

Reconstruction of Upper Strzelecki Stratigraphy based on Vitrinite Reflectance and Palynology Analyses, and New Ideas on the Amount of Erosion and Present Day Thickness*

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Abstract

Strzelecki Group is the first appeared Mesozoic formation within the Gippsland Basin, as one of the largest Australian oil and gas basins, and mainly consists of interbedded mudstones, sandstones and coal beds. This group plays role of basement in eastern part of the basin, however, it experience uplift to the west that provides spectacular outcrops especially along the coastal area between San Remo and Inverloch. There is still questions exist regarding the present day thickness of this group in west Gippsland area and the amount of erosion during late Cretaceous uplift.

Present study mainly focused on unique coastal outcrops of Strzelecki Group in Wonthaggi area at west Gippsland region and tried to reconstruct stratigraphic column of this highly faulted area in order to interpret the sedimentation history and estimate the present day thickness and the amount of eroded section. During the study correlation of measured logs faced number of problems such as unknown lateral extension of units, empty gaps because of either no access or not exposed area, thermally altered sediments, limitation in range of dating by palynology study of spore and pollens, low diversity of palyno-species, effect of multi directional cross-cutting faults and high amount of erosion.

The outcrops were mapped and logged, rich carbonaceous sediments were sampled and analysed for vitrinite reflectance and palynology, and at the end the stratigraphy was reconstructed based on palynology, vitrinite reflectance data and a geothermal gradient of 50 °C/km. Based on the reconstructed stratigraphic column, the Strzelecki Group has been classified into three distinct categories with range of eroded section from 1.4 km to 2 km.

Introduction

The early Cretaceous Gippsland Basin is located in southeastern Victoria, Australia and covers an area of 56,000 km² (Smith, 1982), approximately 70% of which occurs offshore. It lies across the Palaeozoic Tasman Fold Belt ([Figure 1](#)) (Birch and VandenBerg, 2003) towards the eastern end of the major intracratonic rift system that developed from west to east along what is now the southern margin of Australia, and

marked the initial phase of the separation of Australia and Antarctica. In SE Victoria, the rift faults cut at a high angle across the generally north trending structural grain of the underlying Lower Paleozoic rocks.

The early Cretaceous rift-fill sediments are now exposed in the Strzelecki Ranges and around the coastline of west and central Gippsland, while in East Gippsland (and offshore) they are buried beneath a late Cretaceous-Tertiary basin that has been one of the country's major hydrocarbon provinces for the past 40 years (Rahmanian et al., 1990; Willcox et al., 1992; Norvick and Smith, 2001; Willcox et al., 2001).

Lowry and Longley (1991) defined three separate stages of development, including a rift phase with NE-SW extension and deposition of the Strzelecki Group during the Early Cretaceous (120 to 98 Ma), deposition of the Golden Beach Group during NW-SE extension in the mid-Cretaceous, and compression or wrenching and the commencement of the sag phase in the Late Cretaceous and Tertiary and deposition of the Latrobe and Seaspray groups. By contrast O'Brien et al. (1994) defined two stages of the rift history; first NE-SW-directed extension along a major part of the southern margin between about 150-120 Ma, followed by NNE-SSW-directed extension in the period 120-117 Ma.

Subduction along the east coast of Australia ceased about 100 Ma and was replaced by extension that eventually lead to northward propagating sea floor spreading about 85 Ma and formation of the Tasman Sea. During the evolution of the Gippsland Basin two major tectonic phases, one in Early Cretaceous extension, and other one during Cenomanian to Campanian Tasman Sea rifting, affects the three main groups of rocks that occur within the Gippsland Basin: Strzelecki Group, Latrobe Group, and Seaspray Group.

Strzelecki Group

The Strzelecki Group, oldest unit in the Gippsland Basin, was deposited between ~150 Ma (Tithonian) to ~100 Ma in the Albian (Haskell, 1972; Willcox et al., 1992; Megallaa, 1993) and composes of at least 3000m of terrestrial volcanoclastic sandstone, conglomerate, mudstone and coal. The southern margin outcrops have been referred to Rhyll Arkose by Jenkins (1962), while the upper part is described as undifferentiated upper Strzelecki Group unit by Douglas and Ferguson (1988) and Tosolini et al. (1999). The Strzelecki Group is well exposed over a number of the elevated areas and especially along the coastline between San Remo and Inverloch, in west Gippsland ([Figure 2](#)). The topography of the area is a well impression of NW-SE trending late Tertiary compression event that leads to structural inversion of the early Cretaceous depocentre and uplift of Strzelecki Ranges ([Figure 3](#)).

The present study aimed to reconstruct the upper Strzelecki Group stratigraphy based on the coastal outcrops, and using vitrinite reflectance measurements and palynology as controlling factors. The study focused on outcrops along the coastline between Harmers Haven and Inverloch, near the town of Wonthaggi (see [Figure 2](#)), in the western part of the basin, and about 150 km southeast of Melbourne, where the state mine produced more than 22 million tonnes of black coal at an annual rate of 400,000 to over 700,000 tonnes between 1909 and 1968 (Gloe, 1971; Knight, 1975).

Methods

Tasks carried out include geological mapping and stratigraphic logging of the accessible outcrops, sampling of carbonaceous sediments, vitrinite reflectance measurement and a palynology study.

Geological mapping. Using ArcView software geological maps were prepared at various scales of 1:2000, 1:5000 and 1:10000. The results show the main lithological boundaries, major and minor fault trends, strike/dip of bedding, vitrinite reflectance measurements, bores, local names and roads.

Stratigraphic and structural investigations. The coastal stratigraphy was logged and major lithologies and depositional systems were interpreted. In addition, the structural framework was investigated, cross sections compiled and numerous faults were mapped in outcrop and with the assistance of magnetic and Google Earth images.

Sampling. Samples of fine grained, argillaceous sediments and coal were collected from unweathered outcrops along the coastline between Harmers Haven and Inverloch.

