Dahlhaus Environmental Geology Pty Ltd

A.B.N. 81 085 846 813
A.C.N. 085 846 813

P.O. Box 318 Buninyong Vic 3357
Ph: (03) 5341 3994 Fax:(03) 5341 2768
Email: dahlhaus@netconnect.com.au
www.environmental-geology.com.au

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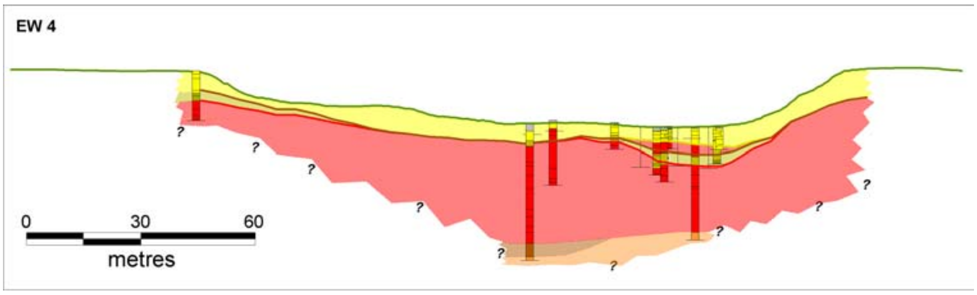
The Dell, Clifton Springs

3-dimensional geological model



September 2003

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Disclaimer

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1 Introduction

The Dell is a natural amphitheatre on the coast of the Bellarine Peninsula near Clifton Springs, Victoria. A.S. Miner Geotechnical Pty Ltd and Parsons Brinckerhoff Pty Ltd have investigated a landslide complex at The Dell since the initial movement in 2001. The complexity of the site geology has created difficulties in establishing credible three-dimensional models for the site. A recent peer-review of the hydrogeology of the site by John Leonard Consulting Services Pty Ltd (Leonard, 2003) identified the need for a conceptual geological model to provide confidence in the proposed remedial works.

This report was commissioned by Mr Anthony Miner, Director, A.S. Miner Geotechnical Pty Ltd to address the knowledge-gap highlighted in the peer-review. The project aims to provide three-dimensional models to assist in the interpretation of the:

- regional geology of the Clifton Springs area
- regional hydrogeology of the Clifton Springs area
- geology of the landslide complex at The Dell
- hydrogeology of the landslide complex at The Dell
- mechanics of the landslide complex at The Dell

1.1 Scope of the project

The vast majority of information available to this project has been supplied by A.S. Miner Geotechnical Pty Ltd and Parsons Brinckerhoff Pty Ltd. Their data has been collected through the geotechnical investigation of the site. The models, discussion and conclusions of this report are based on a desk study of this data (as supplied) and other data available in the public domain. Dahlhaus Environmental Geology Pty Ltd has assumed the validity of the interpretation of the data by the abovementioned consultants, including the stratigraphic interpretation of the geological materials recovered by drilling and the three-dimensional spatial locations of the data or observations as recorded.

Although the author of this report is familiar with the site from previous investigations, field visits or inspection of samples or cores were not undertaken as a part of this project. The intention of this project is to present an impartial and independent interpretation of the three-dimensional geology of the site, within the limitations of the data available.

The project has resolved a geological model for the site, which has addressed the first of the recommendations in the report by Leonard (2003).

While some achievements were made towards resolving the hydrogeological and mechanical models, they were not as comprehensive as initially expected. This is due to the combination of the complexity of the geology and the limitations in the type of data available. Recommendations have been made to improve the data for future modelling.

2 Geology and geomorphology

The Dell is situated on the northern shore of the Bellarine Peninsula at Clifton Springs (Figure 1). The geology of the peninsula is relatively complex and both the neotectonic movement along the major geological structures and the fluctuating sea levels of the recent past has controlled the landscape evolution.

2.1 Regional geology

The basement of the Bellarine Peninsula is regarded as the Lower Cretaceous Otway Group rocks, comprising fluvial sandstones and mudstones comprised of volcaniclastic material. These rocks are exposed at the surface in a relatively narrow strip southwest of Portarlington, along the southern margin of the Curlewis Monocline.

The Cretaceous is bordered to the south by a much larger outcrop of Older Volcanics, comprising basalt, tuff and agglomerate. The Older Volcanics are exposed at the highest part of the Bellarine Peninsula, Mount Bellarine, and smaller outcrops occur along the coast north of Curlewis. The radiometric age determinations for the Bellarine Older Volcanics (39.5 ± 0.6 Ma) are much older than the Curlewis outcrops (22.5 ± 0.5 Ma) (McKenzie *et al.*, 1984). The Bellarine basalts are intercalated with clayey sand, gravel, sandy clay (tuffaceous in part) and occasional brown coal. The sediments and intercalated volcanics are part of the extensive Werribee Formation deposited from the Palaeocene to the lower Miocene. On the Bellarine Peninsula the Werribee Formation is regarded as Eocene in age and grade laterally into the Eastern View Formation to the southeast (Abele, 1988). The Bellarine Older Volcanics are mainly basanites and alkali basalts, regarded as part of the Flinders Province dated as middle to late Eocene (39Ma to 49Ma) (Price *et al.*, 1988).

Surrounding the Otway Group and Older Volcanics of the Bellarine block are the Neogene sediments of the Torquay Group, although outcrops are isolated. Exposures of Fyansford Formation (early to middle Miocene) have been mapped along the coast north of Curlewis and at Clifton Springs (Coulson, 1933, Ladd, 1971). Under the Moolap Sunkland, the Fyansford Formation is thought to grade laterally into the Puebla Formation, exposed around Lake Connewarre (Abele, 1988). Disconformably overlying the Torquay Group and older units are Pliocene age marine sand and sandy clays of the Moorabool Viaduct Formation. The sands are commonly ferruginous and generally less than 30 metres thick.

The western end of the peninsula forms the Moolap Sunkland of very low elevation, which formed a seaway during the Holocene maximum (~6000ka) (Jenkin, 1988). The sunkland is covered by a variety of Quaternary marine and fluvial sediments, including gravels, sands, silts, clays, shell beds and peat.

2.1.1 Structural Geology

The central part of the Bellarine Peninsula (the Bellarine Block) has been uplifted along the west-dipping Bellarine Fault to the east and the east dipping un-named fault on the western side. The uplift probably corresponds to Late Miocene tectonism, probably resulting from the compression of the entire Australian continent due to collision of the Australian plate with the neighbouring Southeast Asian and Pacific plates. At present the Bellarine Peninsula (and indeed the whole of Victoria) are still under strong E– W to SE – NW compression, and faults perpendicular to this compressional axis remain seismically active. There is substantial evidence for continuing tectonic activity throughout the Pliocene and Quaternary up to the present (Joyce, *et al, in press*).

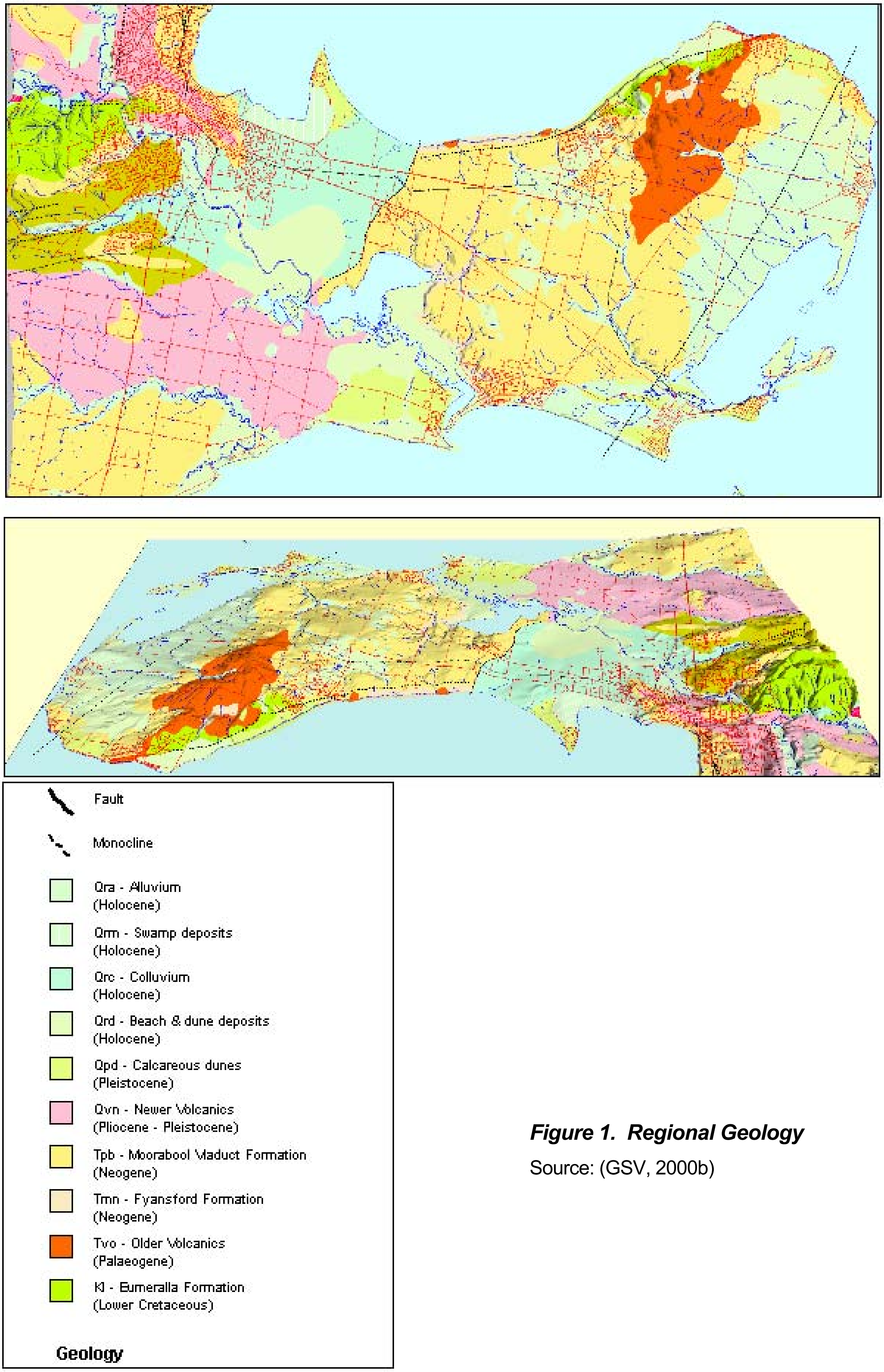

Figure 1. Regional Geology

Source: (GSV, 2000b)

The northern coastline of the uplifted Bellarine Block is bounded by the Curlewis Monocline (Coulson, 1933). The monocline may be the result of the reactivation of a Mesozoic east-west extensional (normal) fault in the Otway Group during the Pliocene – Pleistocene uplift of the Bellarine Block. Evidence for this is given by 1) the exposed Otway Group rocks along the southern boundary of the monocline (perhaps more properly termed a fault at this location); 2) the monocline is bounded by the faults either side of the uplifted block and 3) the monocline has folded the Older Volcanics and overlying Fyansford Formation where they exist along the structure.

2.1.2 *Geophysics*

The available geophysical data was examined to ascertain the subsurface structural features and the extent of the Older Volcanics in the vicinity of The Dell. The data was supplied by the Geological Survey of Victoria (GSV) and the images and details are appended (Appendix A).

The airborne magnetic data has provided the most useful interpretation of the regional geology for the Bellarine Block. The total magnetic intensity (TMI) image (Figure 2) essentially shows the variation in the magnetic susceptibility of the various rocks, which is directly related to their magnetic mineral content. The magnetic minerals record the polarity of the Earth's magnetism at the time of their formation. Igneous rocks containing magnetic minerals (magnetite) are highlighted by the magnetic intensity. The flows of the Older Volcanics on Mount Bellarine are shown by strongly reversed polarity. In particular, the flow towards Portarlington is clearly evident by the juxtaposition with the strongly normal polarity of the Otway Group rocks[1].

The TMI image illuminated from the north east (Figure 2) shows a NW – SE trending linear feature of reversed polarity underlying the general area of The Dell. This feature may represent a volcanic flow and is also evident in the magnetic gradient image (Figure A3, Appendix A).

2.1.3 *Regional bore records*

Regional bore records were sourced from the Corangamite Catchment Management Authority (CCMA) bore database, which has recently been assembled. The database combines bore records from the Victorian Groundwater Database (VGB), Geological Exploration and Development Information System (GEDIS), the salinity bore database, Barwon water, etc. The regional bores are listed in Appendix B.

Approximately 40 bores have lithological information recorded by the driller ("driller's logs"). Interpretation of the logs indicates that the Older Volcanics occur sporadically in the subsurface around Clifton Springs. Bores with basalt recorded include one near the junction of Club Road and Catalina Crescent, and one near the junction of Whitcombes Road and Dumburra Avenue (Figure B1). This suggests the presence of a basalt flow trending north west through part of Clifton Springs to the coast. This flow coincides with the Older Volcanics exposed in outcrop on the shore platform at The Dell.

Most of the bores record a vague lithological description, which is geologically indeterminate (eg. "clays", or "sands"), making correlations impossible.

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[1] The Otway Group rocks are sedimentary rocks made up of fragments of volcanic rocks, and therefore contain a high proportion of magnetic minerals.

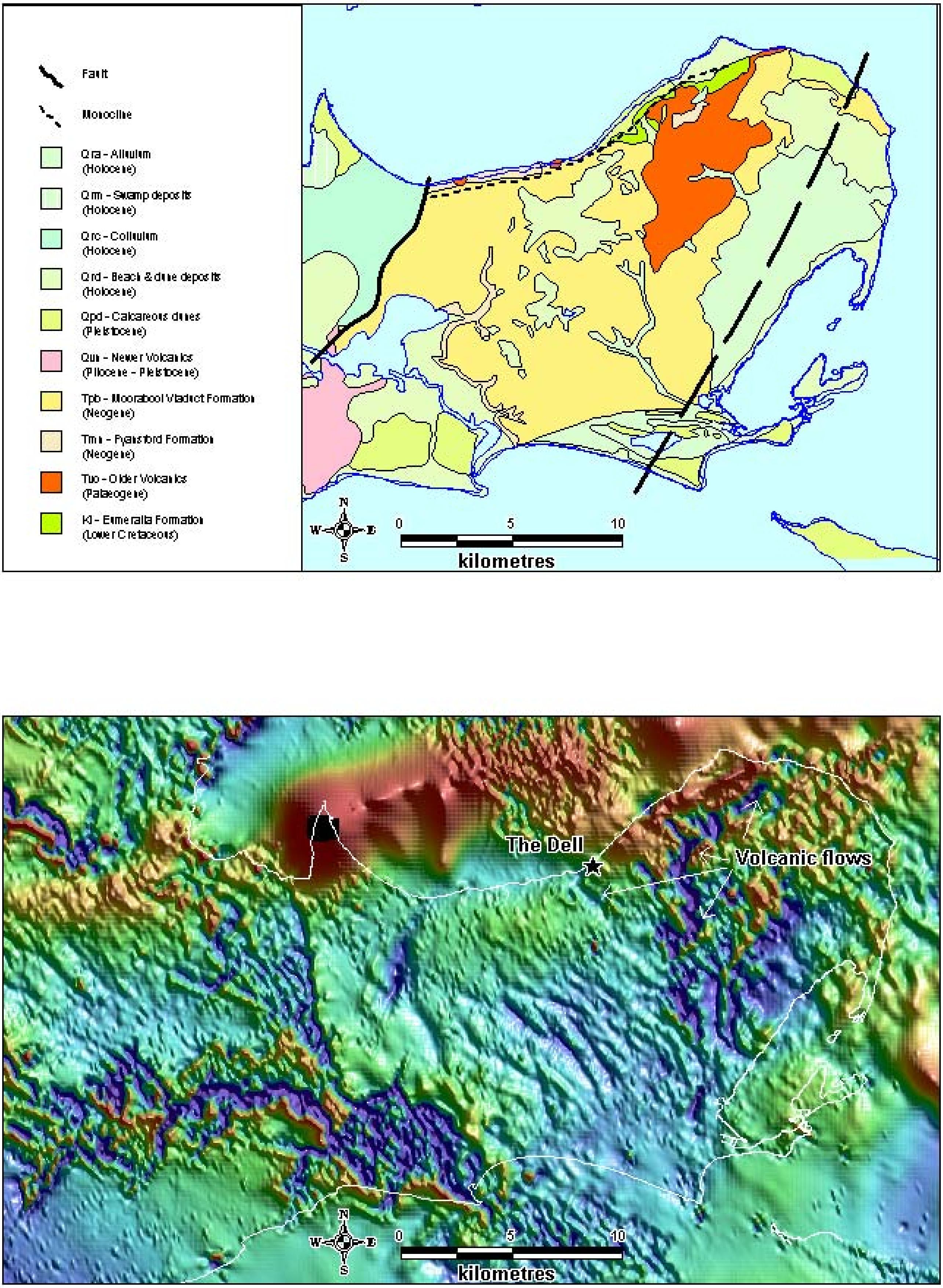

Figure 2. Total Magnetic Intensity image and regional geology.

Source: (GSV, 1999, GSV, 2000a, GSV, 2000b)

2.2 Regional Geomorphology

The Bellarine Peninsula comprises two main geomorphic units: the dissected low hills and plateau of the Bellarine Block, which form part of the Southern Uplands of Victoria; and the Alluvial terraces, alluvium and coastal plains, which form part of the Western Plains of Victoria.

The uplifted block of the Bellarine Peninsula forms a very weakly dissected undulating plain of low elevation (less than 150 metres). The landscape evolution of the Bellarine Block is relatively complex. The Otway Group rocks were exposed at the surface during the Eocene when they were covered by the eruptions of the Older Volcanics and intercalated fluvial sediments of the Werribee Formation. However, the Miocene sea covered at least part (or perhaps all?) of the block, since remnants of the Fyansford Formation overlie the volcanics on the northern flanks of Mount Drysdale. The retreat of the Miocene sea exposed the landscape to erosion, which stripped some of the Fyansford Formation from the Older Volcanics and Otway Group Rocks. Most (if not all) of the block was also subsequently covered by the Pliocene sea, which resulted in deposition of the Moorabool Viaduct Formation. Subsequent uplift has stripped the Pliocene sand and Miocene sediments to expose the Older Volcanics and Otway Group rocks in today's landscape. Drainage from the remnant basalts of the Palaeogene Older Volcanics forms a vaguely radial pattern on the elevated plateau.

2.2.1 Quaternary sea level fluctuations

The fluctuations in sea level during the Quaternary have also impacted on the landscape of the Bellarine Peninsula. In particular, sea level fluctuations over the last 150,000 years have had a dramatic impact on the coastal geomorphology (Figure 3). The extensive coastal plain of the Moolap Sunkland, formed a shallow seaway both during the last interglacial (*ca* 125 000 years ago) and the Holocene maximum (*ca* 6000 years ago) (Marsden, 1988). However, during the last glacial (*ca* 18000 years ago) sea levels were approximately 140 metres lower than present and Corio Bay was exposed as a valley from which rivers flowed through the present-day Port Phillip Bay to the distant coast, at the edge of the Australian Continental Shelf.

