# THE ENGINEERING GEOLOGICAL EVOLUTION OF THE JOLIMONT VALLEY, MELBOURNE, VICTORIA

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## ABSTRACT

Recent investigations within central Melbourne for a number of projects have provided new subsurface information across the width of the Jolimont Valley, a buried valley roughly aligned with the present day course of the Yarra River. Quaternary erosion and deposition have lead to a complex sequence of sediments with incised paleochannels and interbedded lava flows. This paper uses recently acquired subsurface information to present an evolutionary geological model for the Jolimont Valley. The evolution of the valley is described in terms of its depositional history correlated with global and local sea levels and estimated stress changes within the materials infilling the valley.

## 1 INTRODUCTION

Neilson (1992) and Cupper *et al.* (2003) describe the Quaternary age Yarra Delta sediments within the Melbourne area. The Yarra Delta sediments are a series of terrestrial and estuarine sediments with interlayered basalts which overlie a pre-Quaternary erosional surface comprised of Silurian (Melbourne Formation), Neogene (Brighton Group) and Paleogene (Werribee Formation and Older Volcanics) materials. The Jolimont Valley is an early Pleistocene (Cupper *et al.* 2003) channel carved within the pre-Quaternary surface extending to the east of Princes Bridge (St. Kilda Road) and roughly following the present day course of the Yarra River (Figure 1).

An estimation of the extent of the Jolimont Valley has been made by several authors (Neilson 1992, Lamb *et al.* 1999, Hutchinson and Lamb 1998, Cupper 2003). Figure 1 provides an estimate of the extent of the Jolimont Valley formed by compiling these previous estimates and modified to include more recent site investigation data (Golder Associates, private files).

The Jolimont Valley is inferred to extend as far upstream as Burnley. However, the Jolimont Valley is the downstream extension of a network of paleochannels, (deep leads) carved by ancestral courses of the Yarra River and its tributaries and buried by Quaternary sediment and lavas (Kenley, 1967). The paleochannels extend northward from Burnley through the Richmond and Collingwood areas, linking into paleochannels associated with ancestral courses of the Merri Creek.

Recent investigations were undertaken using boreholes, CPT and laboratory testing across the width of the Jolimont Valley, to the east of Princes Bridge (refer cross section location Figure 1). This investigation has allowed a ground model across the width of valley at this location to be developed and provided further information about the geological evolution of the materials infilling the Valley.

## 2 OBSERVATIONAL GROUND MODEL

Figure 2 presents a cross section through the Jolimont Valley based on borehole, CPT and geophysical data. The cross section incorporates information obtained from investigations within the vicinity, including Federation Square, Princes Bridge and the Burnley Tunnel. The approximate cross section location is indicated in Figure 1.

Names of geological units have been assigned through correlation with those described by Cupper *et al.*, 2003 and based on ground models of the Jolimont Valley compiled for the Burnley Tunnel (Lamb *et al.*, 1999, Lamb and Hutchinson 1998). The Quaternary colluvial sediments are a previously unnamed unit. The Princes Bridge Sediments (see Figure 2) are a previously unnamed material comprised of basalt cobbles and boulders within a fine grained matrix. They have been encountered near Princes Bridge as described in this paper, and also further downstream at a site near the Charles Grimes Bridge. This unit appears to pre-date the Moray Street Gravels, and is associated with a period of erosion of the Swan Street Basalt. It is characterised by cobbles and boulders of high strength basalt.

Further discussion on stratigraphy and age of emplacement is provided subsequently in this paper.