Vitrinite reflectance measurement. Vitrinite is the major maceral in coal ([Figure 4](#)) and occurs as dispersed organic particles within sedimentary rocks. It undergoes an irreversible chemical process called maturation or coalification during burial related heating and the level of maturation can be determined from the measurement of the reflectance of vitrinite, which is a well-established means for assessing the thermal history of organic-bearing sediments.

The present day measurement of vitrinite reflectance, with concentration on kerogen, began in the mid-1960s and involves an incident light microscope, a photomultiplier, a microprocessor, and a computer. Usually vitrinite reflectance starts at about 0.2% near surface and increases in an approximate linear relation with depth, but it is not suitable for thermal maturity measurements below 0.4% (Dow, 1977; Robert, 1988). Example of variation of Ro% versus depth in different geothermal gradient is shown in [Figure 5](#). Vitrinite reflectance measurements were carried out on 46 outcrop samples at the GeoGas Laboratory, Wollongong, and the results were used to estimate the maximum depth of burial of each part of the stratigraphy sampled.

Palynology and Dating

Palynological dating, using spore and pollen grains, is especially useful in non-marine sediments, and several spore and pollen biostratigraphic charts have been prepared to help define stratigraphic ranges in southeast Australia, including the early Cretaceous sediments of the Gippsland Basin. Development of the floral biostratigraphy is ongoing, but the reference biostratigraphic chart used in this study is shown in [Figure 6](#). In present research, palynology studies were carried out on 18 carbonaceous samples and the results were used to correlate the various stratigraphic sections measured and assist the structural restoration. Note that significant numbers of the samples were barren or void zone identification.

Summary of Results

The outcrops are dominantly interbedded mudstone and fine-medium grained sandstone with numerous coal beds, especially near Harmers Haven and west of Inverloch. The proportion of mudstone increases to the northwest at Harmers Haven and northeast between Cape Paterson and Inverloch. The outcrops are cut by a number of apparently large faults, numbered from 1 to 12 on the geological maps. Based on the inferred major faults, the coastal geology has been divided into several blocks that are alphabetically named from A to M, as shown in [Figure 7](#). Three generations of faults have been mapped, which in chronological order from oldest to youngest, have dominant trends of E-W, NW-SE and NE-SW. In addition, fault displacements were estimated based on isotherm profile against the structural cross section. The estimation suggests maximum displacement of about 400 m occurs in inferred major faults at SE Harmers Haven and near the Oaks. The section is intruded by a number of dominantly NW trending dykes in which their thermal effect on upper Strzelecki Group sediment has been observed in this study and through significant change in vitrinite reflectance.

The results of the vitrinite reflectance measurements show that Ro% decreases from Harmers Haven, Cape Paterson and west Inverloch. Highest Ro% within thermally unaltered areas was observed at NW Harmers Haven and The Oaks in order 0.76% and 0.73%, while it rises to 1.72% near an intrusion in SE Harmers Haven. Units with the same average vitrinite reflectance value are inferred to have experienced the same maximum depth of burial; however, a problem occurs when the vitrinite reflectance was altered by inferred thermal events such as intrusion of dykes and fluid movement along fault planes. [Figure 8](#) shows the trend of vitrinite reflectance values along the structural cross section and its sharp changes near thermally affected areas or inferred major faults.

Palynological study of outcrop samples from the coastline between Harmers Haven and Inverloch has resulted in the followings:

- Sample of carbonaceous mudstone from northwest of Harmers Haven was located within *F.wonthaggiensis* and *P.notensis* zone (~135-130 Ma).
- Two samples of carbonaceous mudstones from west of Cape Paterson were located in *F.wonthaggiensis* and *P.parvispinosus* zones (>129 Ma) and *F.asymmetricus* zone (~129 Ma).
- Sample of carbonaceous mudstone from east of Cape Paterson was located in *F.wonthaggiensis* zone (~135-130 Ma).
- Sample of carbonaceous mudstone from west of The Oaks was located in *T.reticulatus* and *P.parvispinosus* zone (>129 Ma).
- Sample of ripped up mudclasts from east of The Oaks was located into *P.notensis* zone (~135-130 Ma).
- Sample of carbonaceous mudstone from east of Shack Bay was located in *F.asymmetricus* zone (~129 Ma).
- Sample of carbonaceous mudstone from west of Eagles Nest was located in *P.notensis* and *P.parvispinosus* zone (>129 Ma)
- Sample of carbonaceous mudstone from west of Eagles Nest was located in *F.asymmetricus* and *C.hughesii* zone (<129 Ma).

Understanding the paleo-geothermal gradient of the area during the early Cretaceous is necessary in order to be able to reposition the stratigraphic sections at their relevant depth prior to faulting. Previous work by Duddy and Green (1992) suggests a paleo-geothermal gradient between 45 to 50 °C/km, however, the authors mentioned that this value would need to be confirmed based on a vertical stratigraphic section.

In addition, a paleo-geothermal gradient of 49 °C/km was estimated based on one of the thickest sections (> 1,000 m) of the Strzelecki Group close to the study area drilled by Tarwin Meadows-1, about 15 km southeast of Inverloch (Holdgate, 2003).

Combination of the above suggested/estimated paleo-geothermal gradients and results of this study, mainly based on the measured coastal stratigraphy, a paleo-geothermal gradient of 50 °C/km has been decided for Strzelecki Group stratigraphy restoration (Figure 9). Restoration of the stratigraphy based on palynology and vitrinite reflectance results, and regarding a paleo-geothermal gradient of 50 °C/km, suggests repetition of bio-zones along the coastline and indicates similar age strata experienced different maximum depth of burial. Based on this idea the coastal outcrops were divided into several blocks with similar bio-stratigraphic column but different burial history (Figure 10).