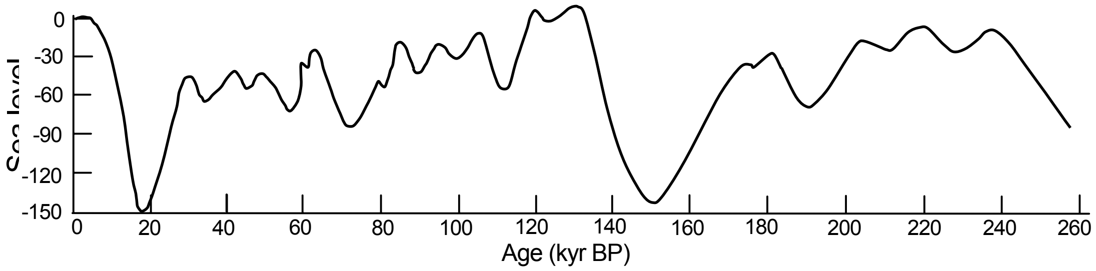

Figure 3. Sea level fluctuations over the past 250,000 years

Source: Williams et al., 1993

These changes in sea level combined with the Plio-Pleistocene uplift along the northern boundary of the Bellarine Block (i.e. along the Curlewis Monocline) must have had a dramatic impact on the coastal erosion and accelerated the development of landslides. Even the slight drop in sea level (~ 2 metres) over the past 6000 years (lowering base level and renewed erosion) or the slight rise in sea levels over the past century (erosion and undercutting of the coast) will have initiated landslide activity. Relatively recent landslides can be seen along the coast east of The Dell.

2.3 Site geology

The geology of the Clifton Springs area is complex as is evident by the conflicting interpretations in the scientific literature over time (Coulson, 1933, Daintree, 1862, Hall & Pritchard, 1894, Ladd, 1971). Most of these previous investigators have attempted to unravel the stratigraphy of the coastal exposures from north of Curlewis to Clifton Springs.

The previous investigations note the presence of the Older Volcanics as basalt overlain by tuff, intercalated sands and gravels, the presence of limestone and marl and the Pliocene sands. Most of the complexity surrounds the relationship between the units, in particular the limestones, marls and tuff.

Coulson (1933) and Ladd (1971) published maps detailing the geology of the coast at Clifton Springs. Their maps and accompanying descriptions indicate that on the eastern side of The Dell, the Older Volcanics are exposed as basalts overlain by tuffs, which are disconformably overlain by the Moorabool Viaduct Formation. On the coastal platform immediately in front of the "…*cliffs near the bath jetty*", Coulson reports the sporadic presence of remnant fossiliferous marls (presumably the Fyansford Formation) on top of the Older Volcanic tuff. West of The Dell, on the coastal platform, both Coulson and Ladd have mapped the Fyansford Formation dipping from 70° NW to 30° NNW. Ladd's mapping shows the Older Volcanics either side of The Dell, with sand and alluvium in-between.

2.3.1 Structural influences at the site

The Curlewis Monocline controls the morphology of the northern coast of the Bellarine Peninsula. The Dell occurs at the point where the monocline (and coast) changes direction, from east - west (west of The Dell) to northeast – southwest (west of The Dell). This change in direction is also associated with a change in the geology exposed along the monocline, with the Cretaceous exposed to the east (perhaps along the exposed underlying fault) and the folded Fyansford Formation to the west. The change in trend direction also coincides with a change on elevation of the topography of the Bellarine Block. It is speculated that the NE – SW trend may be associated at depth with an extension of structural lineament in the basement (Otway Group) rocks, such as the Torquay Fault, whereas the E – W trend may be associated with a separate basement structural lineament. Put more simply, The Dell may be at the junction of two faults at depth.

At The Dell, the monocline is very close to the coastline and its axis is broadly mapped along the southern edge of the amphitheatre. It could be logically argued that presence of the groundwater discharge on the shore platform at The Dell (i.e. the Mineral Springs) is also related to the proximity of the underlying fault. The regional groundwater, recharged through fractured Older Volcanics of Mount Bellarine, may be discharged along the fault, which is exposed at the coast.

Similarly, there is logic in the occurrence of the amphitheatre at the change in direction of the geological structure. The underlying fault, being a conduit for groundwater and a weakness in the rock is more prone to erosion through mass wasting processes. Upward groundwater pressures, coastal erosion at the cliff, sporadic seismicity, the presence of the monocline / fault, and landscape dissection by stream erosion, all combine at this location. Consequently, The Dell represents an erosional feature formed by continuous mass wasting through geological time. The present day landslide is a continuation of this erosion process.

3 Modelling

Much of the data for the construction of three-dimensional geological models was supplied by A.S. Miner Geotechnical Pty Ltd and Parsons Brinkerhoff Pty Ltd. These data included the geotechnical bore logs, geotechnical test results, inclinometer data, piezometric data, groundwater levels and groundwater chemistry. Survey data was supplied by TGM Pty Ltd, both as *AutoCAD* files and raw data in ASCII format. The data was used 'as is' and re-interpretations or modifications were not undertaken, although clarification was sought when required.

These data sets were supplemented by Geographic Information System (GIS) data and other database data held by the author.

All data used in this project is appended in digital format on CD (Appendix C).

3.1 Numerical surface models

The topographic and sub-surfaces were modelled using two numerical surface modelling packages, *Vertical Mapper* (v2.5) and *Encom Discover* (v5.01), both add-in packages to the GIS software, *MapInfo Professional* (v7.0). Several numerical models were initially constructed using three algorithms: inverse distance weighting; spatial neighbour with inverse distance weighting; and triangulation with smoothing. All methods produced similar results, although variations were evident. Triangulation with smoothing was chosen as the final method, although it produces the most 'angular' surfaces, the algorithm honours the data best.

Four surfaces (grids) were modelled using *Discover*:

- Topographic surface using the raw survey data as supplied by TGM
- Structure contours[2] of the Moorabool Viaduct Formation (Tpb)
- Structure contours of the top of the 'mid level sands' (Ts)
- Structure contours of the top of lower Older Volcanics (Tvo2)

These grids were then exported to *Vertical Mapper* and manipulation of the surfaces (grid arithmetic) produced:

- Isopachs[3] of the upper Older Volcanics (Tvo1 = Tpb – Ts)
- Isopachs of the upper Older Volcanics and the mid-level sands (Tvo1 + Ts = Tpb – Tvo2)

The contours were generated from the isopach grids for display purposes.

The resultant grids were then displayed using *Vertical Mapper* both as plan views and oblique views. The *AutoCAD* contours supplied by TGM were draped on the topographic surface model to check the validity and the locations of the bores were also displayed on the surfaces. City of Greater Geelong (CoGG) orthophotoimagery was displayed using *MapImagery* (v6.526) and draped on the final topographic surface model to provide context to the models.

All the resultant models are illustrated in Figures 4 to 9 (plan views) and 12 to 19 (oblique views).

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[2] Structure contours are related to the Australian Height Datum (AHD)

[3] Isopachs are isolines of unit thickness.

3.2 Cross-section models

A series of geological cross-sections were generated through The Dell both perpendicular and parallel to the coastline (Figures 10 & 11). These sections were generated using *Discover* and included the numeric surfaces as mentioned in the previous section. The sections are illustrated as normal-scale (no vertical exaggeration) and both the east-west sections and the north-south sections are the same scale.

Note that the sections represent a 7.5 metre wide slice along the section line. Bores located within the slice are projected to the centre line. The profiles of the sub-surface models (structure contour models) are drawn along the centre line. This can lead to an apparent mismatch between the structure contour surface and the bore log displayed on the section.

3.3 Limitations

The modelled surfaces and sections are interpolated from the available data according to the algorithm of the software used. They do not record reality, but rather an <u>interpretation</u> of the sub-surface conditions at the site. The interpretation is limited by the spatial distribution of the data, the interpretation of the drilling logs, the chosen modelling algorithm, and the parameters chosen for the interpolation between data points. While all due care and expertise has been taken in the construction of the models, it is inevitable that the interpretation will be modified by further investigation or subsurface exploration.

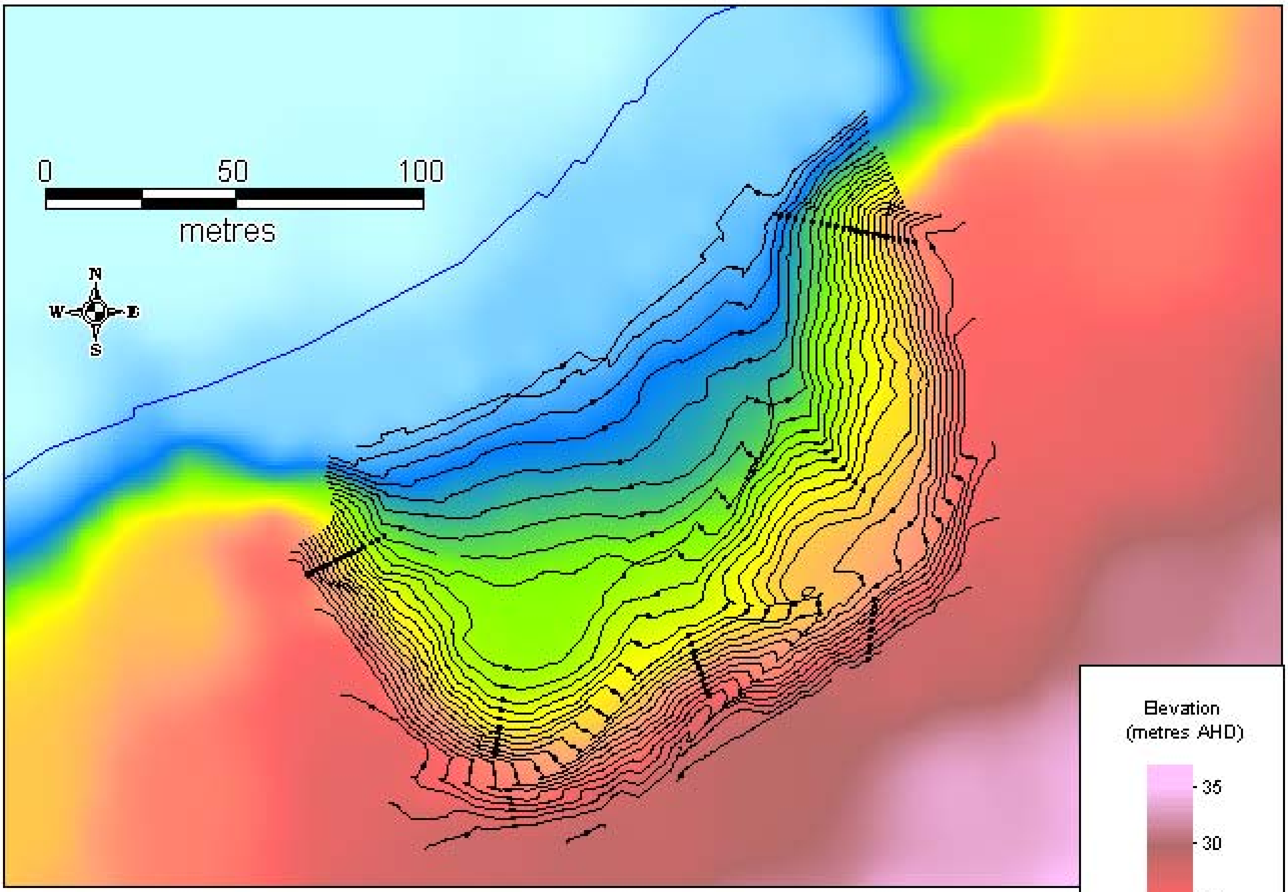


Figure 4. Topographic surface model with surveyed contours overlain.

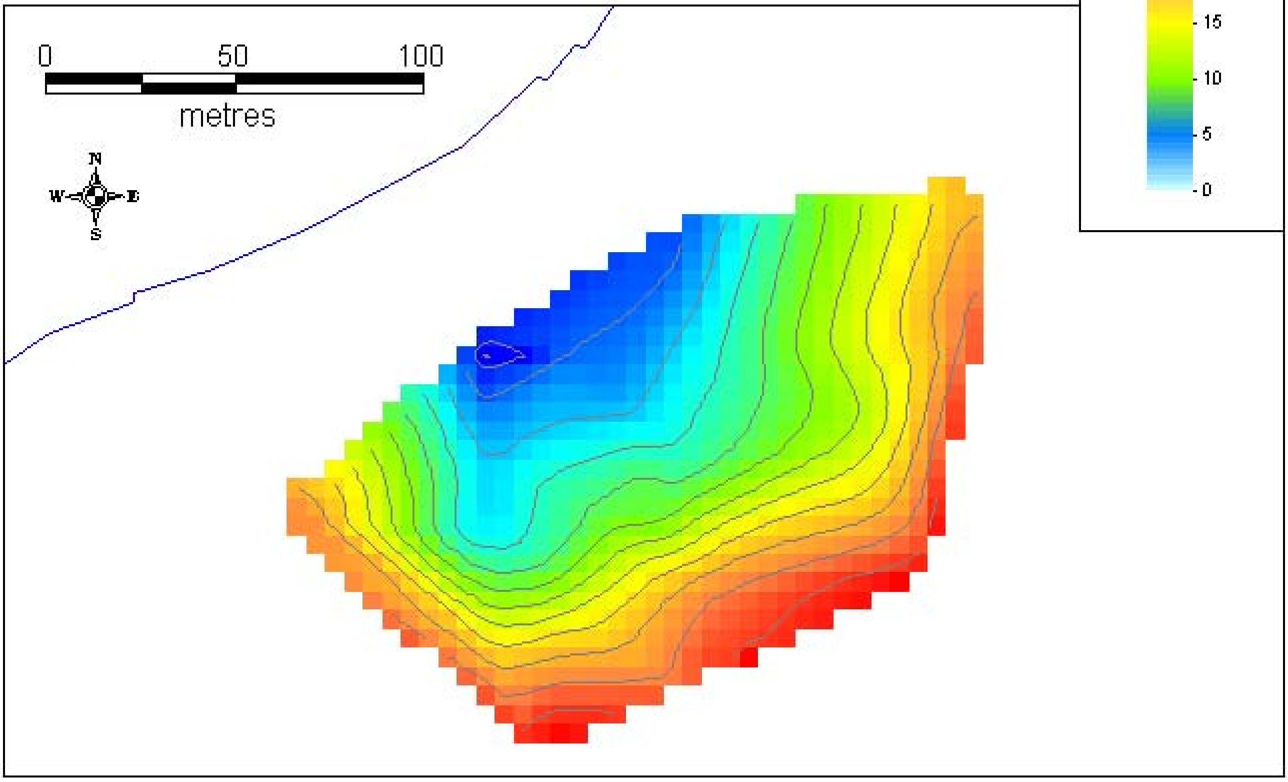


Figure 5. Structure contours of the base of the Moorabool Viaduct Formation

(2 metre contour interval)

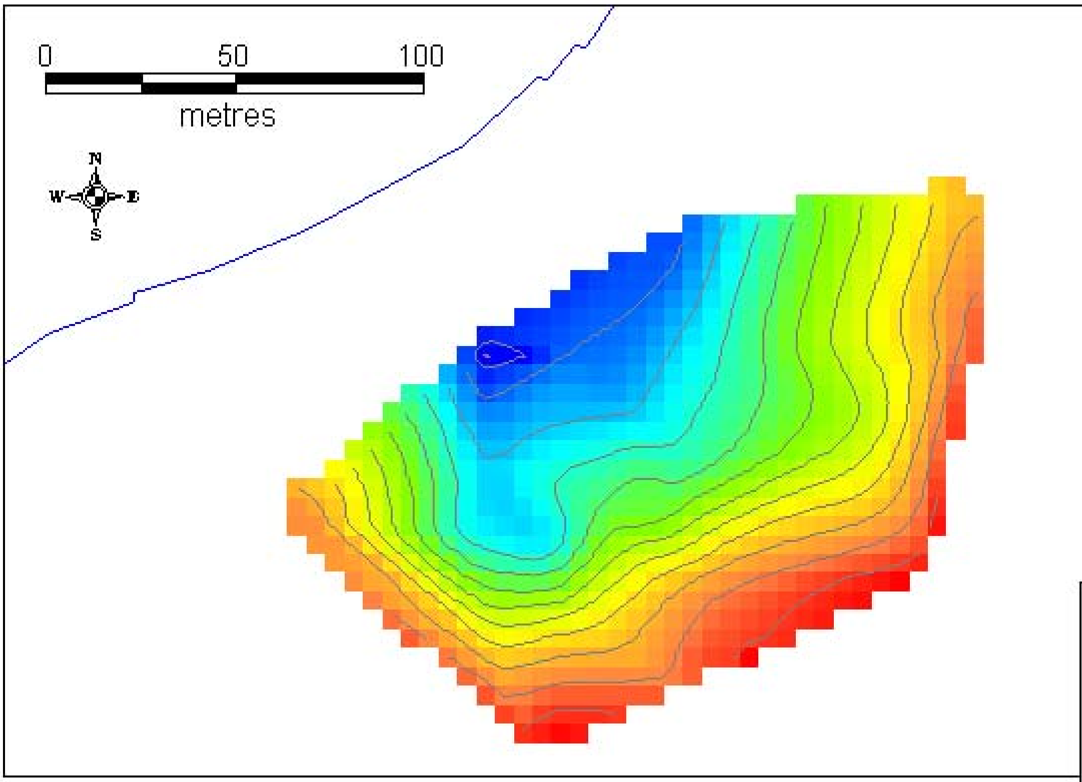
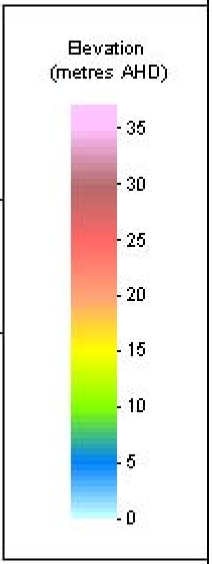


Figure 6. Structure contours of top of the mid level sands.

(2 metre contour interval)



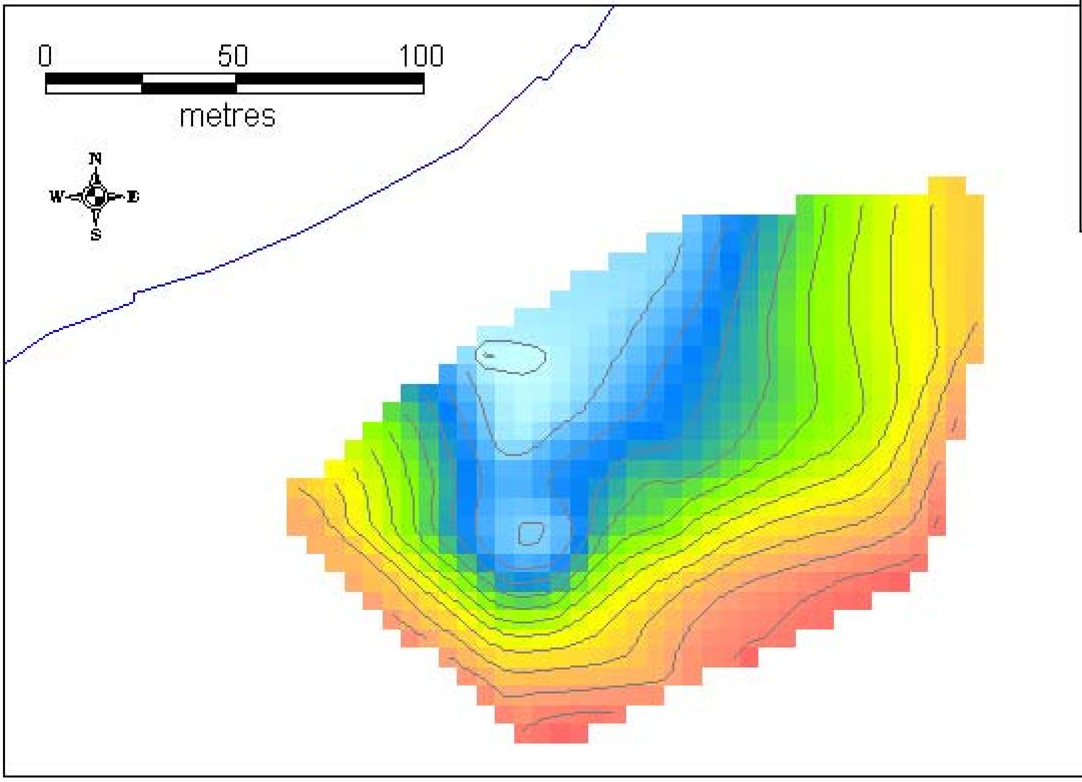


Figure 7. Structure contours of the top of the lower Older Volcanics

(2 metre contour interval)

Figure 8. Isopach of the upper Older Volcanics.

