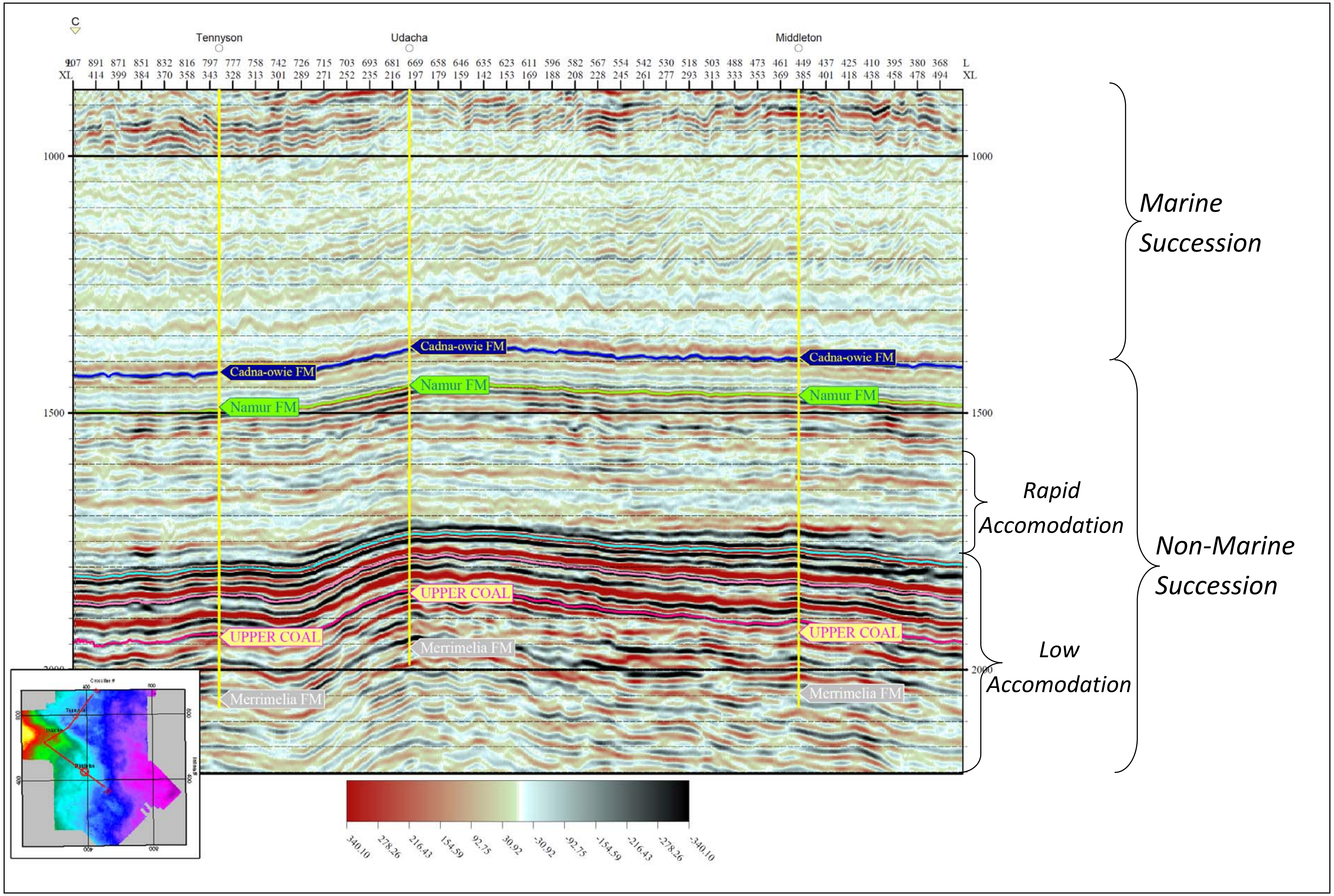
APPENDIX B
BASIC SEISMIC INTERPRETATION

Structural/Fault Picking

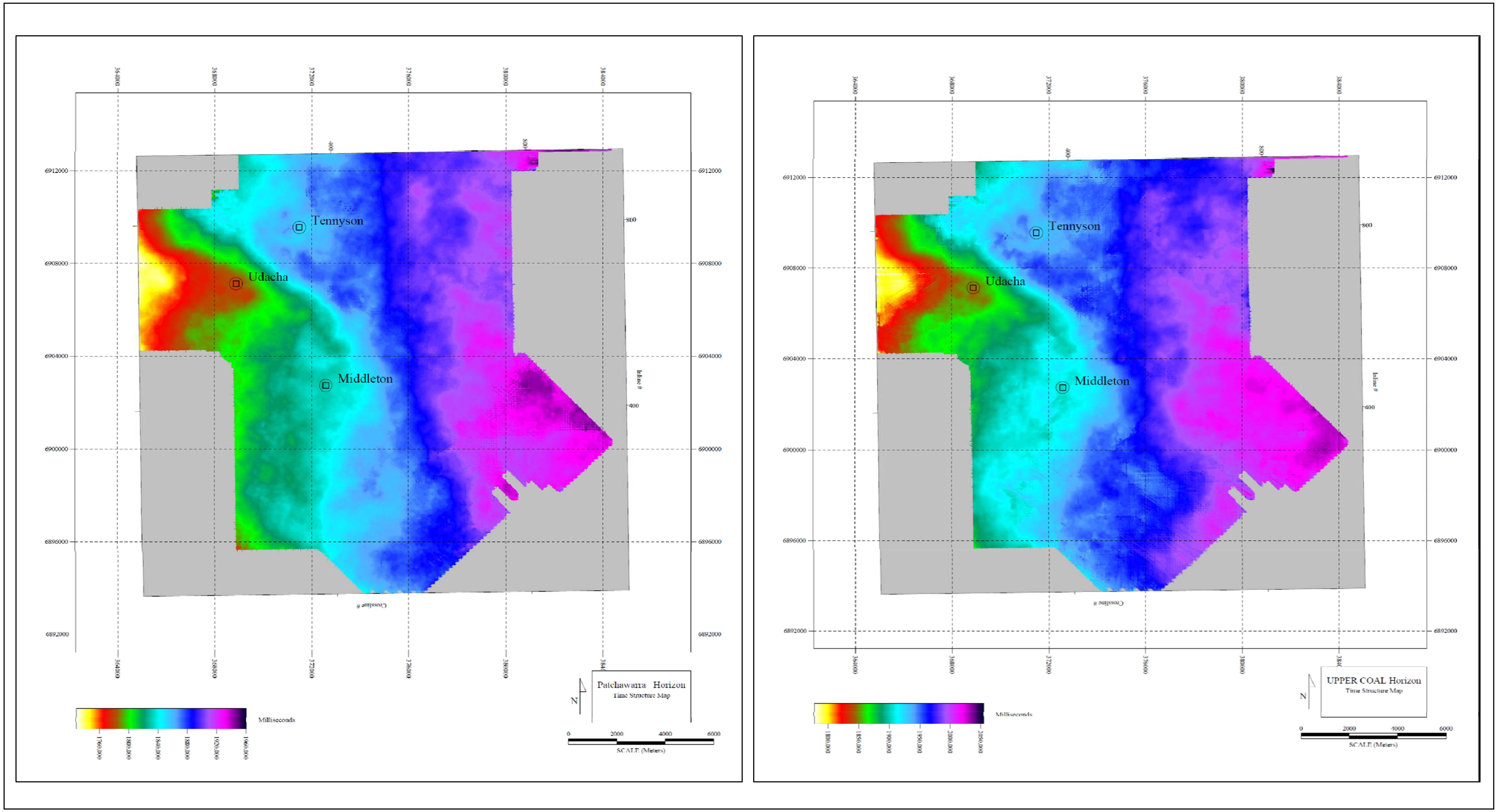




Horizon Picking