Conclusions

- This study provides example of how vitrinite reflectance measurement and palynology can be used in complicated process of fluvial sediments stratigraphic restoration with a focus on early Cretaceous Gippsland Basin outcrops along the coastline near the Wonthaggi Township.
- Overlap of palynology and vitrinite reflectance trend reveals repetition of Strzelecki Group stratigraphy along the coastline between Harmers Haven and Inverloch, which could be explained through several active stress regimes of extension and compression in the history of the west Gippsland Basin.
- At the time of Strzelecki Group deposition in Early Cretaceous, Wonthaggi area was under high geothermal gradient of 50 °C/km and sedimentation rate of 35-200 m/Ma is being suggested based on restored stratigraphic column.
- Vitrinite reflectance measurements shows a sharp reduction, also called vitrinite suppression, near Eagle's Nest with the appearance of *C.hughesii* (<129 Ma) which could be due to several reasons such as unconformity, fault or effect of brackish water. Note that this change has been reported in Megascollides-1 well report as well (see Preston (2005)).
- Thermal maturity was increased near dyke, and return to its normal trend away from the intrusion.
- The study suggests a present day thickness of 300 m for the Strzelecki Group in Wonthaggi region with variable amount of erosion from ~1.4 km to ~2 km in order from Inverloch to Harmers Haven.

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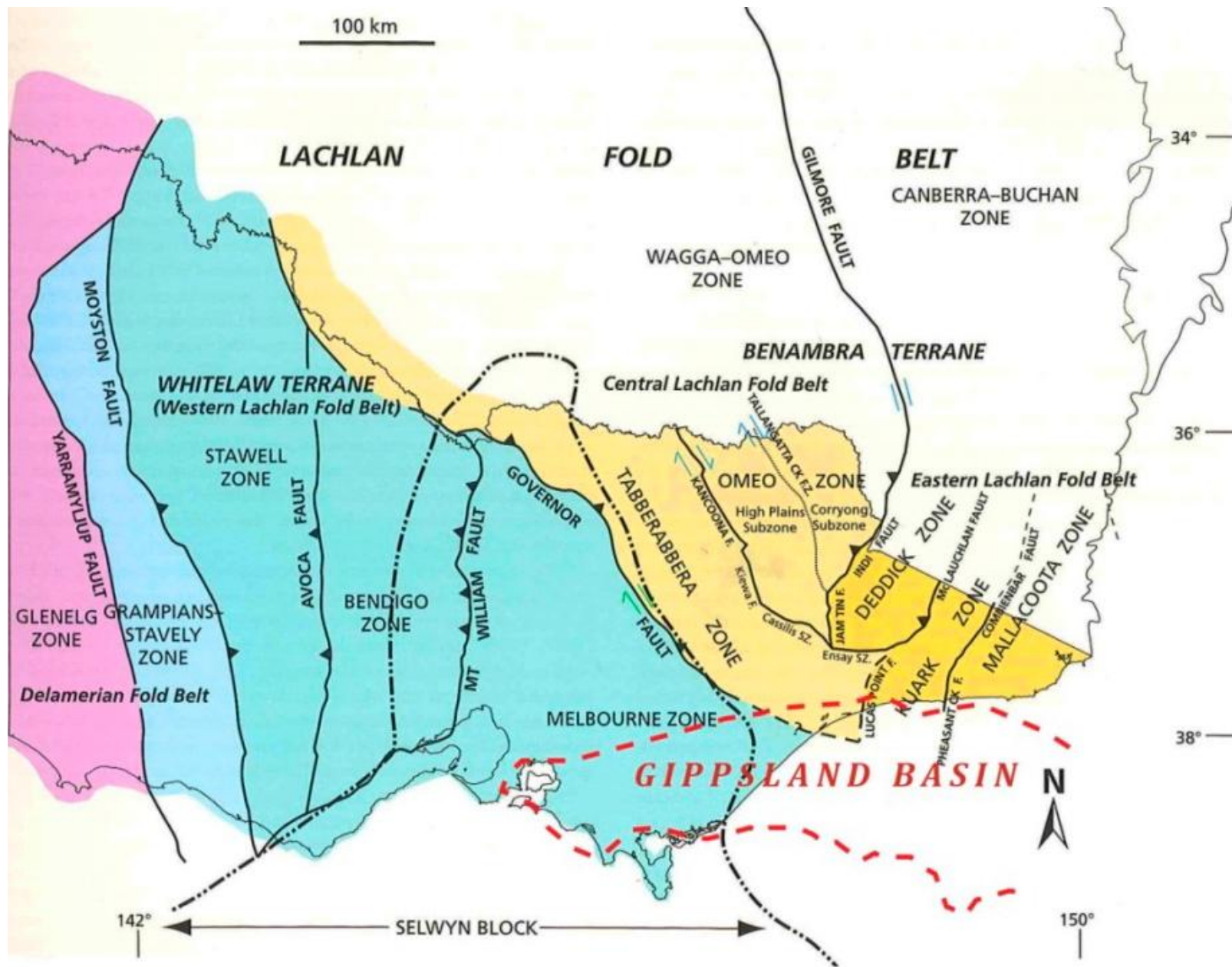


Figure 1. Map showing the major structural zones in Victoria and the position of the Gippsland Basin (modified from VandenBerg et al. (2000)).