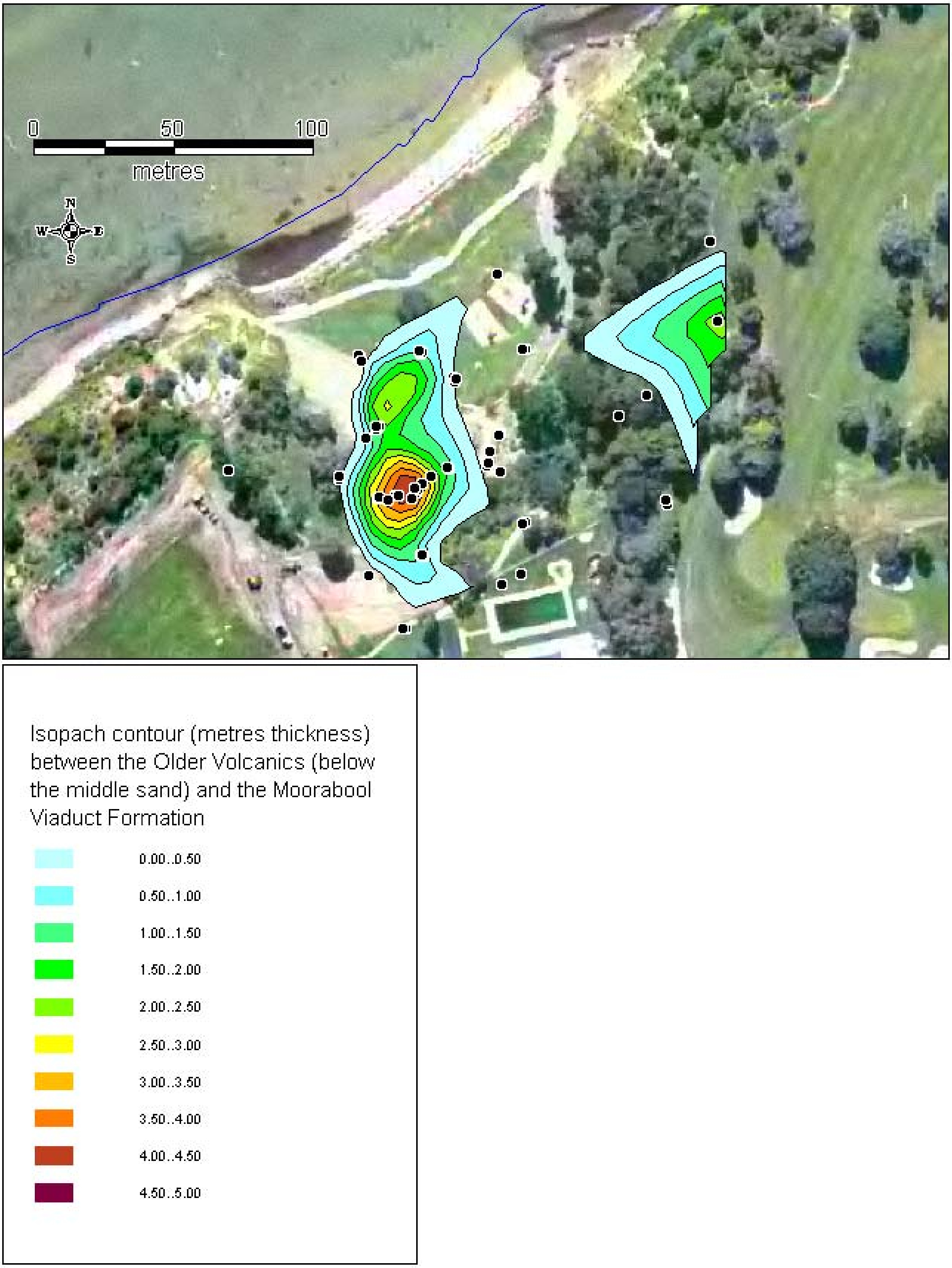
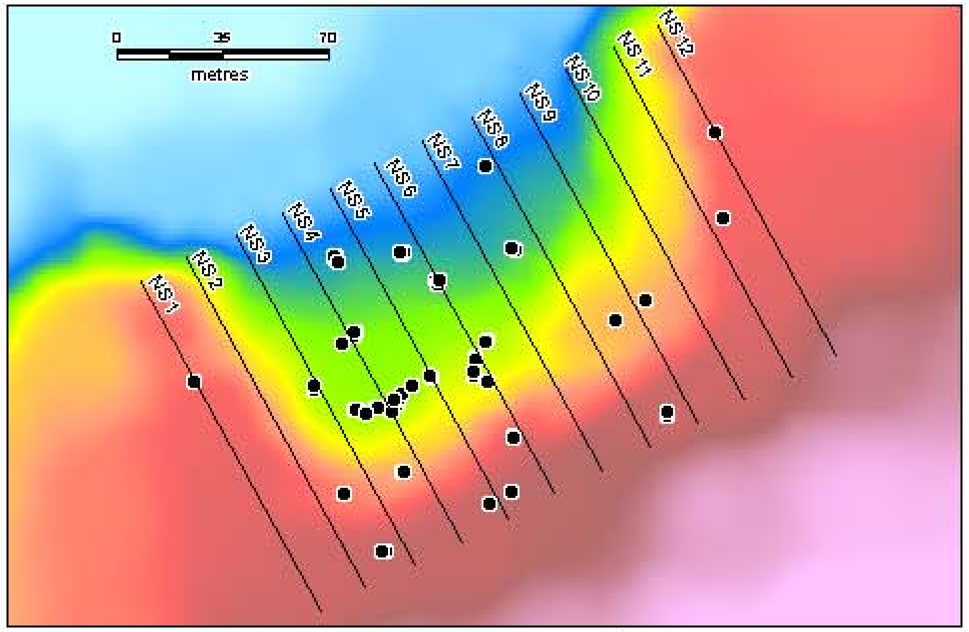
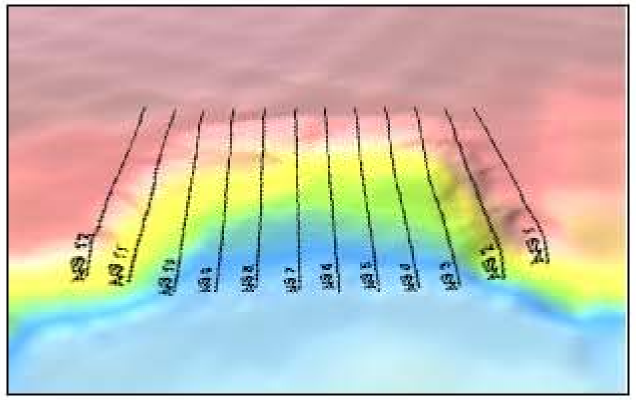


Figure 9. Isopach of the upper Older Volcanics and mid-level sands.





Stratigraphic Legend

▨ *Fill*

🟨 *Tpb - MVF sands*

🟩 *Ts - Mid-level sand*

🟥 *Tvo - Older Volcanics*

🟫 *Tea - Lignite*

🟧 *Tew - Werribee Fm gravel*

North-South cross sections through The Dell.
The sections are oriented NNW-SSE perpendicular to the coast.
View direction looks towards 16 degrees.
Sections are 7.5 metres wide. Vertical : Horizontal =1
Sub-surface boundaries are the gridded models

Note that the modelled surfaces are taken along the centre-line of the section, whereas the bores may be projected from behind or in front of the centre-line.

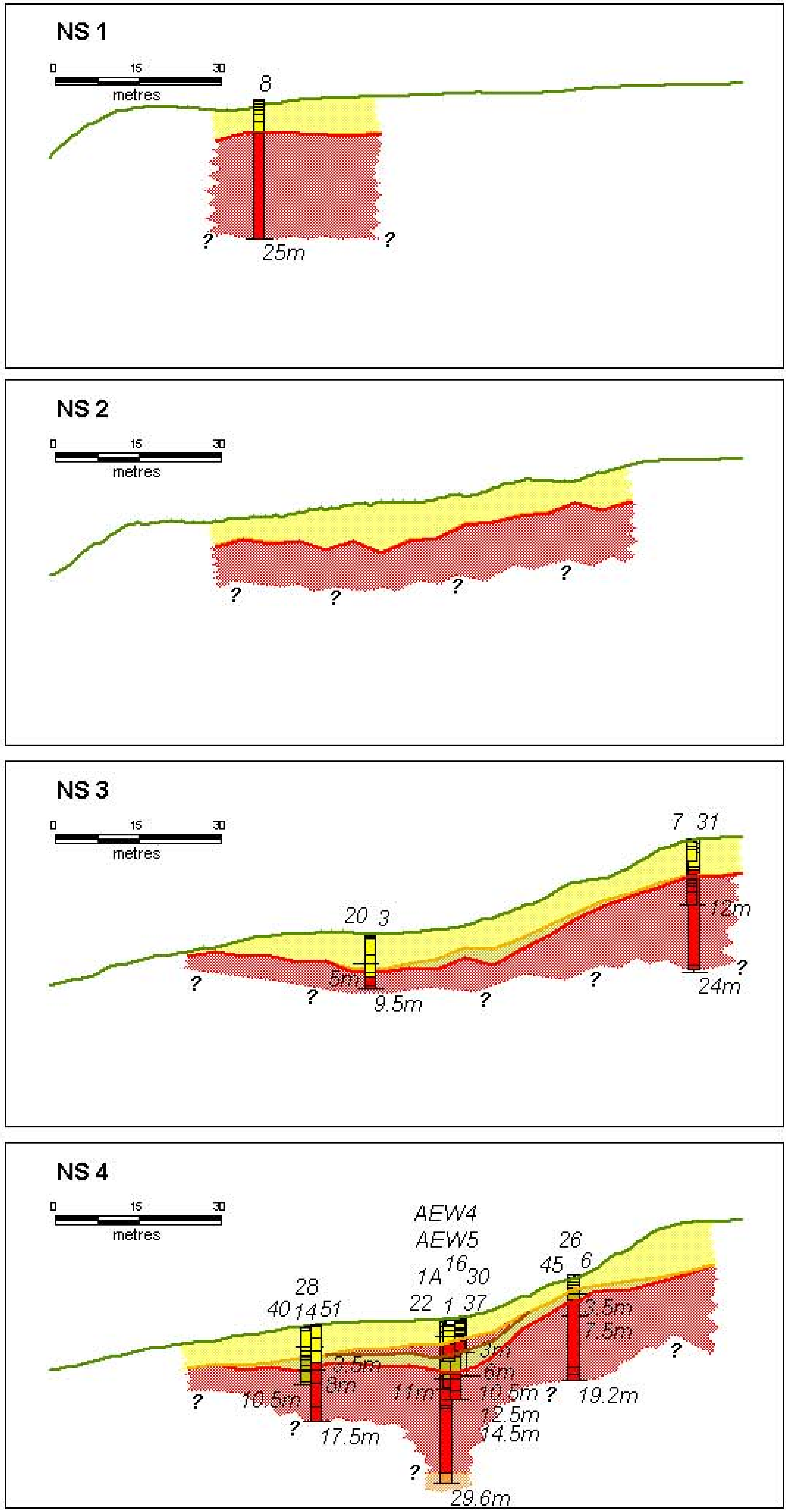
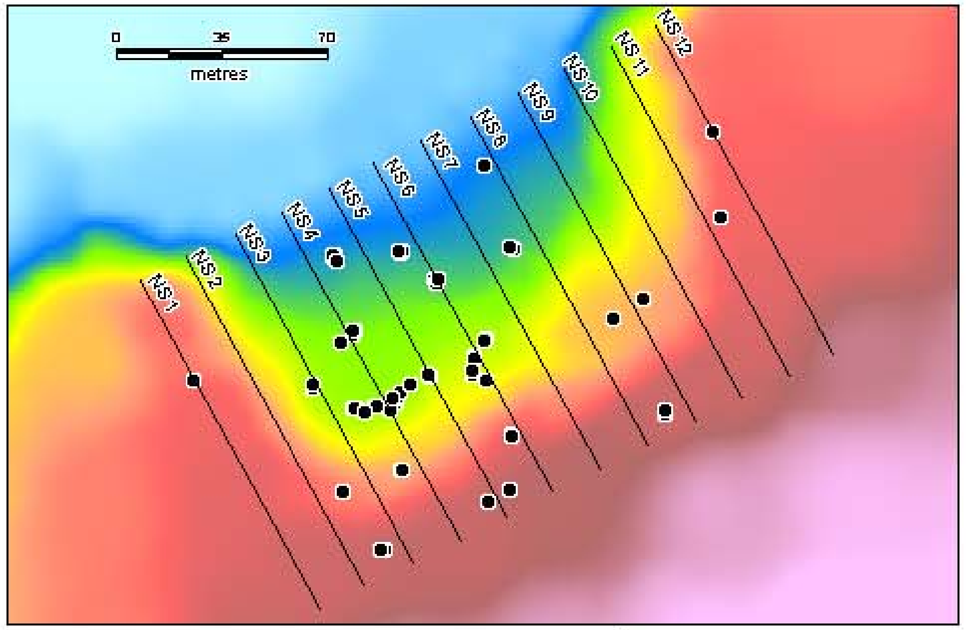
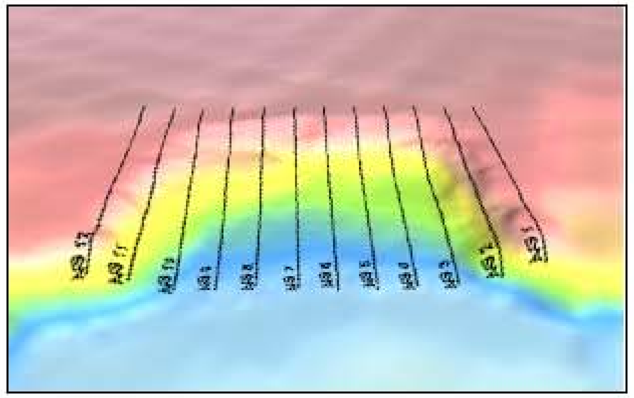


Figure 10. North – south cross-sections through The Dell.





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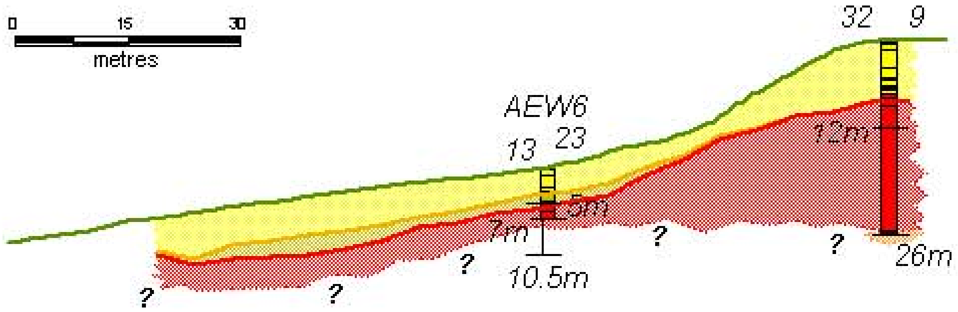

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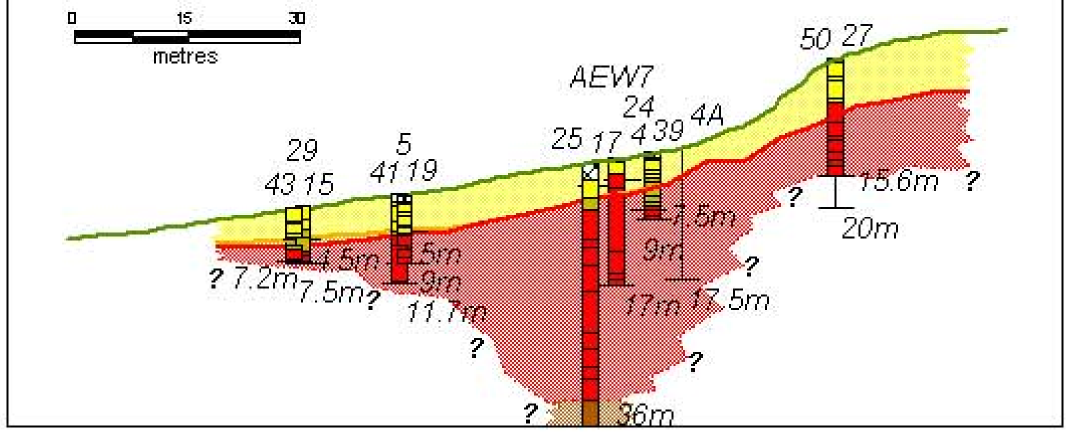

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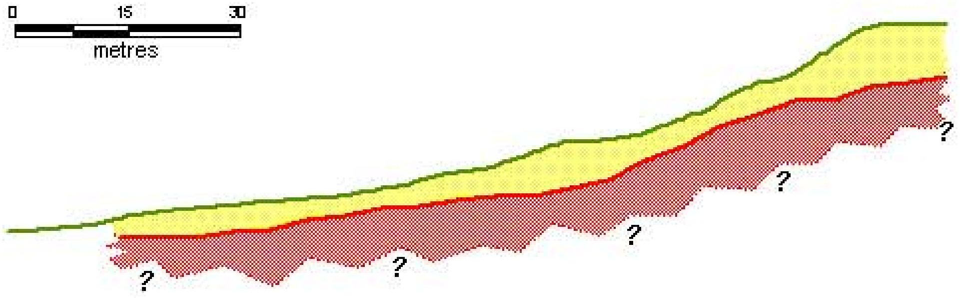

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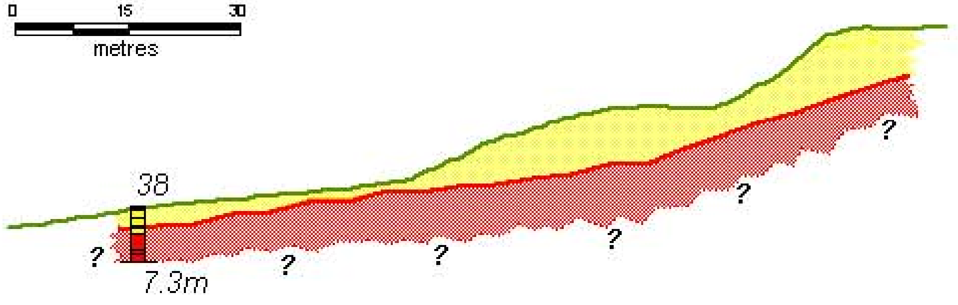