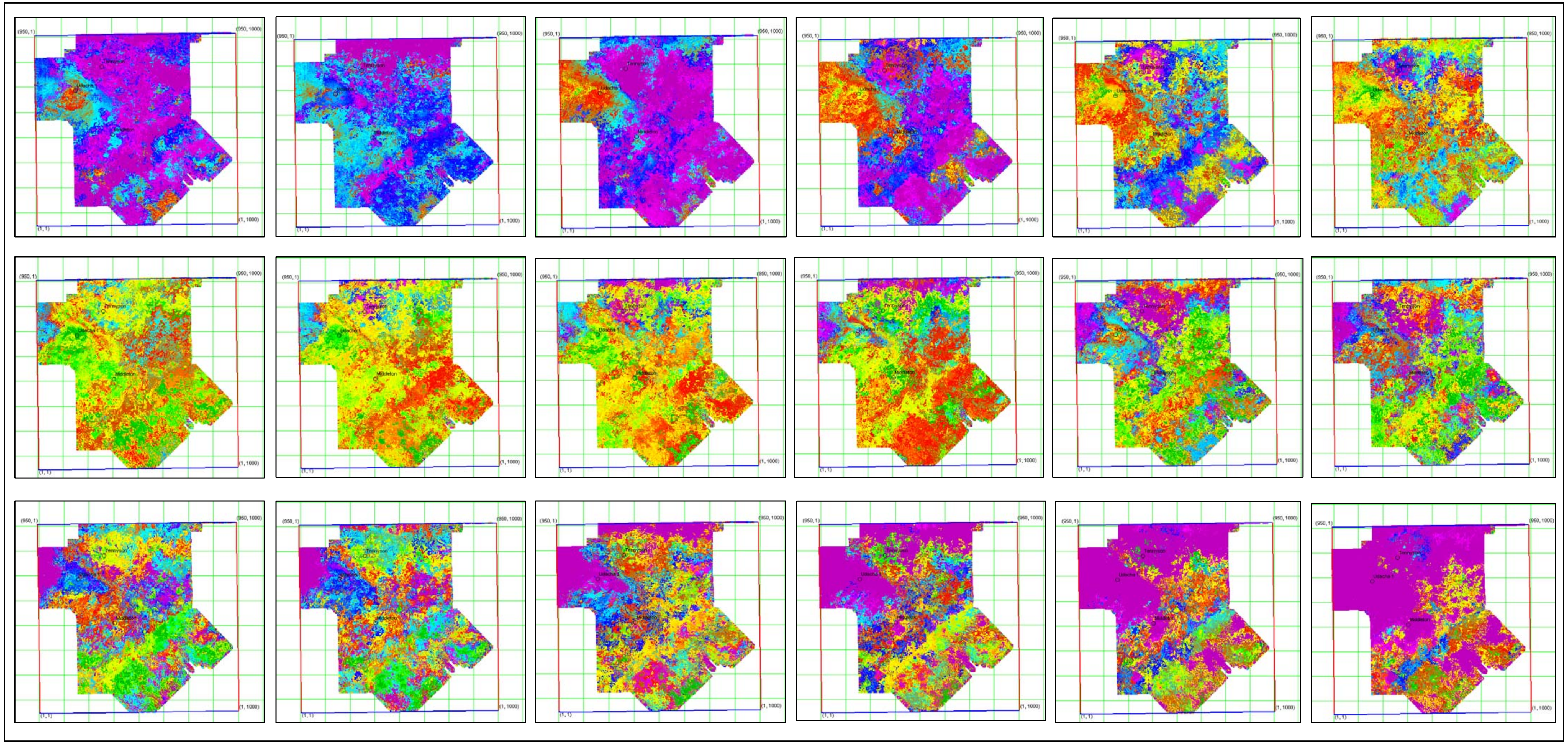


Time Structure Map of Patchawarra FM and UPPER COAL



APPENDIX C
MODEL-BASED AI INVERSION

5 ms Steps Through the Patchawarra Coal Seam Gas Package Using Running Average in 5 Samples Starts From 30 ms Below the Patchawarra FM



5 ms Steps Through the Patchawarra Coal Seam Gas Package Using High Cut Filter Starts From 30 ms Below the Patchawarra FM