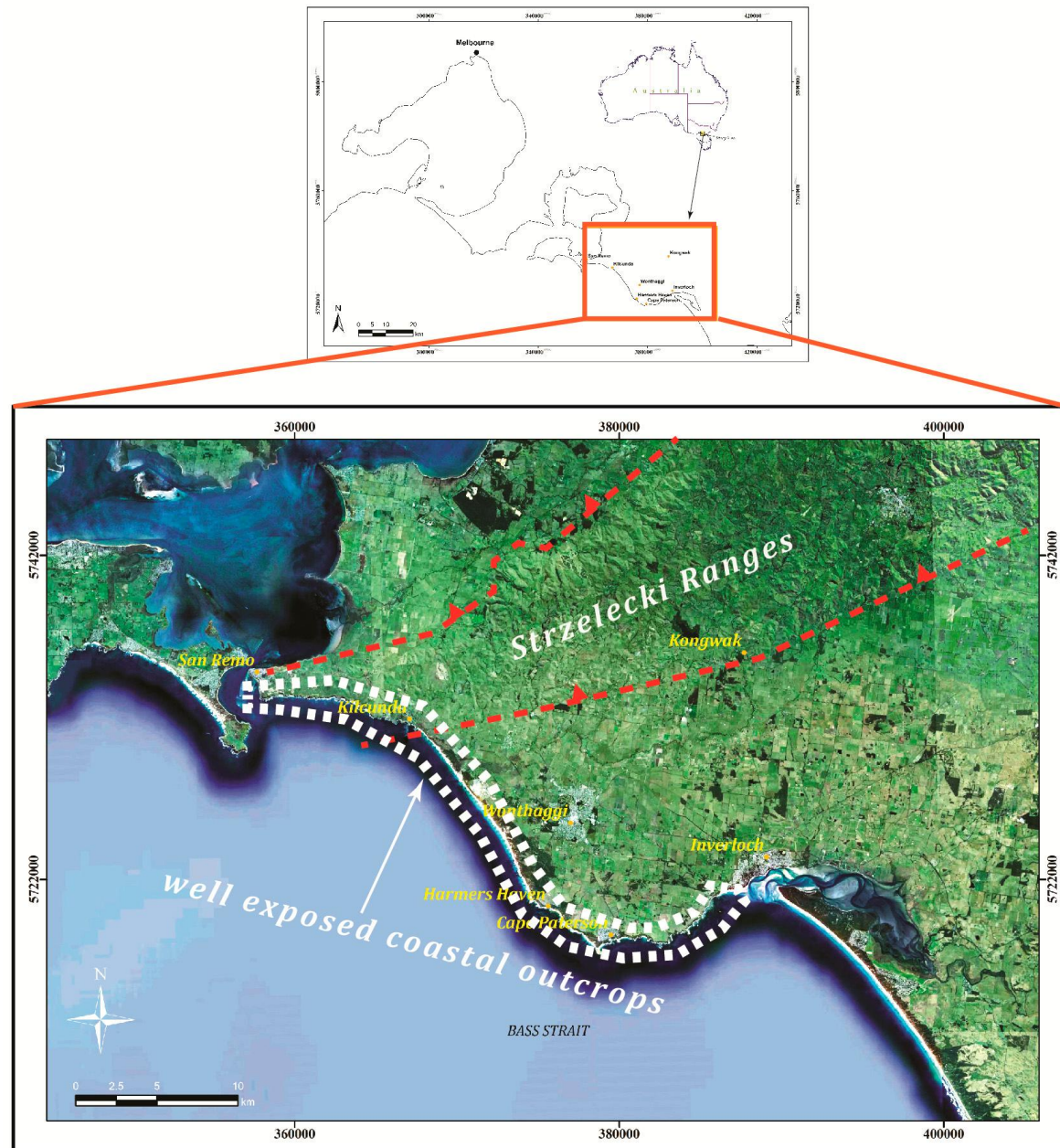


Figure 2. Location of well-exposed coastal outcrops of Strzelecki Group along the coastline between San Remo and Inverloch, west Gippsland.

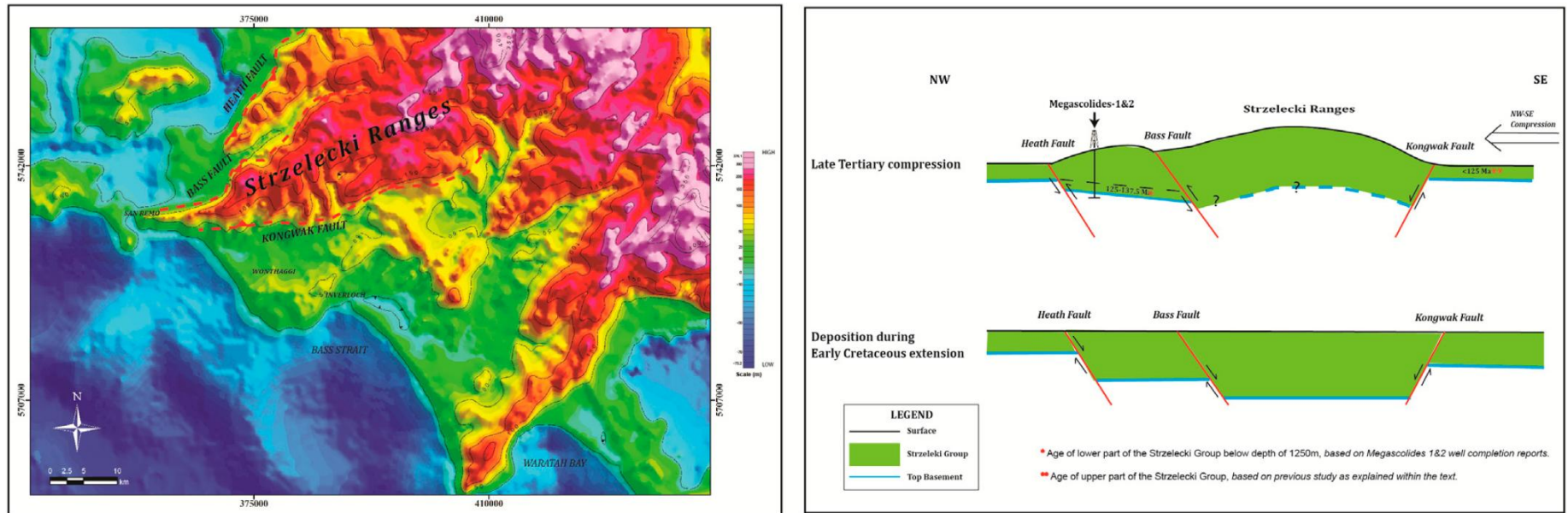


Figure 3. The topography of the area and its relationship to late Tertiary NW-SE directed compression.