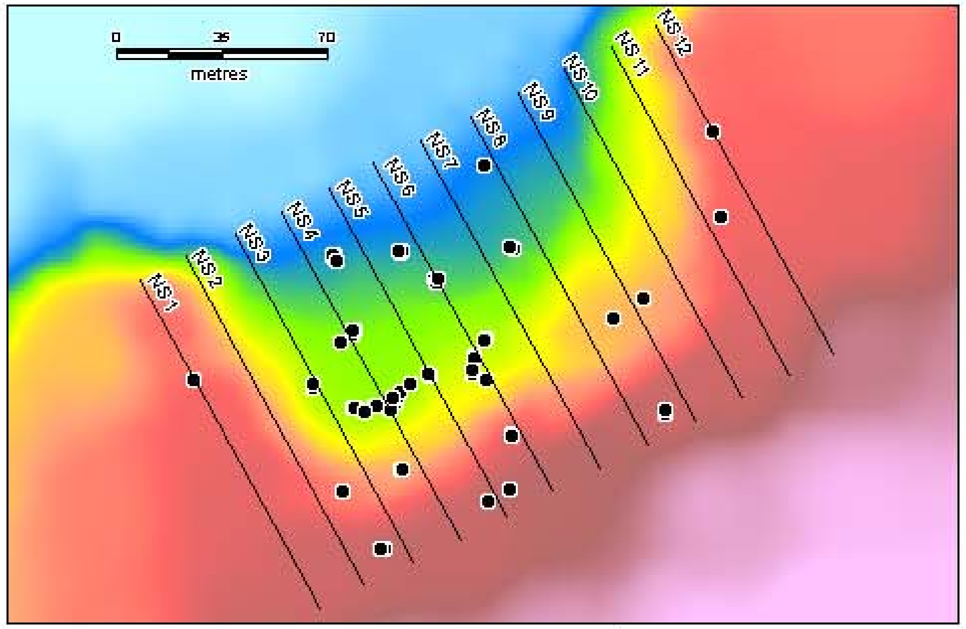

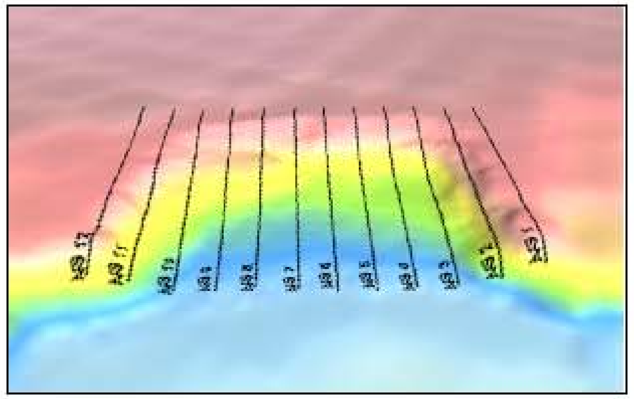

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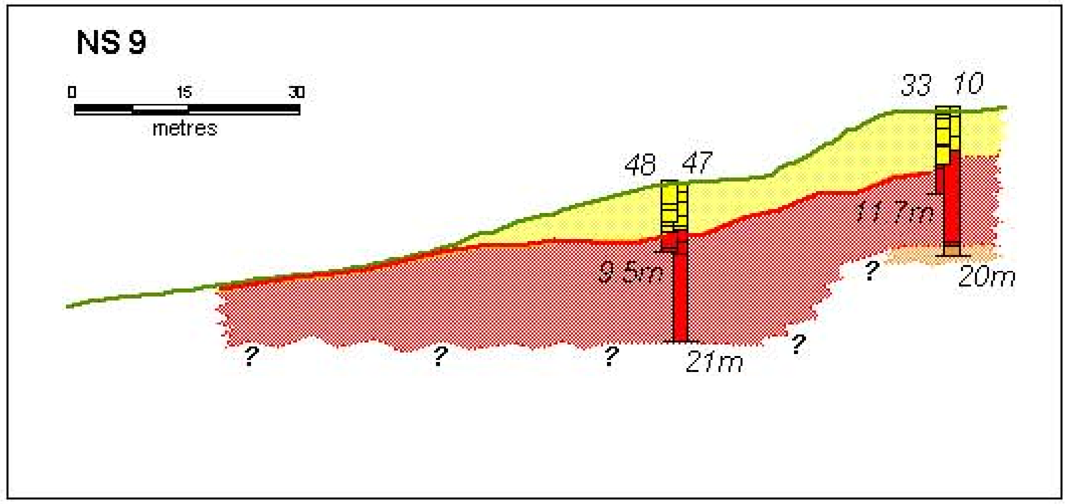
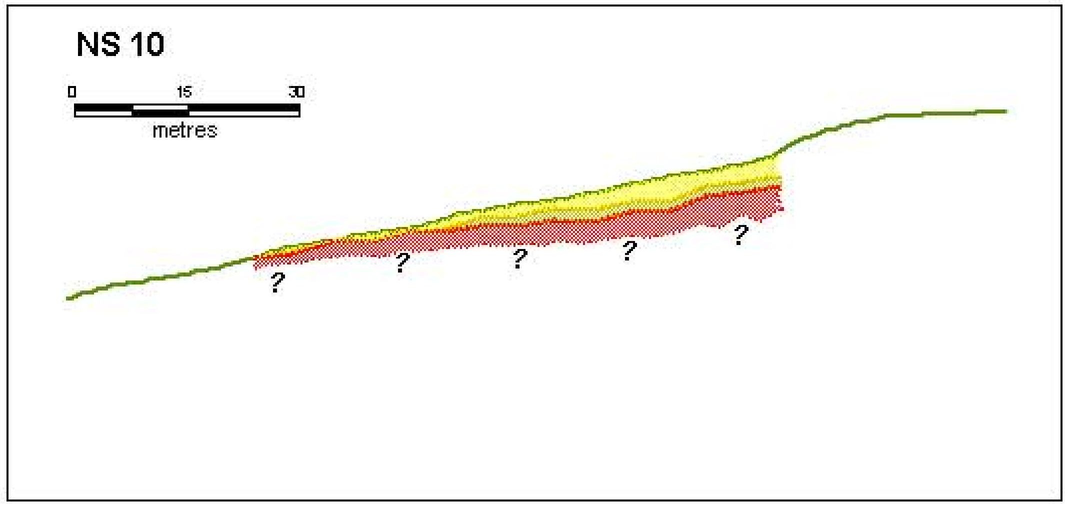
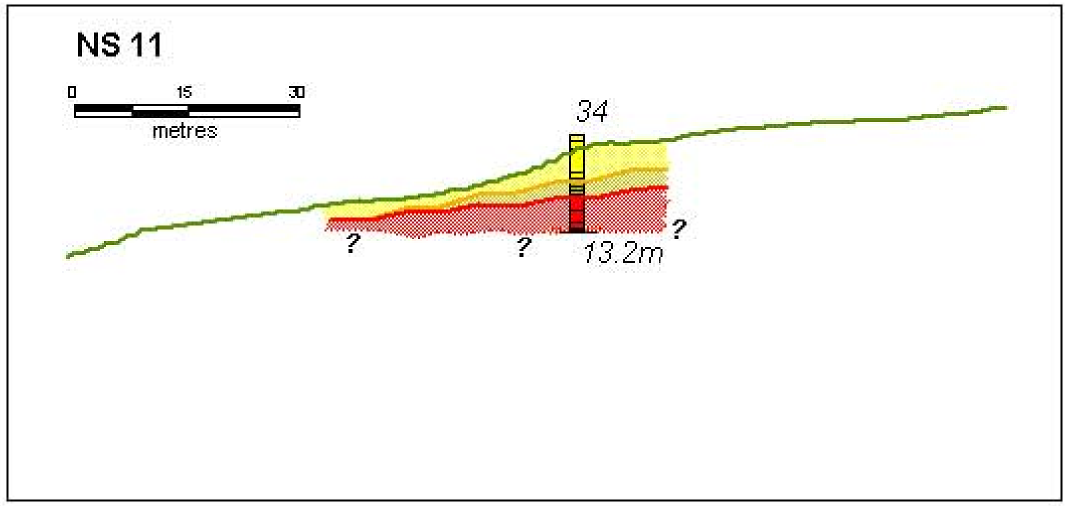
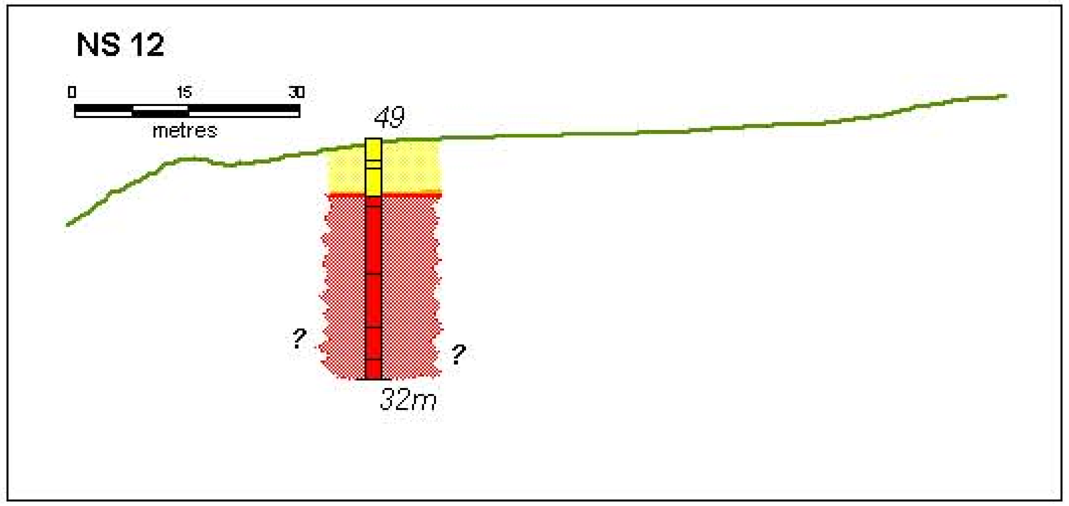
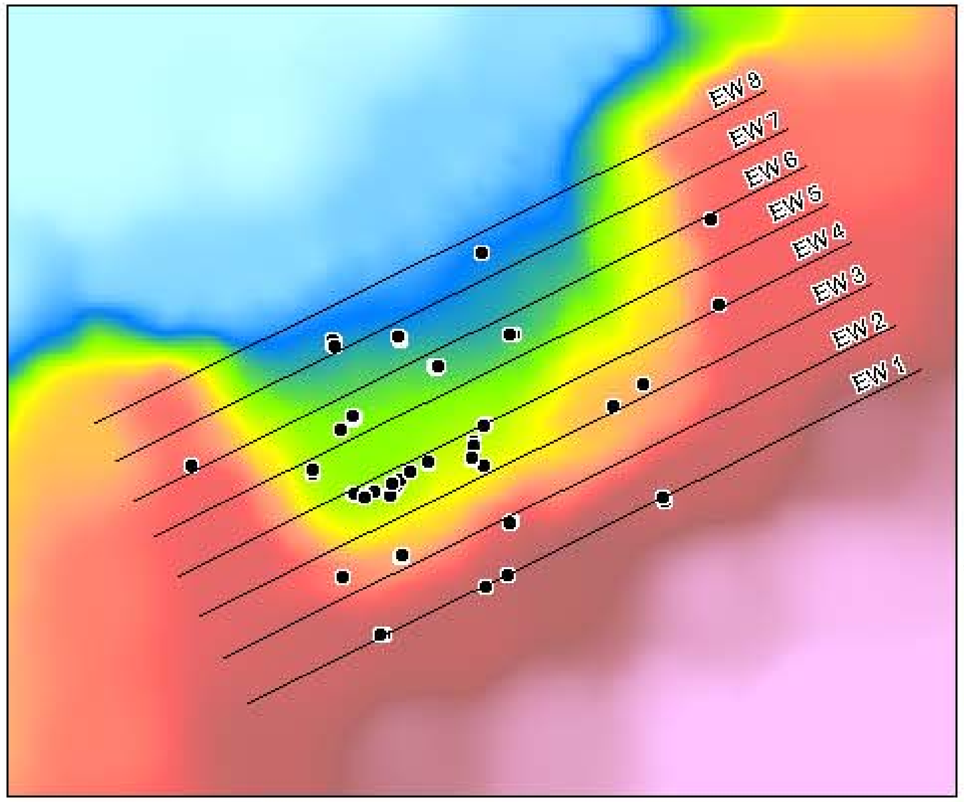
Note that the modelled surfaces are taken along the centre-line of the section, whereas the bores may be projected from behind or in front of the centre-line.

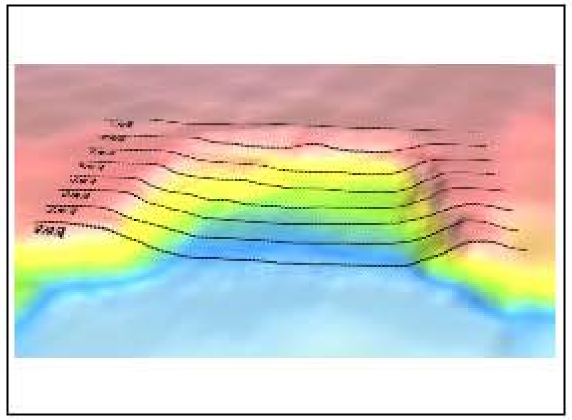












East-West cross sections through The Dell.
The sections are oriented ENE-WSW parallel to the coast.
View direction looks towards 154 degrees.
Sections are 7.5 metres wide. Vertical : Horizontal =1
Sub-surface boundaries are the gridded models

Stratigraphic Legend

- ▩ *Fill*
- 🟨 *Tpb - MVF sands*
- 🟩 *Ts - Mid-level sand*
- 🟥 *Tvo - Older Volcanics*
- 🟫 *Tea - Lignite*
- 🟧 *Tew - Werribee Fm gravel*

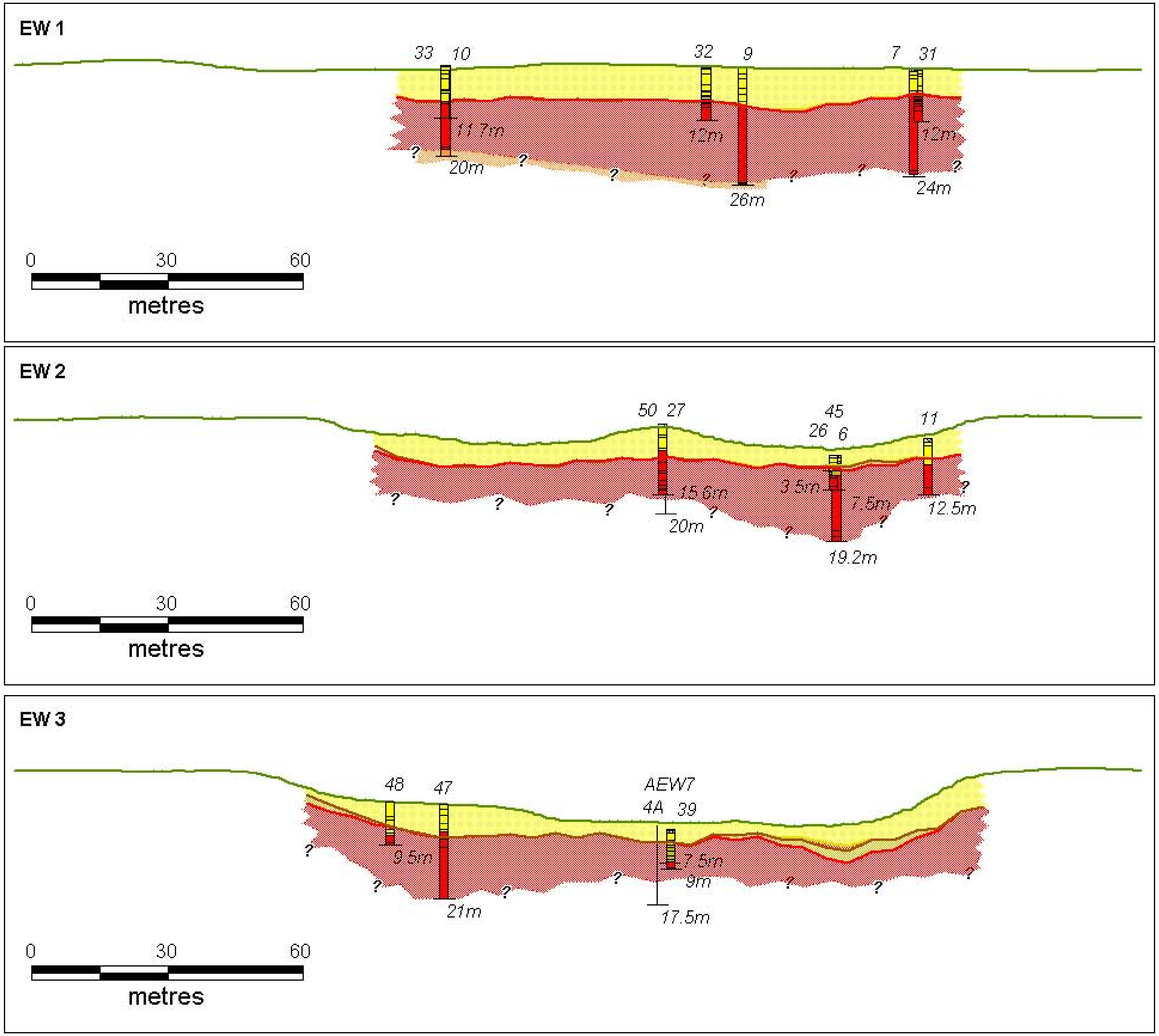
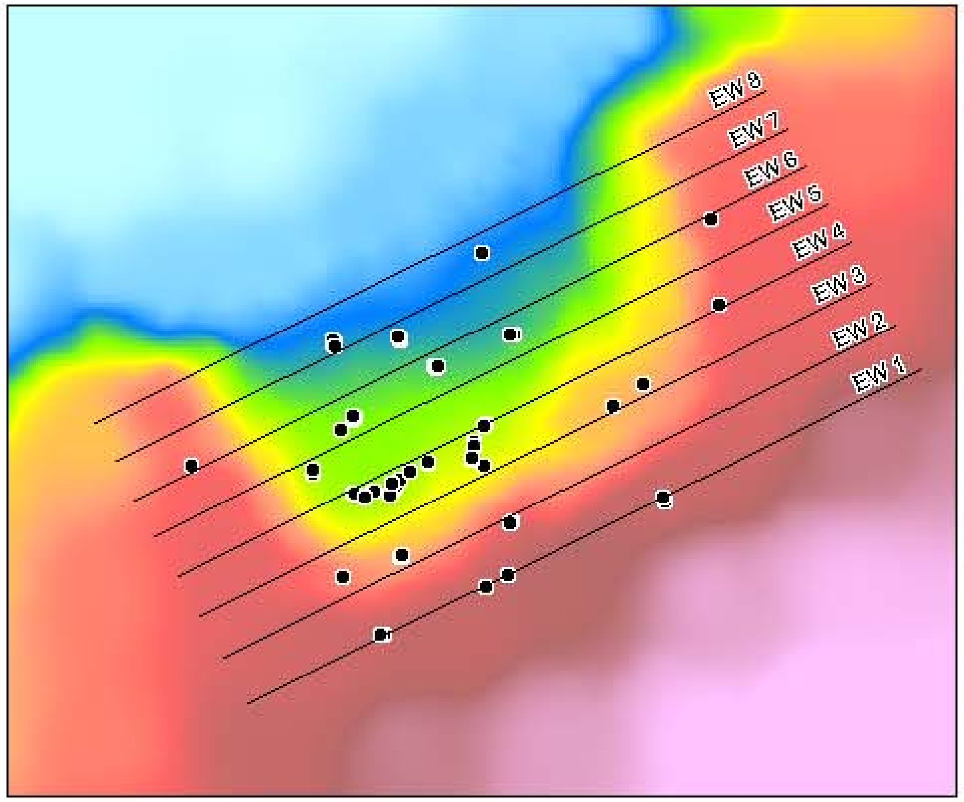
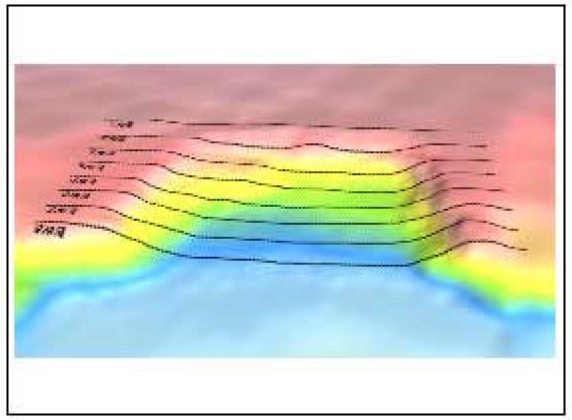
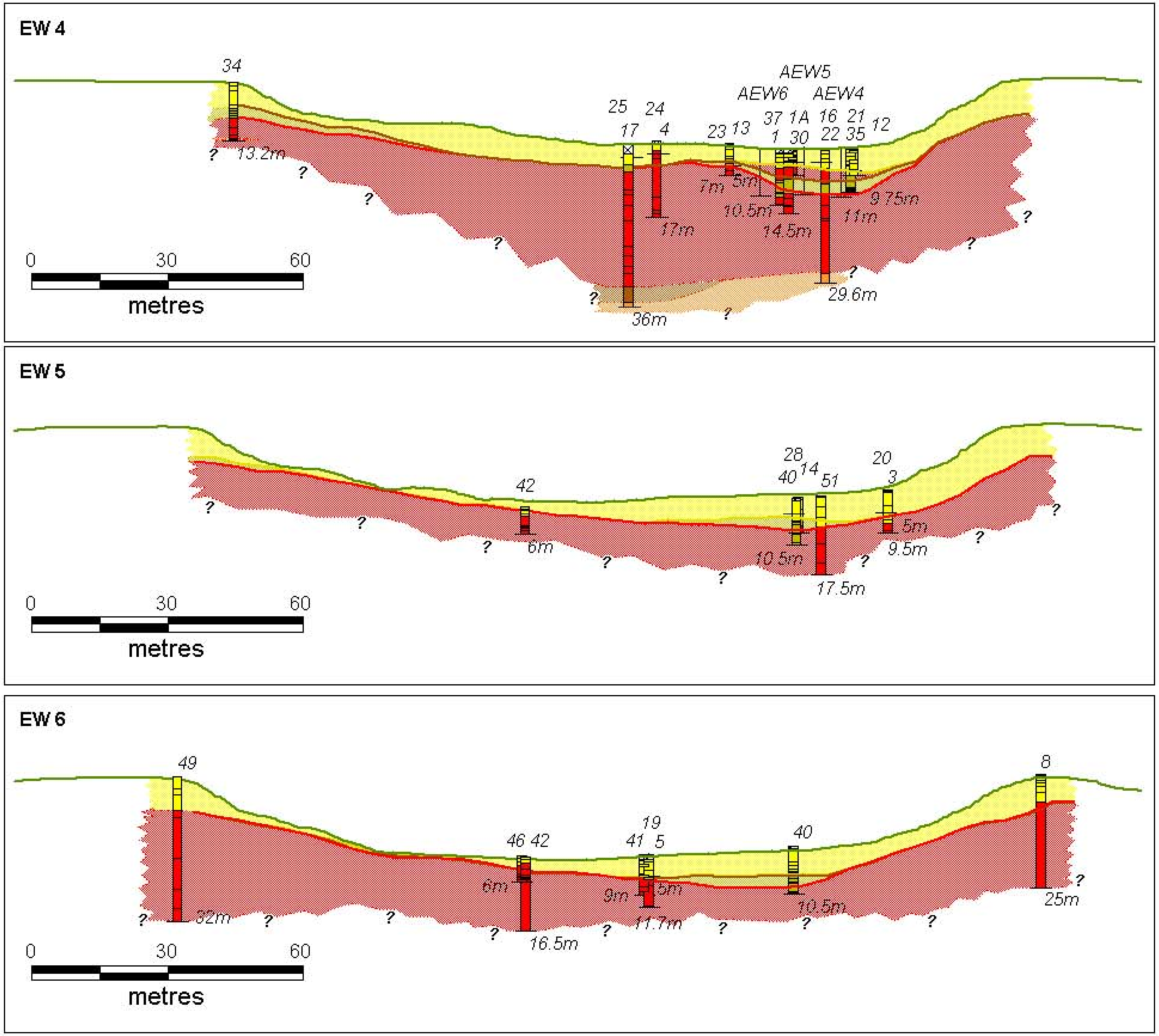