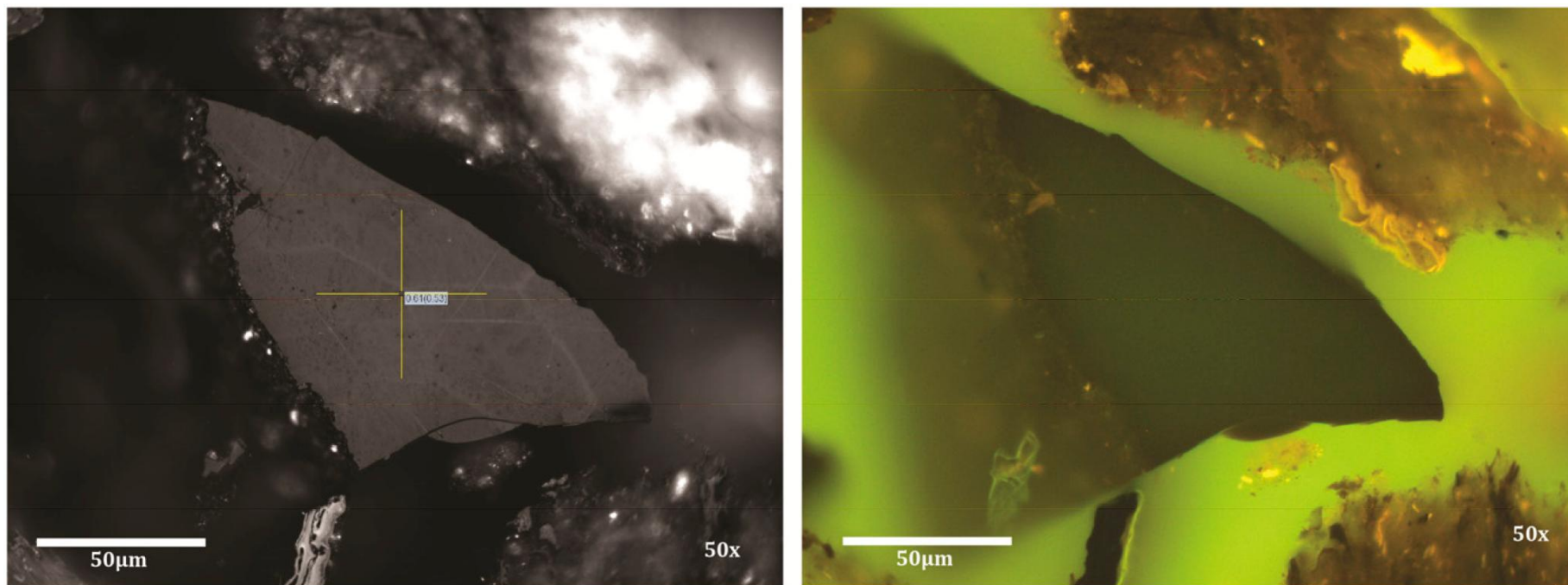


Figure 4. Microscopic image of vitrinite maceral, $R_o=0.61\%$, in reflected white light (left) and fluorescence mode (right); 50X.

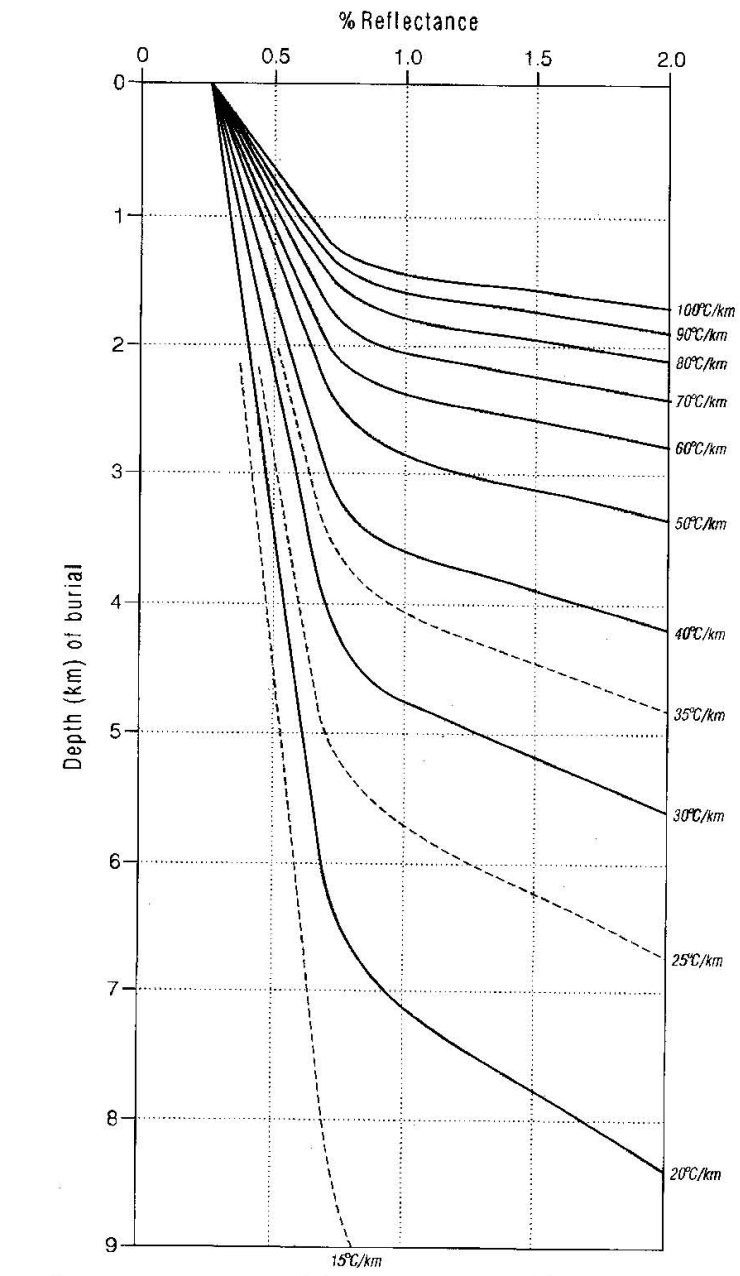


Figure 5. Variation of vitrinite reflectance with depth in different geothermal gradient for a surface temperature of 15°C (after Suggate (1998)).









Gippsland and Otway Basins Spore-Pollen Biostratigraphy (Dettmann, 1986)		Spore-pollen first and last occurrences used in this study	Suggested ages * published in Wagstaff et al. 2012 ** pers comm	Geologic age
Dictyotosporites speciosus Zone	C. striatus subzone	 Crybelosporites striatus	112 Ma*	100 Ma Albian
	Upper	 Cooksonites variabilis		113 Ma Aptian
		 Clavatipollenites hughesii  Foraminisporis asymmetricus	Approx 129 Ma **	126 Ma
		 Pilosisporites parvispinosus		Barremian
	Middle	 Triporoletes reticulatus		130 Ma
	Lower	 Pilosisporites notensis	Approx 135-130 Ma**	Hauterivian
		 Foraminisporis wonthaggiensis		

Figure 6. Reference biostratigraphic chart used in present study (modified from Dettmann (1986) and Wagstaff et al. (2012).

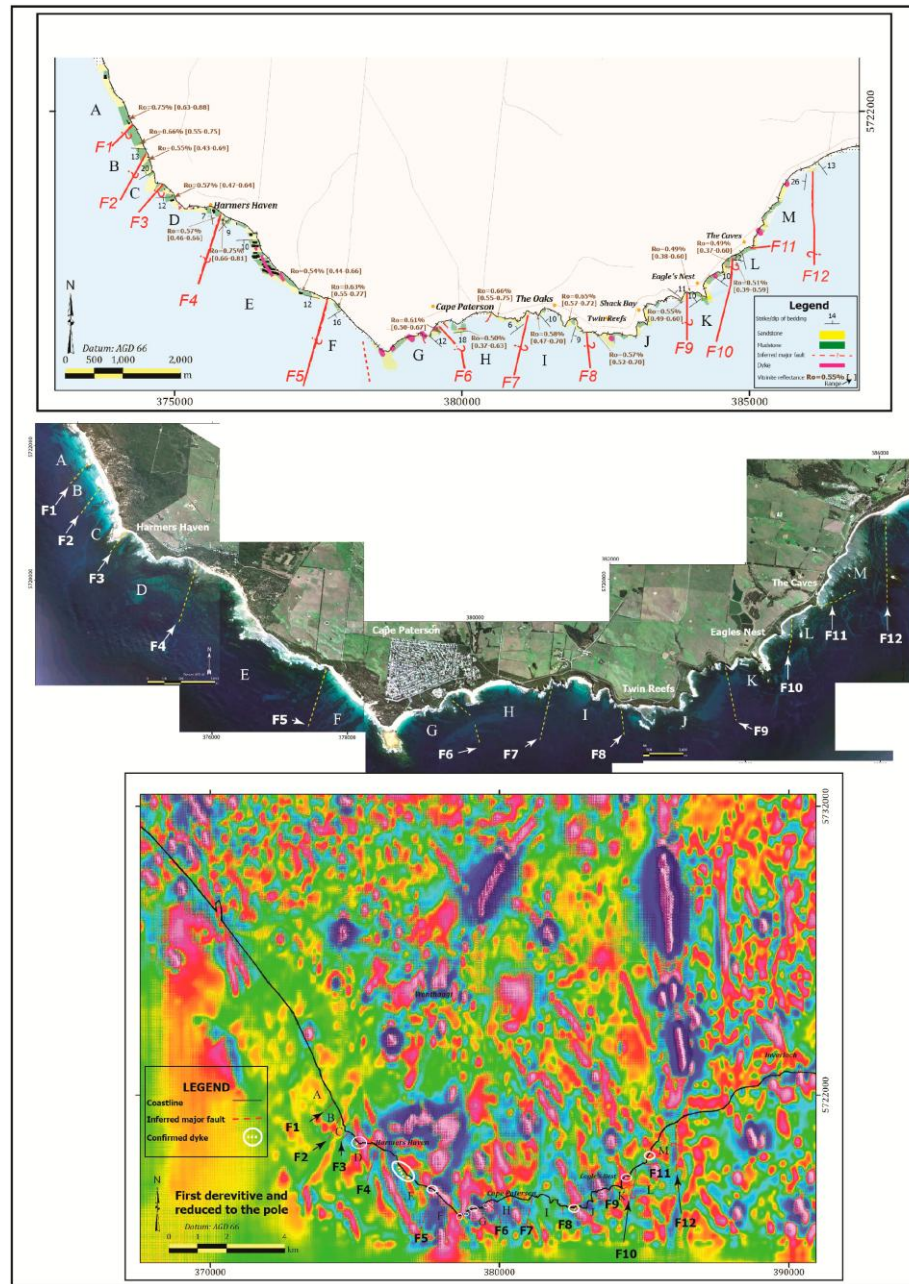


Figure 7. Locations of inferred major fault blocks along the coastline between Harmers Haven and Inverloch.