Figure 11. East – West cross-sections through The Dell.







East-West cross sections through The Dell.
The sections are oriented ENE-WSW parallel to the coast.
View direction looks towards 154 degrees.
Sections are 7.5 metres wide. Vertical : Horizontal =1
Sub-surface boundaries are the gridded models

Stratigraphic Legend

- ▨ *Fill*
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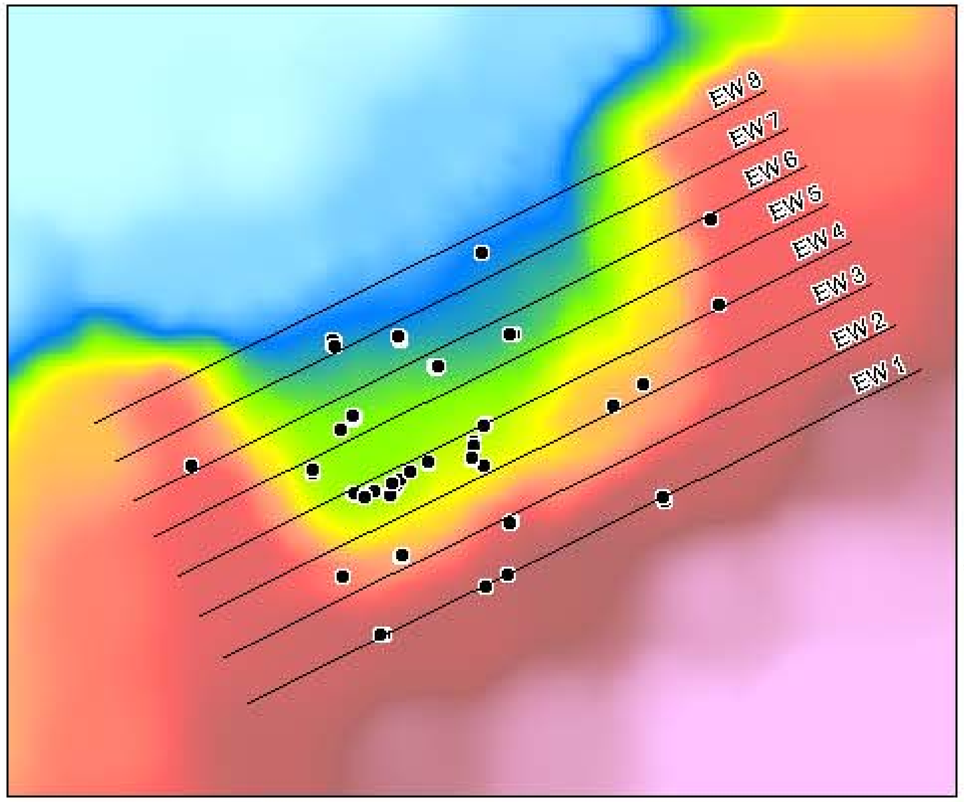

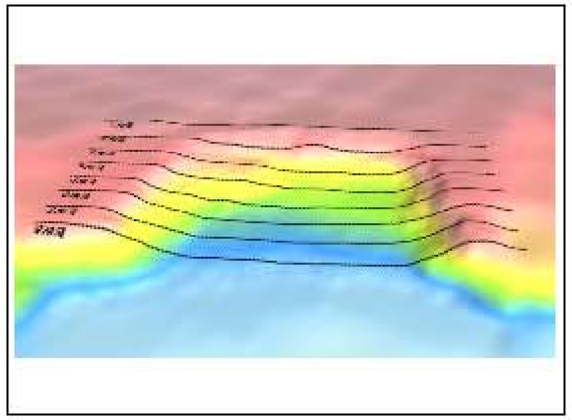

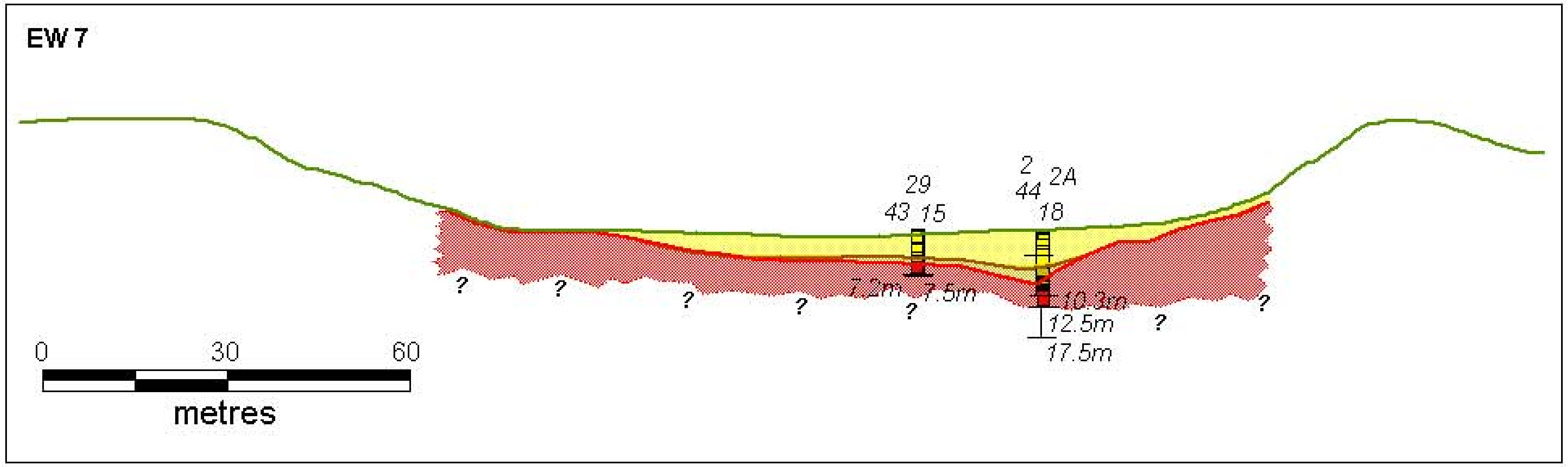

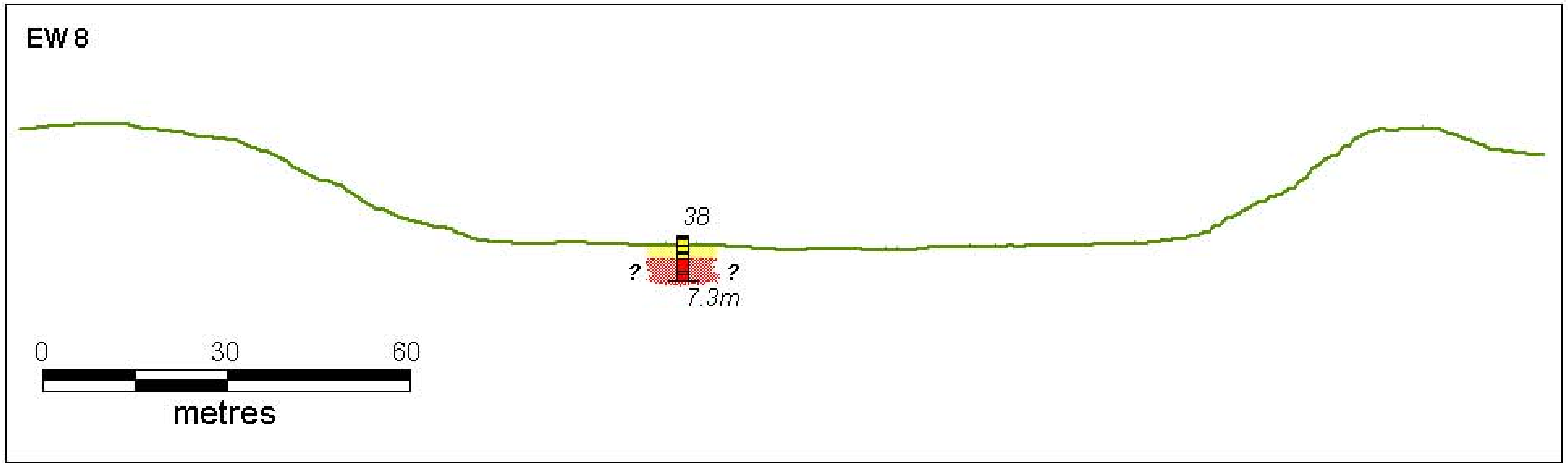

East-West cross sections through The Dell.
The sections are oriented ENE-WSW parallel to the coast.
View direction looks towards 154 degrees.
Sections are 7.5 metres wide. Vertical : Horizontal =1
Sub-surface boundaries are the gridded models

Stratigraphic Legend

▩	*Fill*
🟨	*Tpb - MVF sands*
🟩	*Ts - Mid-level sand*
🟥	*Tvo - Older Volcanics*
🟫	*Tea - Lignite*
🟧	*Tew - Werribee Fm gravel*

Figure 12. Oblique view of orthophoto imagery draped over terrain model

(looking from Azimuth 330°, inclination 35°, distance 300 m. No vertical exaggeration)

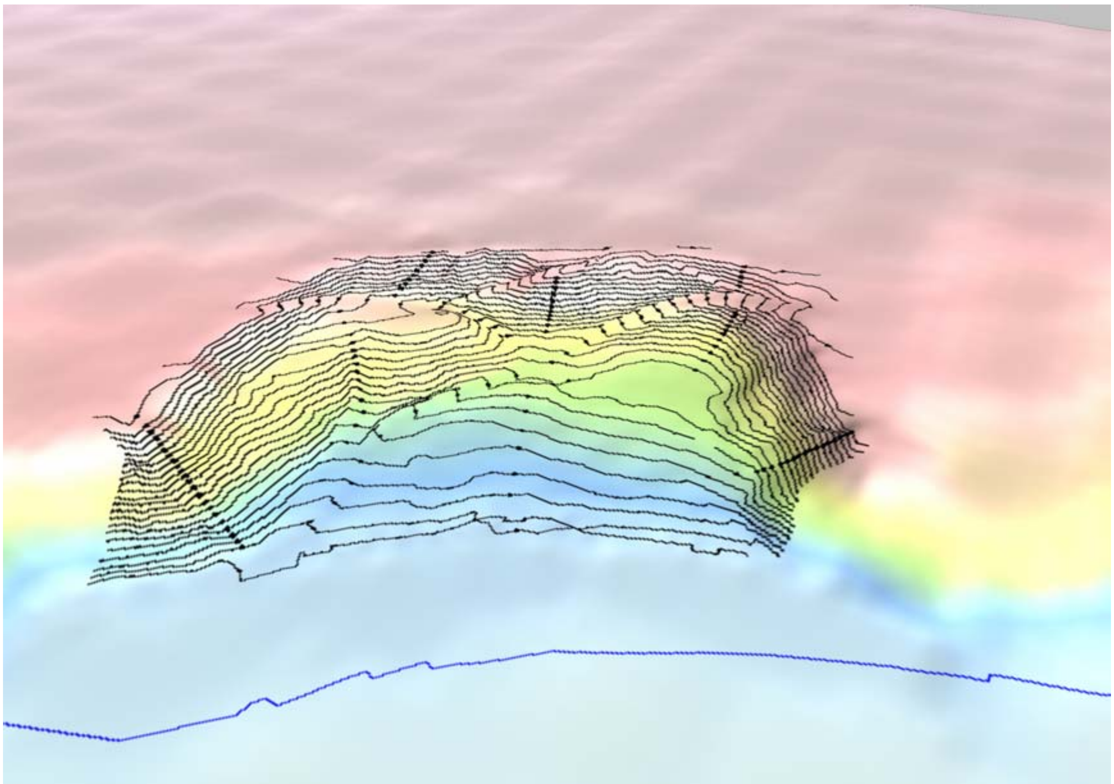

Figure 13. Surveyed contours draped over terrain model

(looking from Azimuth 330°, inclination 35°, distance 300 m. No vertical exaggeration)

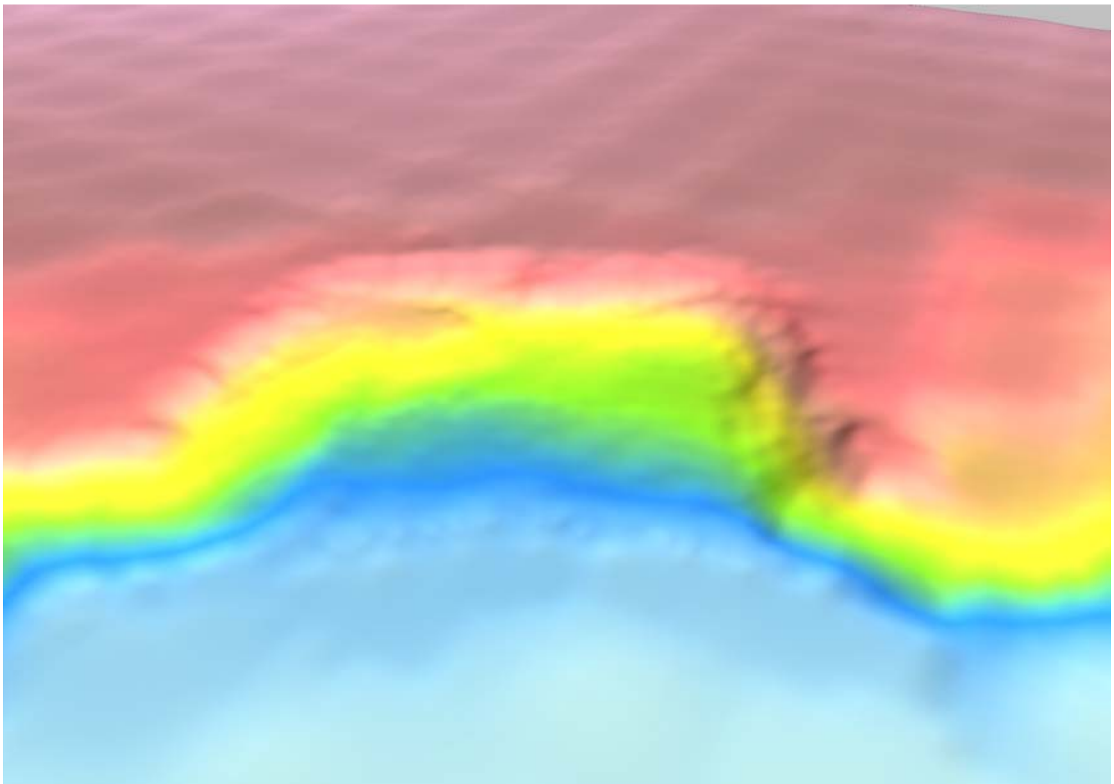

Figure 14. Terrain model

(looking from Azimuth 330°, inclination 35°, distance 300 m. No vertical exaggeration)

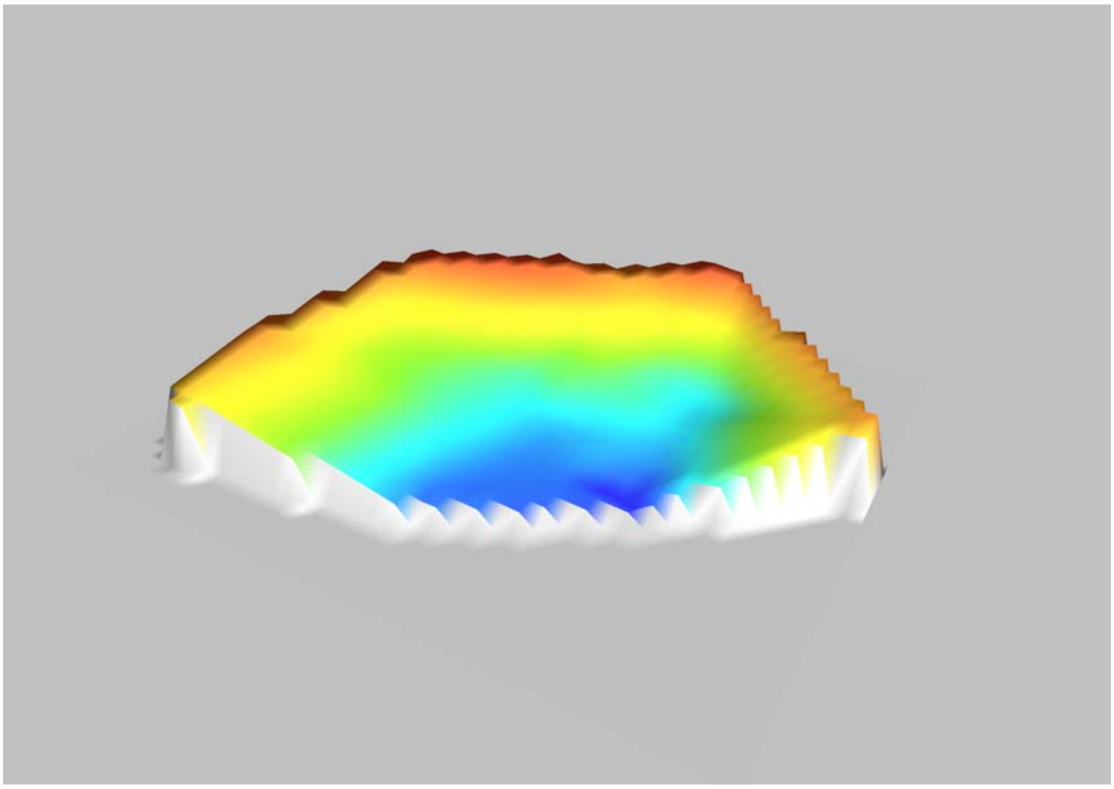

Figure 15. Base of Tpb

(looking from Azimuth 330°, inclination 35°, distance 300 m. No vertical exaggeration)