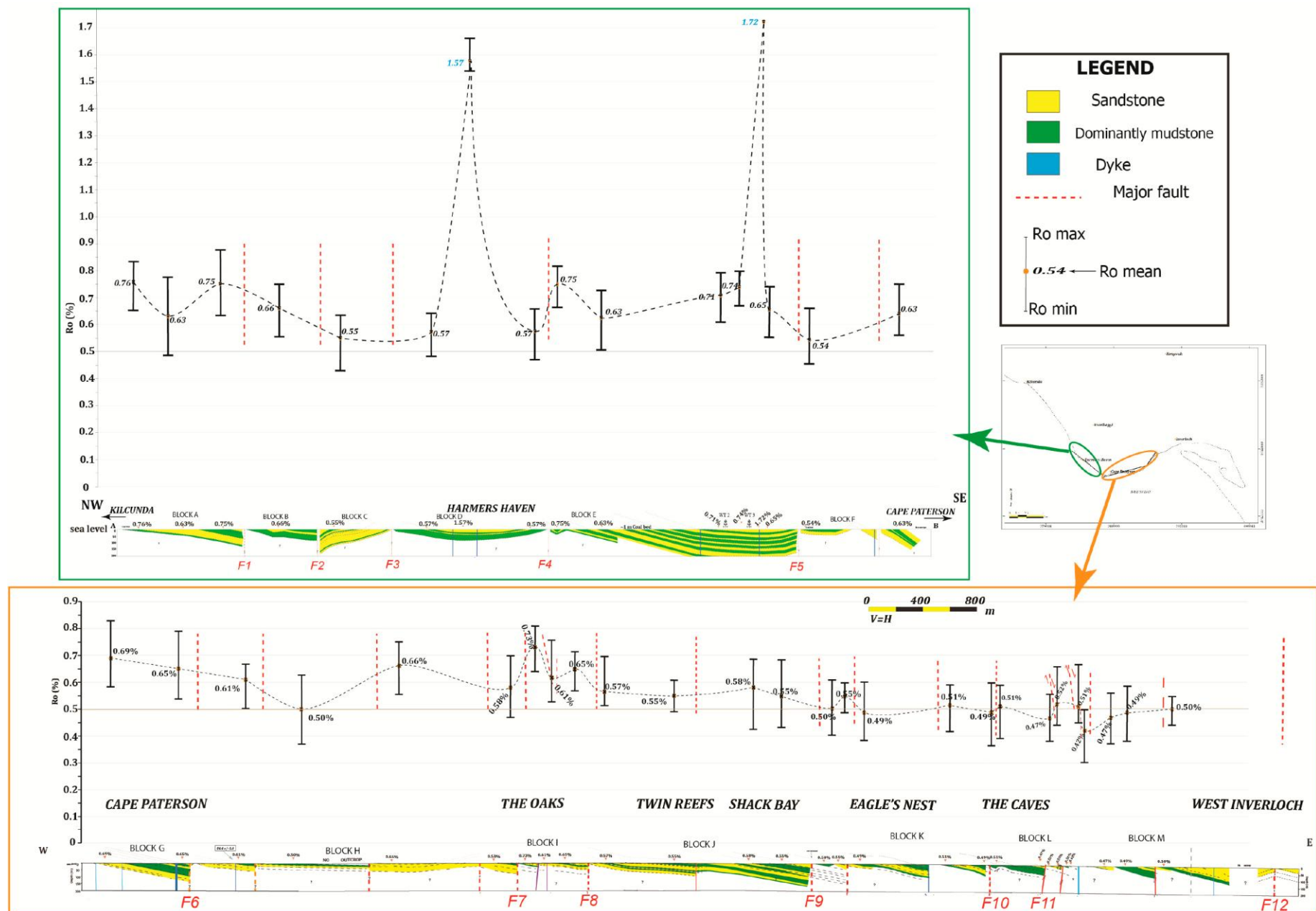


Figure 8. Profile of vitrinite reflectance trend against structural cross section of the coastline between Harmers Haven and Inverloch.

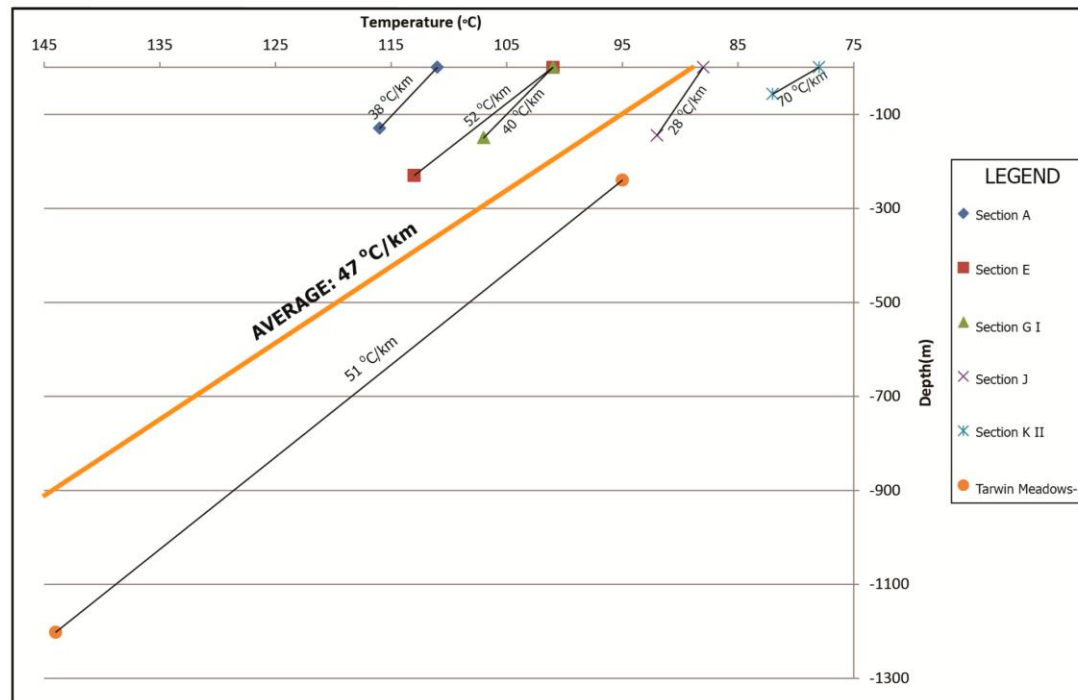
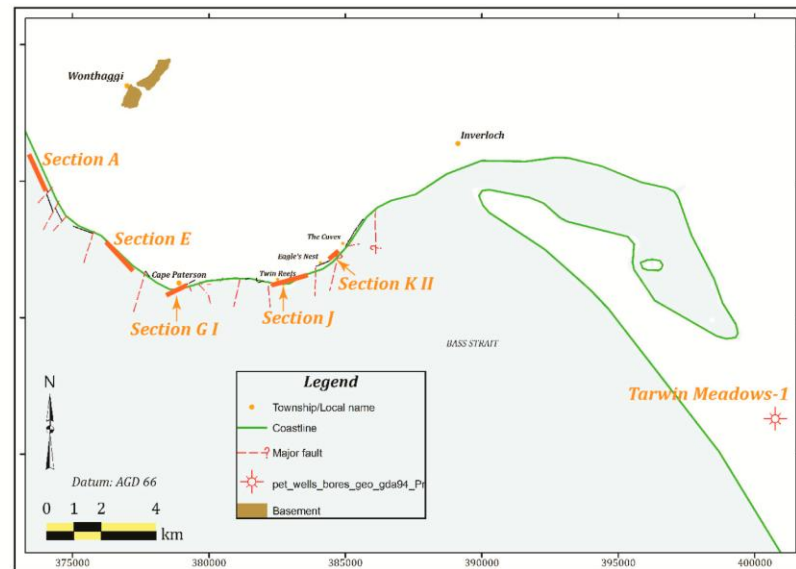


Figure 9. Estimated paleo-geothermal gradient based on measured logs and Tarwin meadows-1.

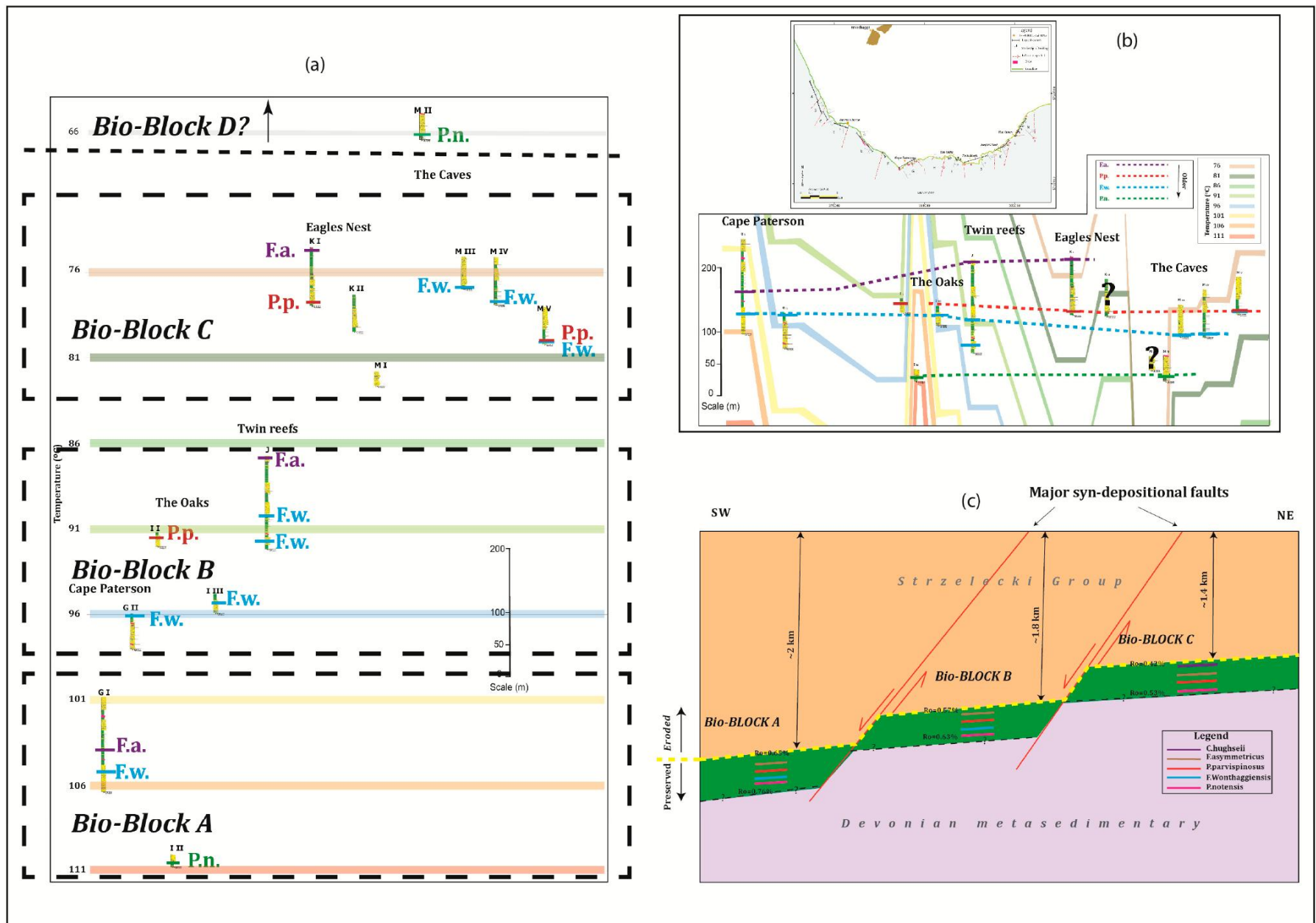


Figure 10. showing restored stratigraphic column based on (a) parallel isotherms (b) parallel bio-zone; (c) possible back-Back-stripped model of Wonthaggi area geology at the end of deposition and before uplift, erosion and recent compression.