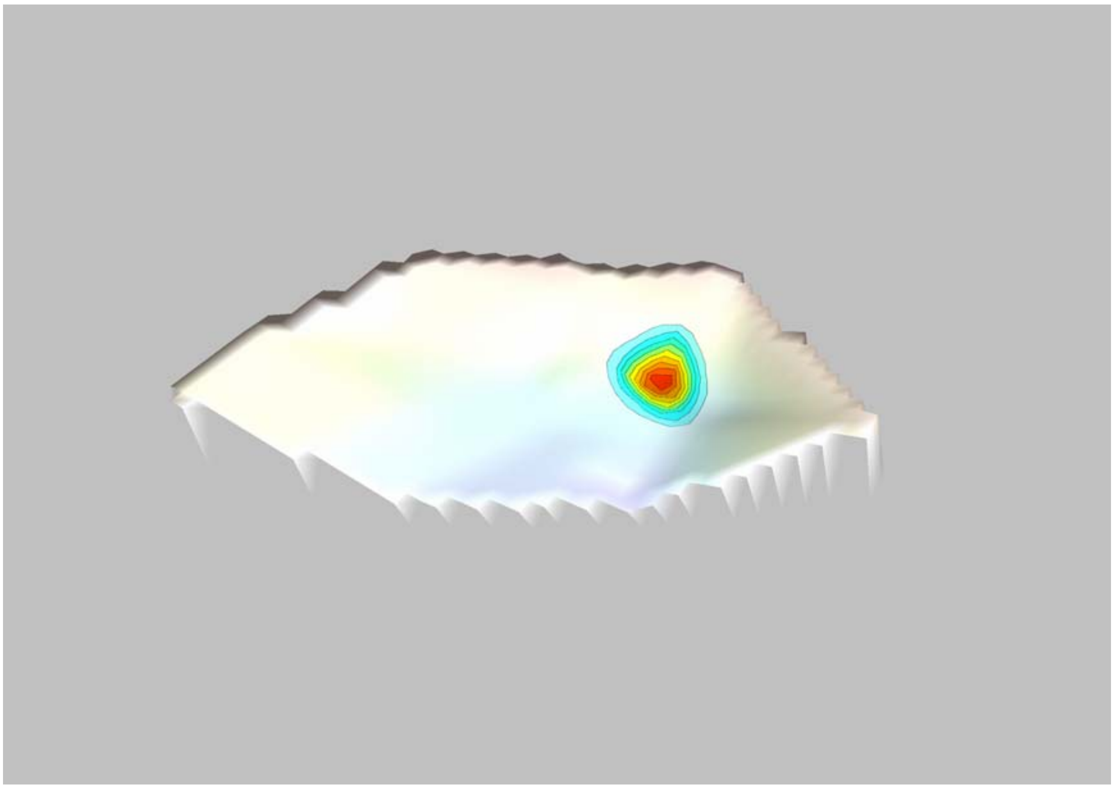

Figure 16. Isopach contours of Tvo1 draped on surface of Ts (and Tpb base)
(looking from Azimuth 330°, inclination 35°, distance 300 m. No vertical exaggeration)

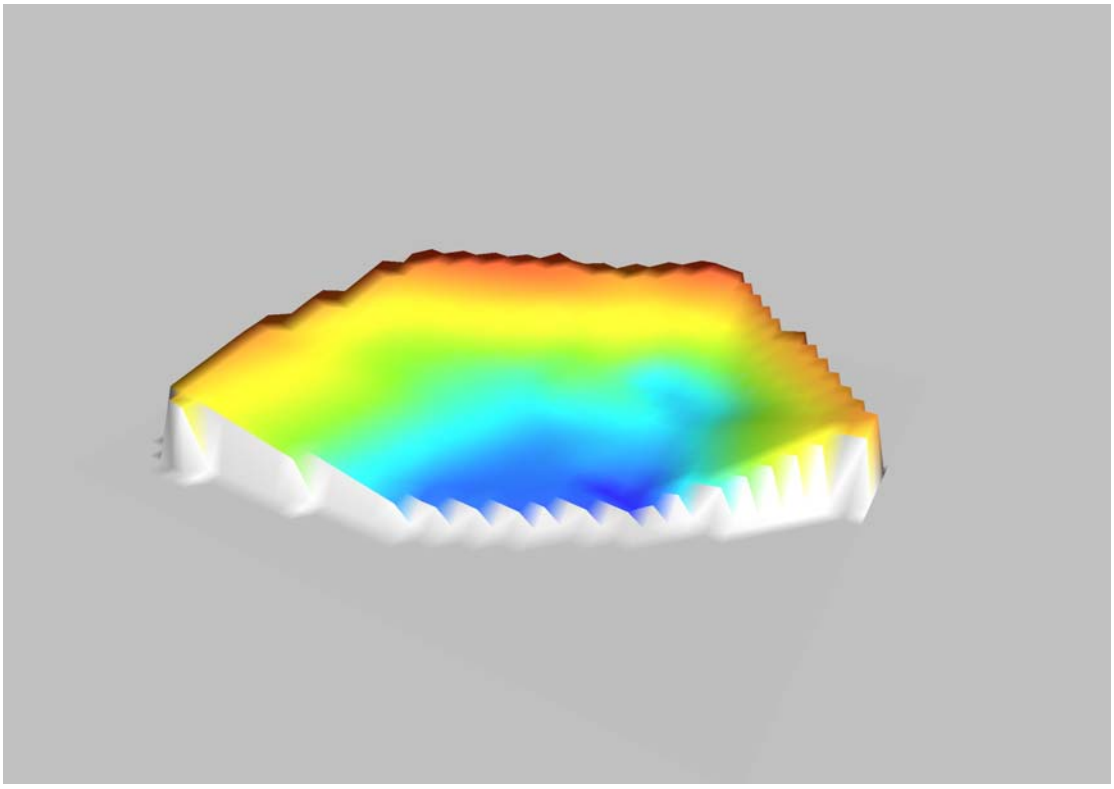

Figure 17. Top of Ts (and base of Tpb where Ts is not present)
(looking from Azimuth 330°, inclination 35°, distance 300 m. No vertical exaggeration)

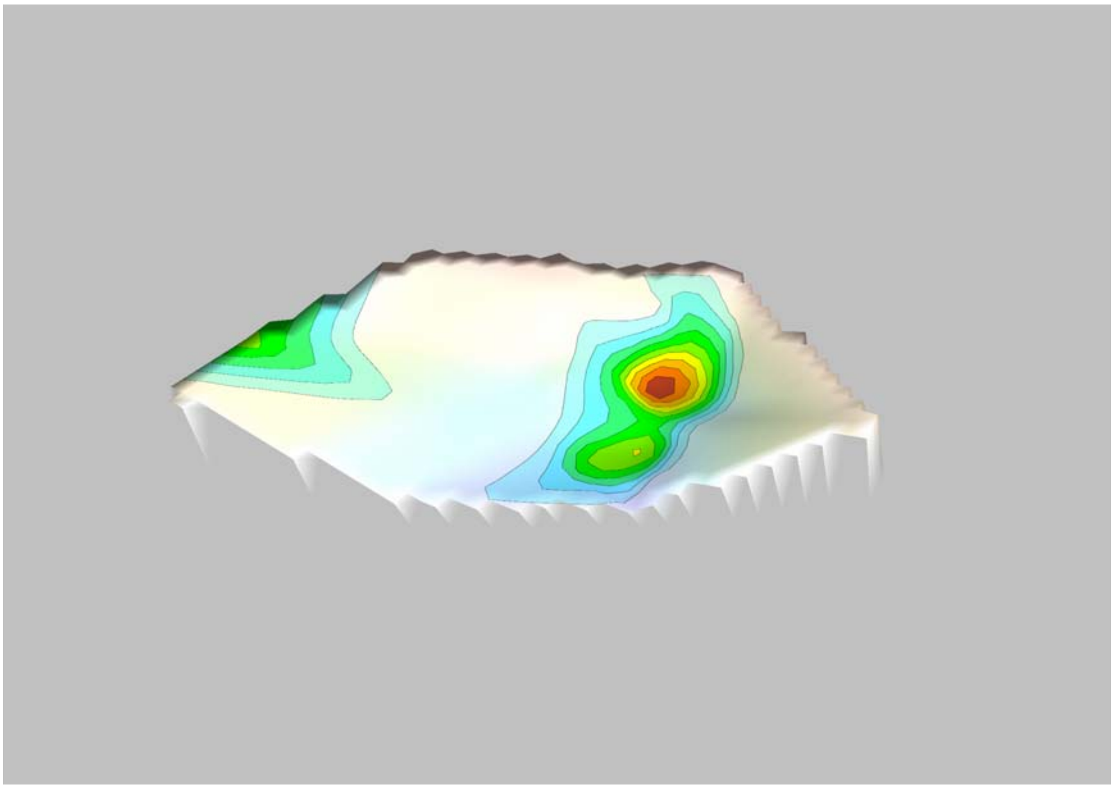

Figure 18. Isopach contours of Ts and Tvo1 on the surface of Tvo2

(looking from Azimuth 330°, inclination 35°, distance 300 m. No vertical exaggeration)

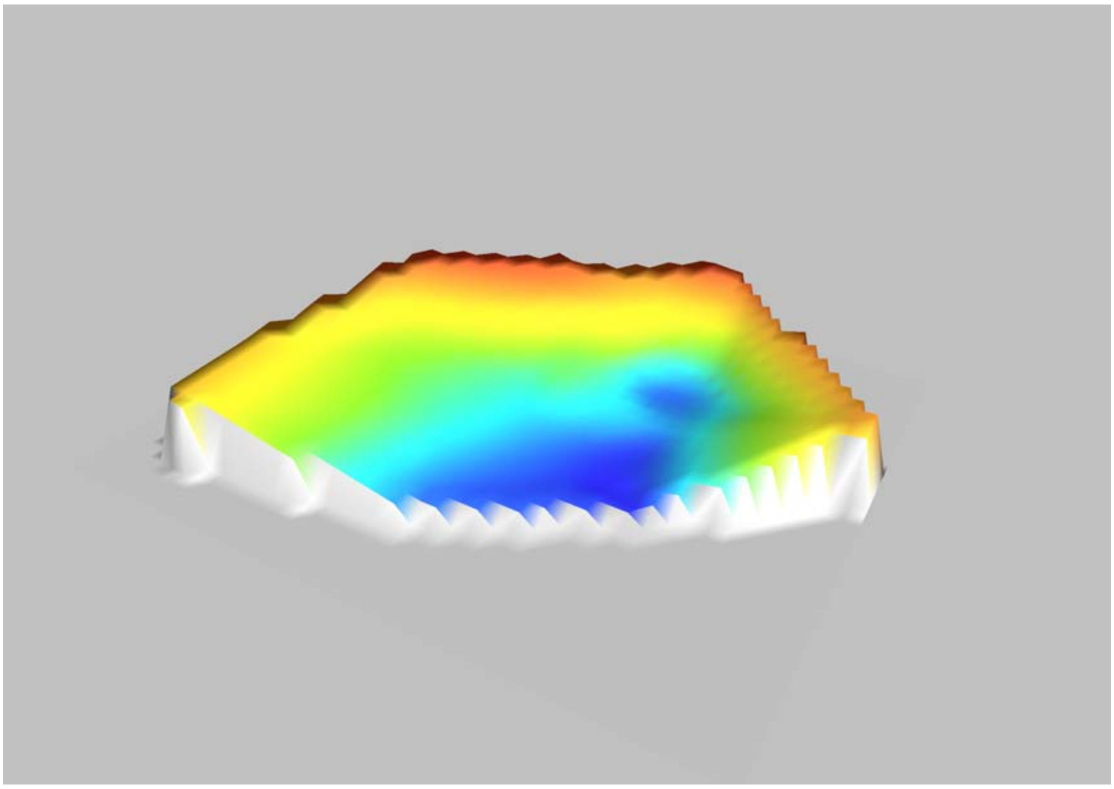

Figure 19. Top of the lower Older Volcanics (Tvo2)

(looking from Azimuth 330°, inclination 35°, distance 300 m. No vertical exaggeration)

4 Discussion and conclusions

The most striking outcome of the model is the spatially limited distribution of the upper unit of the Older Volcanics (Tvo1). Their spatial coincidence with the underlying (although more extensive) 'mid-level sands' (Ts) indicates a redistribution of the Older Volcanics by previous landslide activity. This theory is confirmed by reference to the cross-sections, particularly NS3 to NS5, and EW2 to EW6.

Alternative theories could be that the upper Older Volcanics represents an isolated (or remnant?) tuff, or that the intercalated 'mid-level sand' is an isolated fluvial deposit later covered by tuff. However both these theories are difficult to substantiate in light of the shape of the deposit (suggestive of a landslide), their limited spatial occurrence across the site, and their vertical positioning in relation to the majority of the Older Volcanics.

The 20 to 30 metre displacement of the Werribee Formation gravels (which underlie the Older Volcanics) from ~ +5 to +10 metres AHD along the southern boundary of the amphitheatre to ~ -15 to -19 metres AHD in the centre of the site has two plausible explanations. Either the southern edge of the amphitheatre lies along the Curlewis Monocline, or the entire amphitheatre represents a massive large rotational slump, the centre of which has been eroded through geological time. There is no convincing evidence to rule out either hypothesis, but the presence of the monocline near the site gives more credibility to the former theory. The displacement is evident in section NS9 (and NS5 & NS4) where the gravels of the Werribee Formation occur at a higher elevation in the southernmost bores. Although the cross sections (particularly EW6) also suggest that entire coastal amphitheatre (The Dell) has formed by the erosion of large-scale mass wasting through the Older Volcanic tuff, there is no clear evidence (such as failure surfaces) for a single large-scale feature.

Landslides have occurred in the body of the amphitheatre as shown in the cross-sections and subsurface models. The upper Older Volcanic tuff (Tvo1) and some of the mid-level sands have been rafted downslope over the lower Older Volcanics (Tvo2) and overlying pre-existing sand wash deposited in The Dell from redistribution of the Pliocene sands and equivalents. The morphology of the slope on the eastern side of the amphitheatre also suggests landslides have occurred (and creep is probably still occurring) in that section of The Dell. If more sub-surface information were available it would almost certainly show a complex arrangement of landslides within the amphitheatre.

4.1 Implications of the model

4.1.1 Geomechanical

The conceptual three-dimensional geological model developed through the numerical surface models and cross-sections provide a shape and size of a possible pre-existing landslide complex. The current landslide could be a reactivation of all or part of this pre-existing landslide, since the strength of the materials will have been modified by the initial failure.

However, the suggested geometry of the pre-existing landslide and its relationship (if any) to the current movement needs to be verified. This could be achieved by reworking the inclinometer data to resolve the rate and direction (azimuth and dip, if possible) of movement at depth. The rates and directions should then be spatially located within the geometry of the pre-existing landslide suggested by the model. This task, which was outside of the scope of this project, could assist in refining the location of the failure plane and the direction of the movement along the failure plane.

Similarly, the soil strength properties need to be evaluated in relation to the overlay of the current movement in the context of the subsurface geological model. The vane shear, pocket penetrometer, moisture values and soil strength tests could be plotted for each bore and overlaid on the cross-sections of this model along with the rate and direction of movement. This task would provide the appropriate parameters and geometry of the current movement for analyses of slope stability using appropriate geotechnical techniques.

4.1.2 Hydrogeological

Both the regional hydrogeology and the site groundwater records were examined in detail for in this project. Although many hydrogeological issues remain to be resolved, the development of the geological model does assist in the hydrogeological interpretation.

The Werribee Formation comprising the Older Volcanics and intercalated sediments is regarded as the most extensive regional aquifer. The main recharge areas are probably the elevated areas of Mount Bellarine, where the Older Volcanics exposed in the quarries is fractured basalt of relatively high transmissivity (Jerinic, 1992). The connectivity of the regional basalt and intercalated gravels to The Dell is assumed by the discharge of groundwater on the shore platform and former Mineral Springs area. In the deeper piezometers, which intersect gravels of the Werribee Formation, the vertical gradient appears to be upwards. However, the interpretation of the vertical gradients requires the data on the rate and duration of pumping, which was not available for this project.

Based on the lithological descriptions in the bore logs, it appears that the Older Volcanics, which underlie The Dell amphitheatre site, are either weathered tuff, or deeply weathered basalt. Hydrometer tests show very high clay content of the samples, suggesting that the hydraulic conductivities of the clays would be very low, and it can be assumed that they behave as a confining bed. The upward pressure indicated by the potentiometric surface of the Werribee Formation will keep the overlying confining bed fully saturated and increase pore water pressures, which may be partly responsible for the instability at the site.

The mid-level sands probably form a perched aquifer of limited extent, possibly recharged by leakage through the overlying Pliocene sands (an assumed unconfined aquifer) and runoff from the southern edge of the amphitheatre. It is not known if they are hydraulically connected to the underlying Werribee Formation (including the Older Volcanics) by hydraulic pathways. Connections to the Werribee Formation are possible along the southern margin of the amphitheatre, where the gravels of the Werribee Formation are at a higher elevation, and through the basalt and/or tuff if fractures or hydraulic pathways exist.

Drainage or dewatering of the interpreted pre-existing landslide shown in the geological model may be the most cost-effective method of landslide stabilisation, provided that the relationship to the current movement can be determined. The mid-level sands probably have sufficient hydraulic conductivity to allow drainage[4] to occur, although this needs to be confirmed. By lowering the head in the mid-level sands reductions in the pore water pressure in the underlying tuff will result, even if it is being slowly ‘recharged’ from below.

An alternative is to reduce the potentiometric head in the Werribee Formation as discussed in the report by Leonard (2003). However, as observed by the author of that report, there may be a lengthy lag-time between the lowering of the potentiometric surface in the underlying Werribee Formation and the effect in the mid-level sands due to the very

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[4] Drainage in this context refers to the installation of sub-surface drains.

low hydraulic conductivity of the intervening confining bed. The pore-water pressure in the clay is the sum of the contributions made by the overburden pressure (including the hydrostatic pressure) and the upward pressure of the potentiometric head. A reduction in the potentiometric head may not be as effective as reducing the hydrostatic head. Observations made during the current pumping trials should resolve this issue.

The review of the hydrogeology of the site (Leonard, 2003), recommended the development of a three dimensional hydrogeological model. Within the time and budget of this project, it was not possible to develop a credible three-dimensional hydrogeological model, given the complexity of the geological data and the insufficient detail required to resolve the hydrogeology. In particular, more detailed data of the bore construction and the rates and times of pumping are required.

Further resolution of the hydrogeological model is required by reinterpretation of the groundwater levels in relation to the three-dimensional geological model. This would greatly benefit by:

1) Detailing the construction of observation bores and piezometers in a similar way to a standard lithological bore log. The log should include the depths and descriptions of the filter pack, sealing and fill material, the type of screen (including filter cloth) or piezometer used and bore development details.

2) Detailing the pumping rates and times.

3) Evaluation of the hydraulic parameters of the different materials, by conducting analysis of the drawdown from the pumping (i.e. pumping test analysis) or single bore recovery tests or slug tests (eg. Hvorslev tests).

4) Improving the water level records, especially by converting them to relative levels so that there is no confusion with measuring standing water levels (from top of casing? Or from ground level?, etc.).

Once the details of these data have been acquired, the hydrogeological model can be resolved to confirm the connectivity between aquifers, the response (lag-time) between aquifers, and the options for manipulating water tables, potentiometric surfaces and pore-water pressures.

4.2 Conclusions

1) The Dell is a geomorphological feature formed by mass wasting. Landslides have redistributed the geological materials at the site.

2) The axis of the Curlewis Monocline is probably coincident with the southern boundary of the amphitheatre.

3) The current landslide is probably a reactivation of an existing landslide.

4) The Werribee Formation (both fractured basalts and intercalated sediments) forms an extensive regional aquifer under the site.

5) The mid-level sands probably form a perched aquifer of limited extent in the main body of the existing landslide.

6) Dewatering the perched aquifer may be effective in site remediation.

5 Recommendations

1. The three-dimensional geological model has been determined from the available data and information supplied. The model should be reviewed by the consultants in respect to their observations and understanding of the current landslide at the site. Does the model make sense? Does the suggested pre-existing (old) landslide relate to the current movement?

2. Assuming that a possible pre-existing landslide and the current landslide are related, stability analyses of the current landslide may be modelled using the geometry of the subsurface conditions. The model would be enhanced by the work outlined in section 4.1.1, i.e. calculating the three-dimensional vectors of the inclinometer data for interpretation of the spatial movement of the landslide and combining these with the known strength parameters.

3. Further analysis of the groundwater data as detailed in section 4.1.2 is required before the hydrogeology of the site can be resolved in detail. While sufficient data is available for the stability analysis to proceed, a more detailed hydrogeological model will need to be resolved before the long-term effects of drainage or dewatering (pumping) can be determined.

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Appendix A Geophysical images

The geophysical images are useful aides to interpret the regional geology of the Bellarine Peninsula and provide the geological context of the units at The Dell. The images have been produced using *MapImagery* Version 6.526 (July 2 2002) from data supplied by the Geological Survey of Victoria. World Geoscience Pty Ltd acquired the data in 1999 using aircraft flying at 200 metre line spacings and 80 metre height.

MAGNETICS

Magnetic surveys measure the strength of the magnetisation induced in the Earth's materials by the Earth's magnetic field. The data is presented as total magnetic intensity (TMI) in units of nanoTesla (nT). Variations in TMI can be related to the magnetite content of the rock, the depth and geometry of the magnetic body, and the inclination of the Earths magnetic field. The first vertical derivative (1VD) shading highlights the magnetic gradient in nT/m, which enhances the edges of the anomalies and that may relate to geological boundaries or faults.

RADIOMETRICS

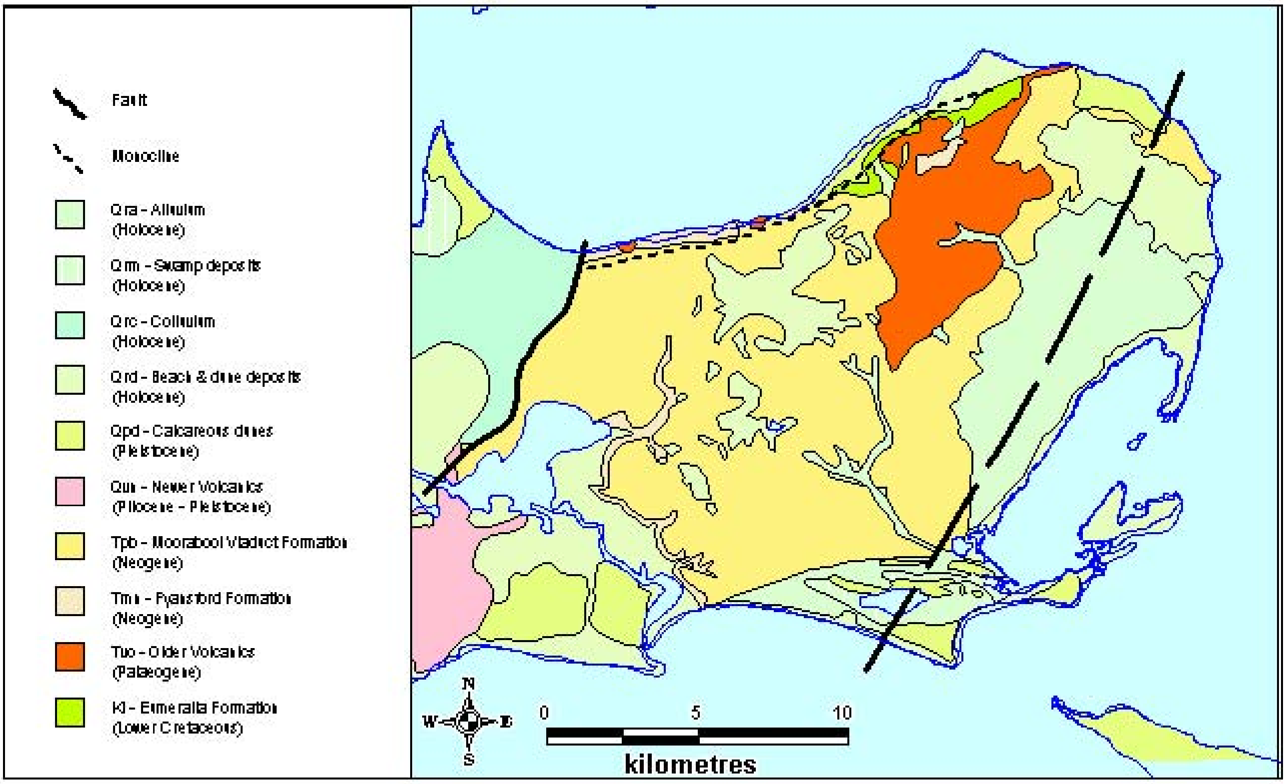
Radiometric surveys measure the gamma rays emitted by the decay of radioactive isotopes within the top few centimetres of the Earth's surface. The response varies with the mineralogy of soil and rock types, ground cover, moisture conditions at the surface, flight height and detector specifications.

The data is presented as:

The **ternary ratio image** provides the relative proportion of potassium, thorium and uranium response by assigning each channel to a given colour (potassium = red, thorium = green and uranium = blue). The relative proportion is useful for mapping the variations in the mineralogy of the surface materials and shows a strong correlation to geology and soils.

Potassium measures the part of energy spectrum which relates to the decay of K^{40} isotopes. It is presented in units of equivalent percent (%). The potassium response varies with the mineralogy of the soils and rocks at the Earth's surface. Some feldspars (especially orthoclase), muscovite mica, illite and some montmorillonite clays are potassic.

Thorium measures the component of the energy spectrum which relates to the decay of Th^{232} isotopes, and is presented in units of equivalent parts per million (ppm). Monazite, thorianite, thorite and xenotime are among the thorium-rich minerals usually present in granites and coastal sand deposits (as "heavy mineral sands").



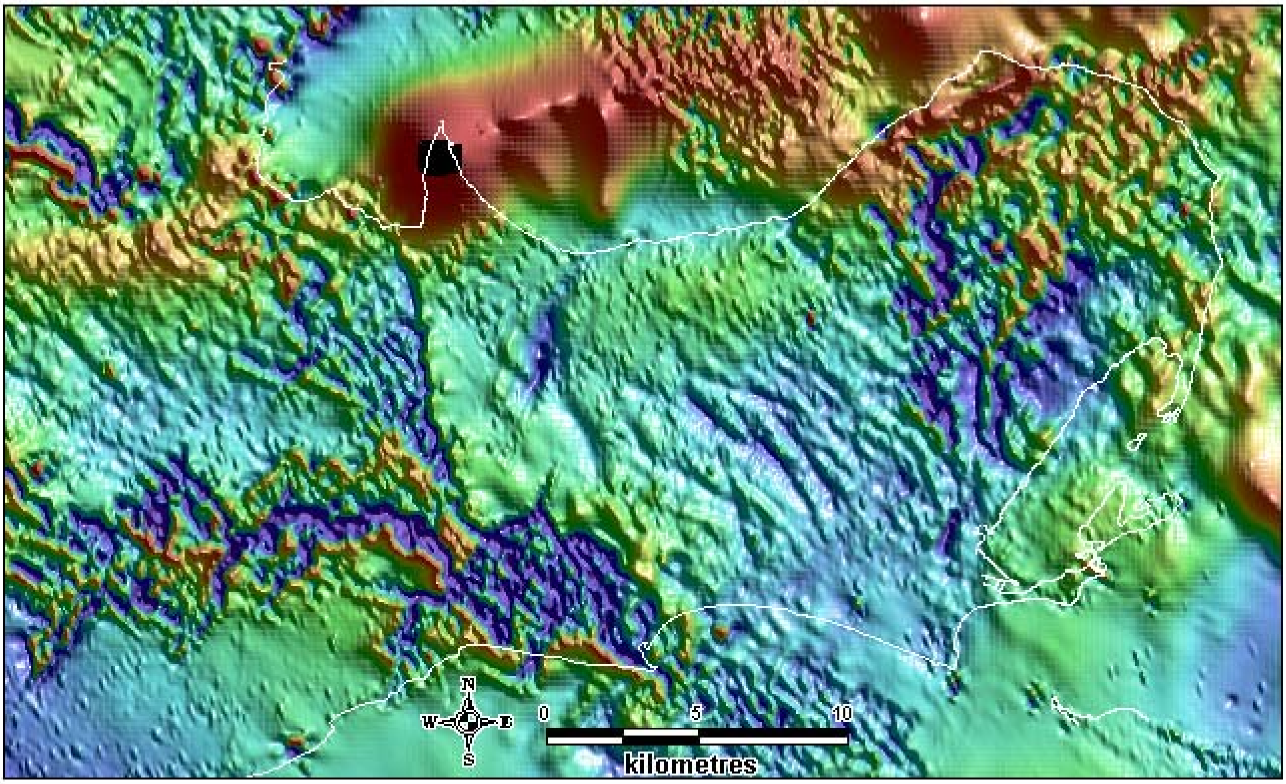
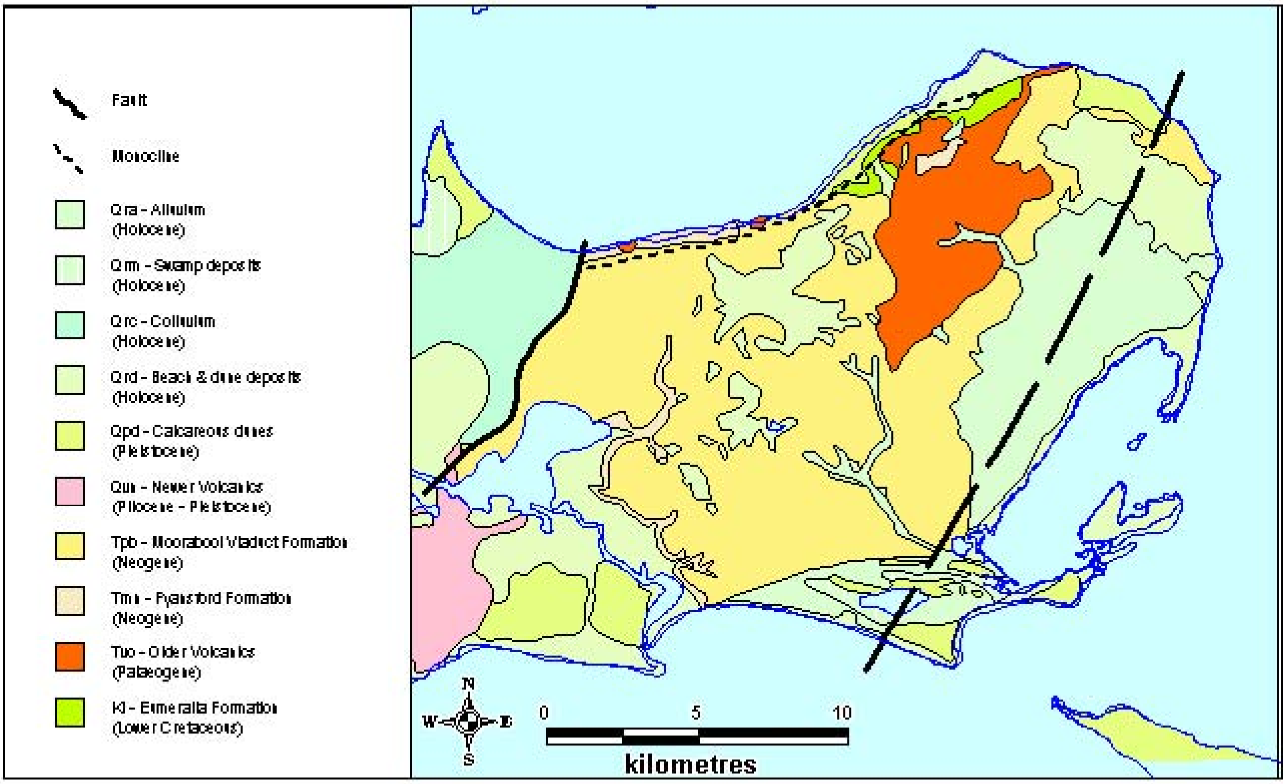


Figure A1. Total magnetic intensity (illuminated from the north east)



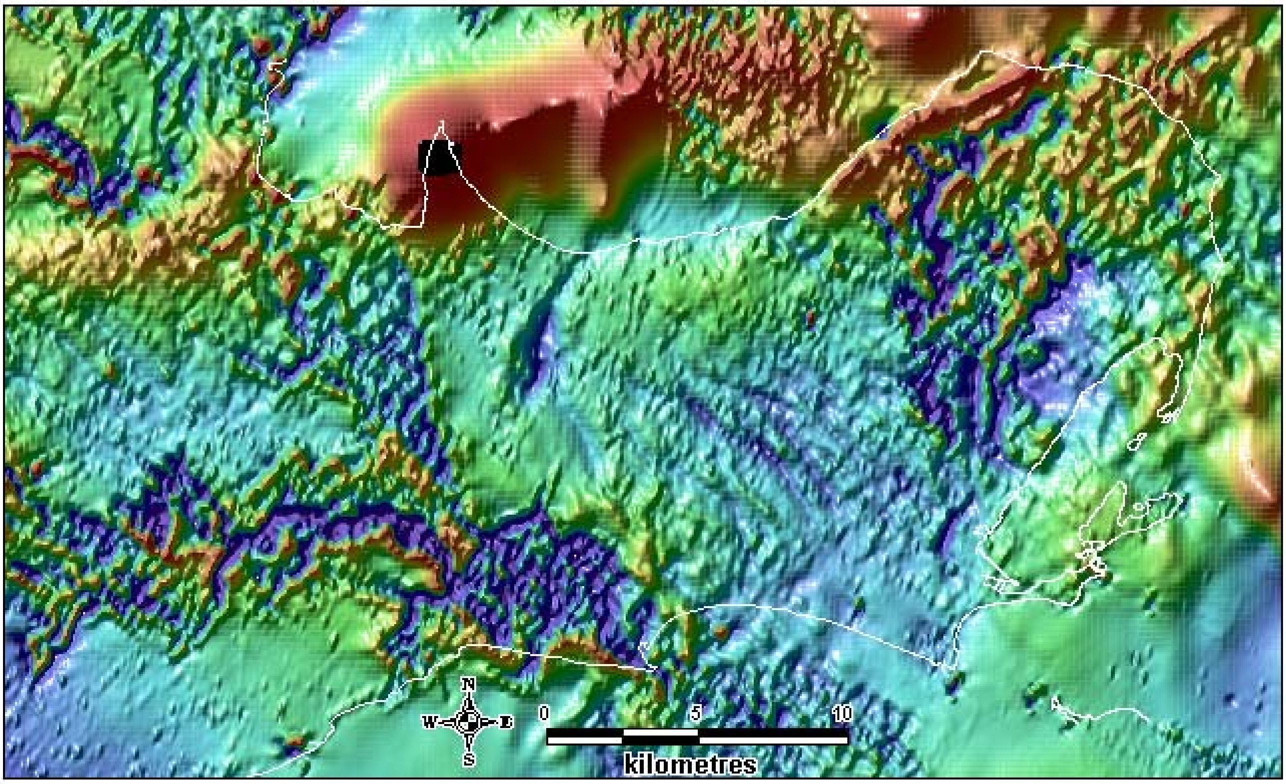


Figure A2. Total magnetic intensity (illuminated from the north west)

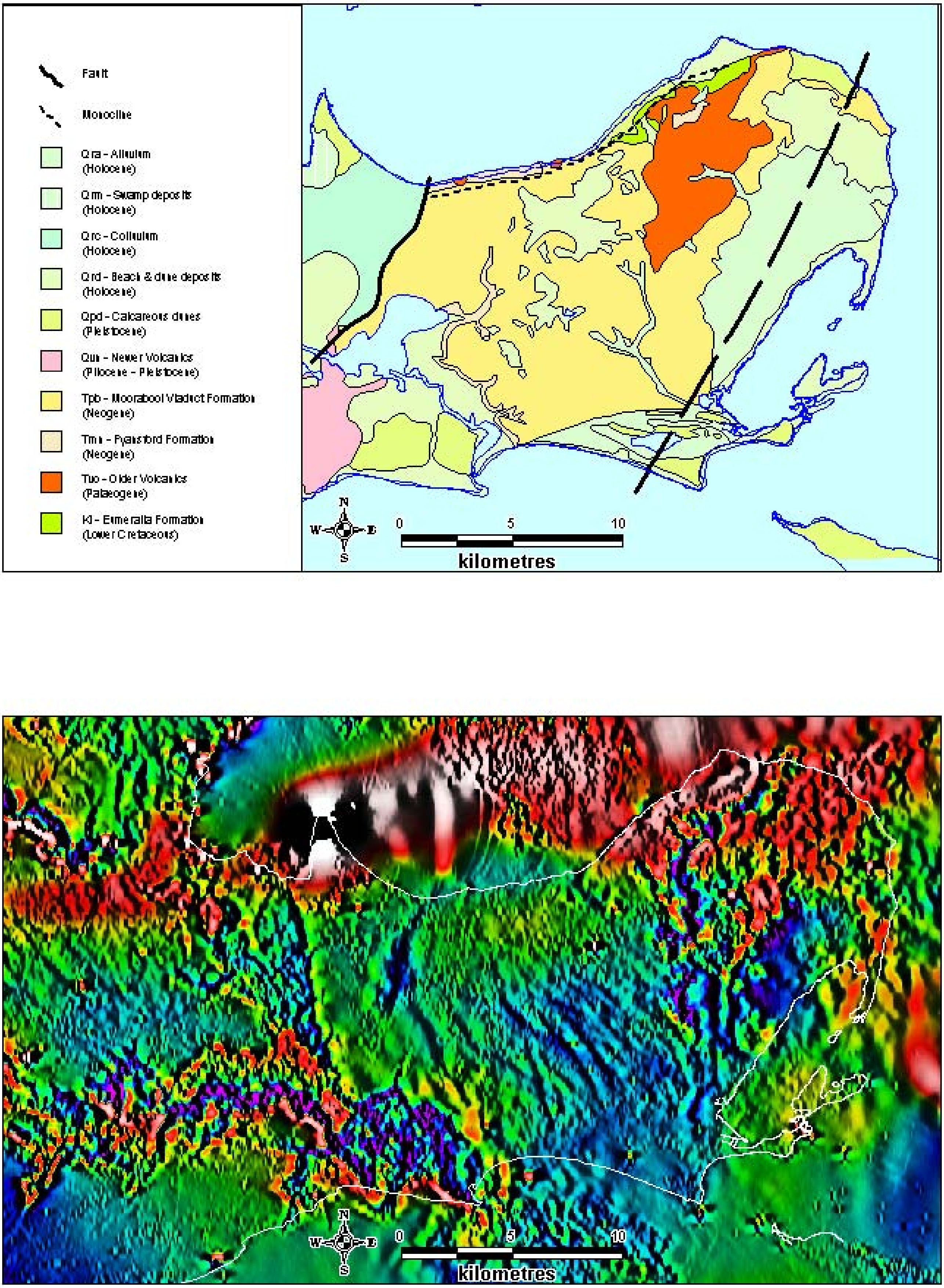
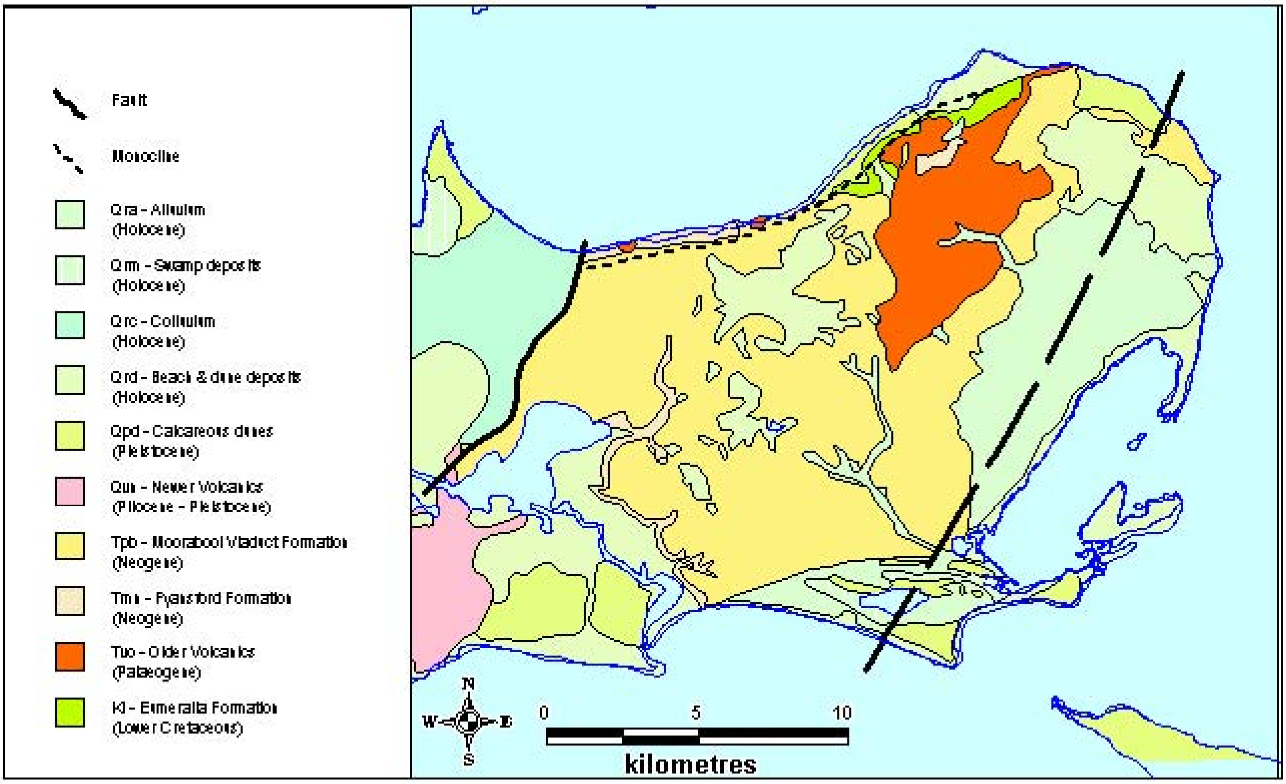


Figure A3. Magnetic gradient (first vertical derivative)



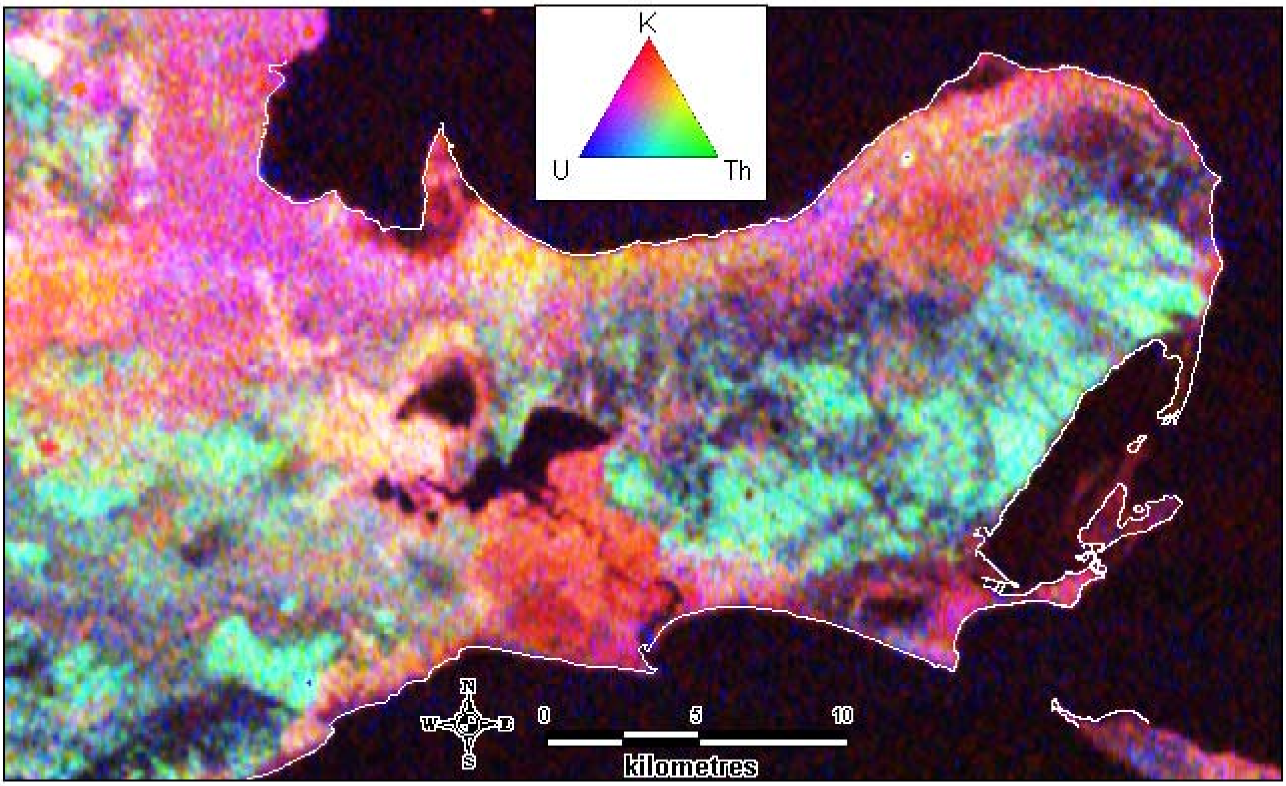


Figure A4. Radiometric ternary ratios

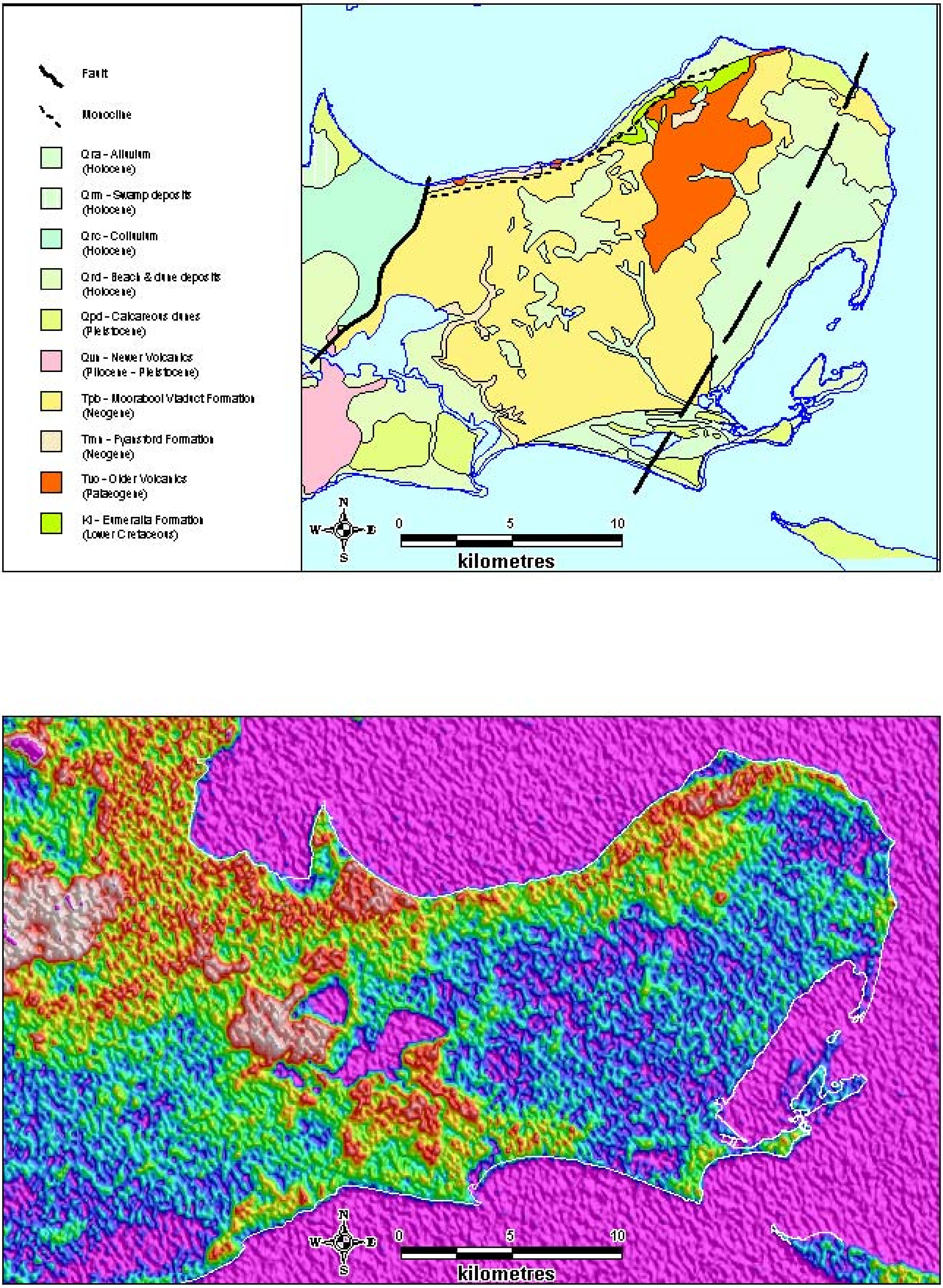


Figure A5. Radiometric Potassium

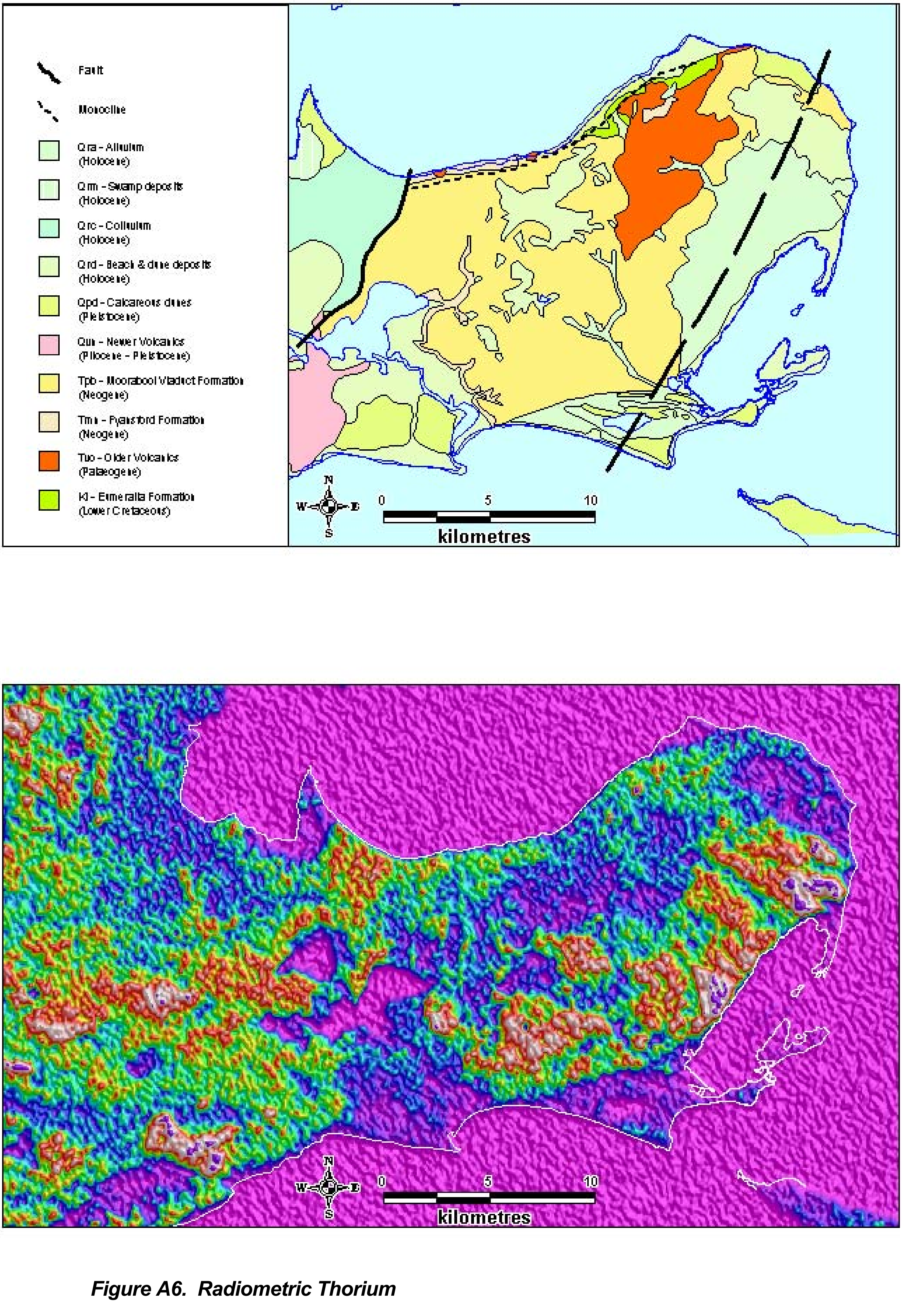


Figure A6. Radiometric Thorium

Appendix B Regional bores

Available data on the bores in the region around The Dell was accessed from the Groundwater Monitoring and Research Database compiled by the Corangamite Catchment Management Authority (CCMA). The database was compiled in August 2002 by Nolan-ITU Pty Ltd and has since been modified by the University of Ballarat.

The CCMA database combines bore records from the:

- Victorian Groundwater Database (VGB), held by the Department of Sustainability and Environment (DSE) and managed by Sinclair Knight Merz Pty Ltd
- Geological Exploration and Development Information System (GEDIS), held and managed by the Geological Survey of Victoria, Department of Primary Industries (DPI)
- the salinity bore database, held and managed by Primary Industries Research Victoria (PIRV), DPI
- Barwon water,
- Universities and other research organizations

Bores within the area around The Dell are those originally sourced from GEDIS and the VGB databases (Figure B1 and Table B1). The majority were drilled for groundwater investigation and exploration.

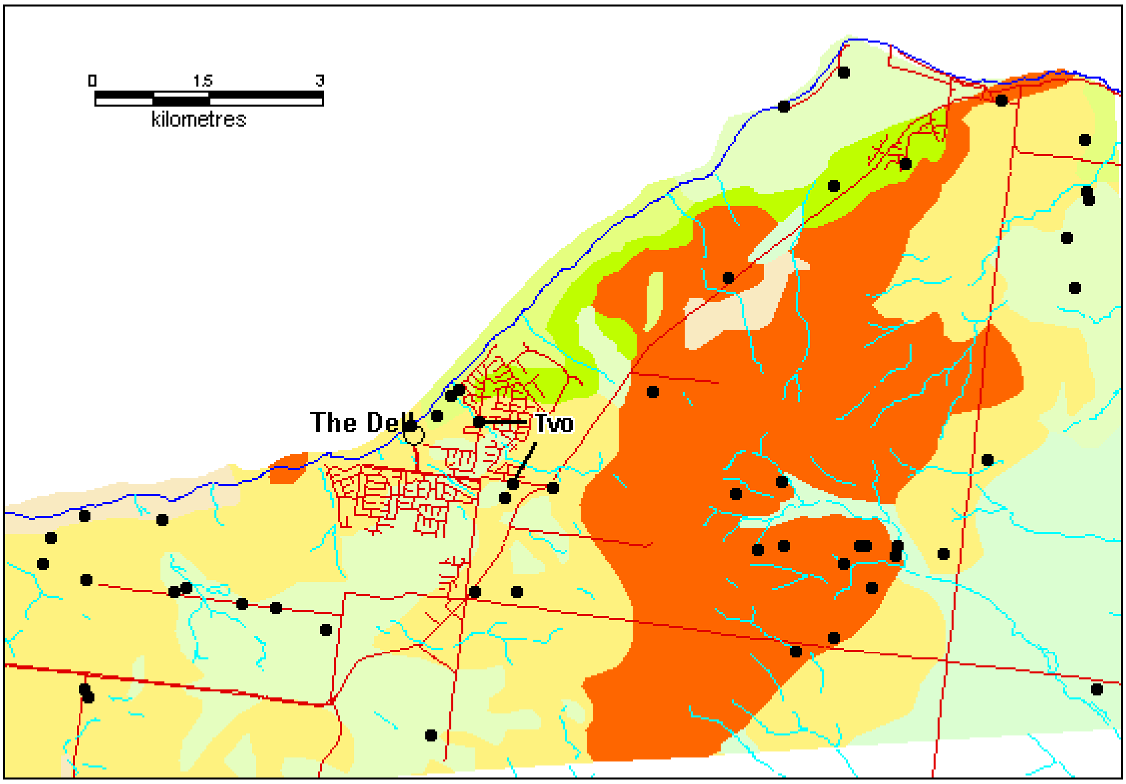


Figure B1. Regional bores

Bore identifier	AMG Easting	AMG Northing	Total depth (metres)
48838	286670	5770195	77.72
48841	290711	5773403	
48842	291357	5772712	56.99
48843	291015	5772650	54.25
48845	290619	5776261	2.74
48846	286932	5774692	
48848	286736	5774444	
48849	287030	5774784	
48850	292160	5778980	1.5
48851	287257	5772096	53.34
48852	288293	5773490	22.86
48853	292003	5777475	38.1
48854	287650	5773350	18.5
48855	285250	5771600	18
48856	287750	5773532	13
48857	283400	5772150	18.3
48858	291340	5773560	60.77
48862	282100	5770700	56.36
48863	282100	5770700	43.03
48864	282100	5770700	108.83
48867	291500	5771300	52.46
48868	292025	5771500	30.5
48872	287800	5772100	46
48876	289610	5774745	40
48877	291360	5778540	46
48878	287300	5774350	90
80117	282050	5773100	32
80118	282090	5772250	34
87826	295213	5776130	24.99
87827	295102	5776800	24.68
87854	295375	5777394	23
87862	295400	5777300	36.88
87863	295500	5770800	18
87869	294050	5773850	33.48
87873	295340	5778100	9.1
122828	293470	5772600	50
132607	292960	5777760	48
134234	283100	5773050	12.8
134237	284600	5771900	20.8
134238	284150	5771950	15.8
134239	283250	5772100	20
134244	282050	5770800	30
134530	292834	5772577	42
134531	292860	5772725	18
134532	292436	5772712	30
134533	292146	5772462	26
134534	292372	5772712	30
134535	292514	5772167	38
141656	281610	5772810	22
142182	281500	5772485	30
301701	294230	5778615	457.56

Table B1. *List of bores in the region of The Dell*

Source: *CCMA Groundwater Monitoring and Research Database, 2003*

Appendix C Data supplied for this project

Data as supplied by AS Miner Geotechnical Pty Ltd, Parsons Brinkerhoff Pty Ltd and TGM Pty Ltd.

(on CD ROM)