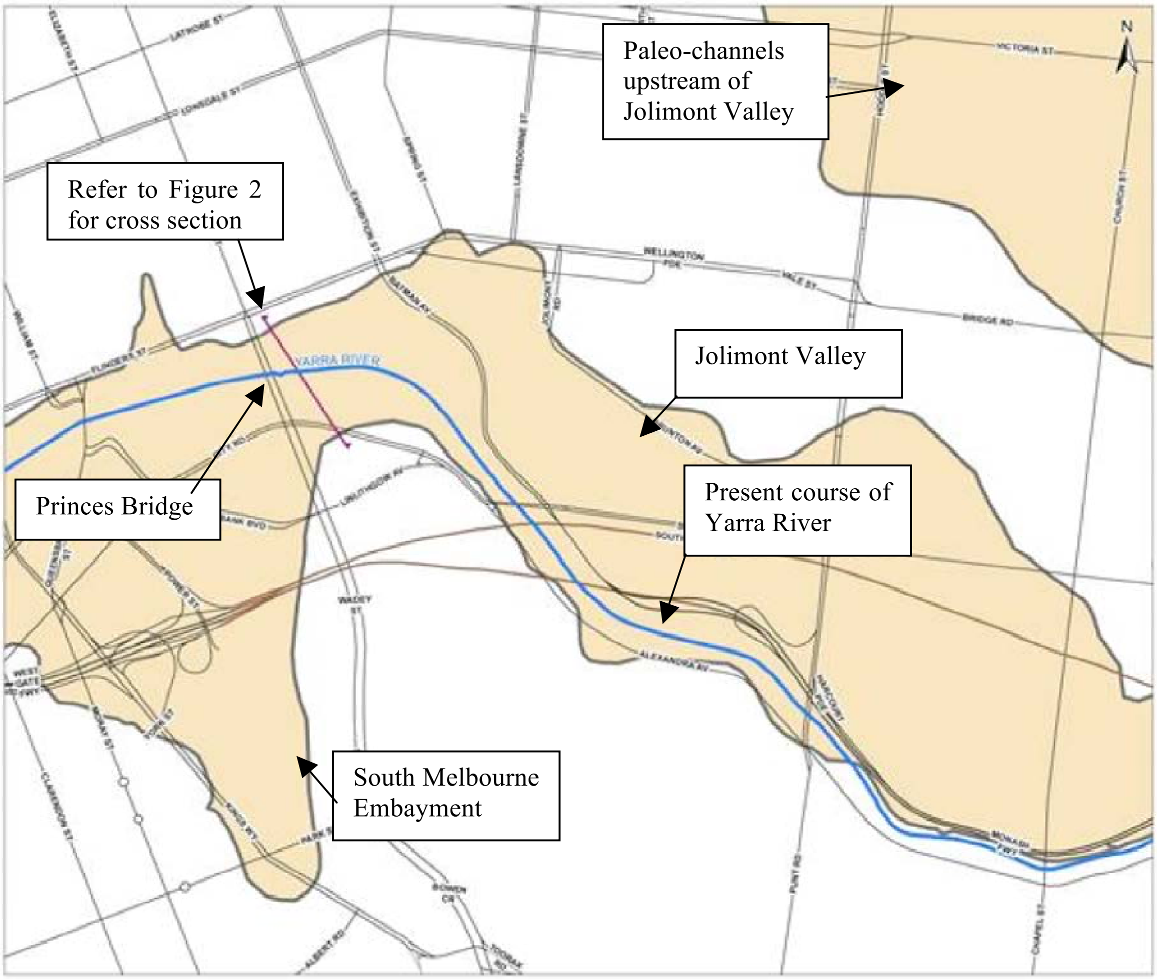

Figure 1: Extent of Jolimont Valley. Modified from Neilson 1993, Lamb *et al*. 1998, Hutchinson and Lamb, 1998; Cupper *et al.,* 2003 using data obtained from a variety of project investigations.

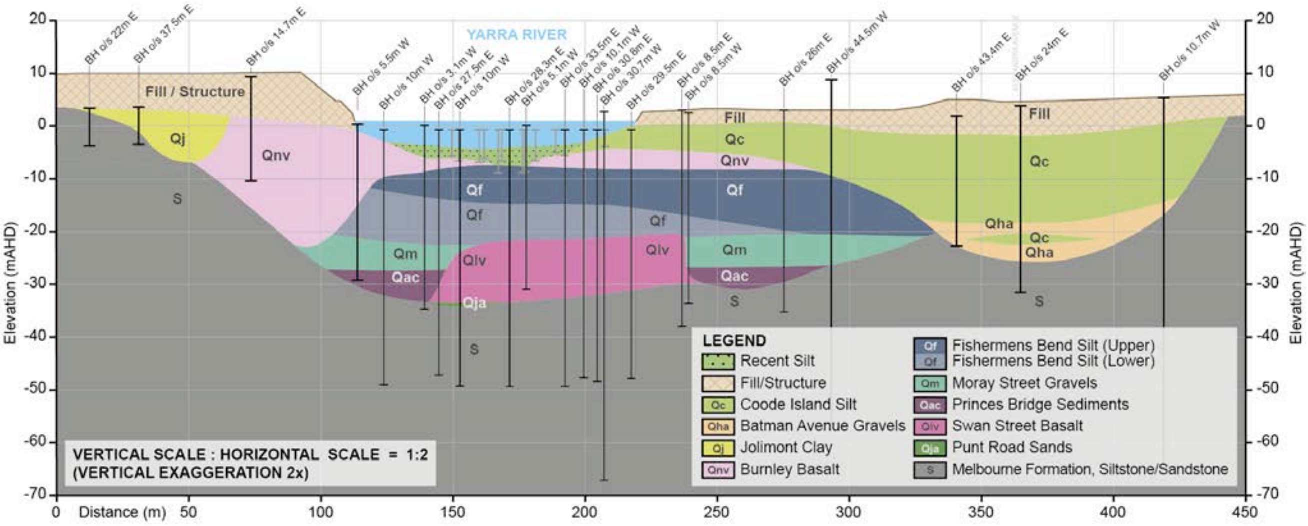

Figure 2: Two dimensional ground model across Jolimont Valley, within 50 m to the east of Princes Bridge.

A brief lithological description of the geological materials observed in boreholes is presented in Table 1. The stratigraphic names prescribed are not necessarily indicative of the material types observed in this investigation (for example Coode Island Silt is mostly clay). However, the name has been included for consistency with previous interpretations.

Table 1: Lithological description of materials encountered within the Jolimont Valley, near Princes Bridge.

| Stratigraphic Name (Cupper et. al. 2003) | | Lithological Description |
|---|---|---|
| - | Recent Silt | Fine grained, dark grey, very soft clay and silt. Ongoing deposition with periodic dredging. |
| - | Fill | Variable material including dredge spoil, clay, building refuse (concrete, brick, steel) and other waste. |
| Qc | Coode Island Silt | Very soft to firm dark grey clay with some sand. |
| Qha | Batman Avenue Gravels | Fine to medium grained sand with some gravels and cobbles. |
| Qj | Jolimont Clay | Stiff, orange and grey clay with minor sand and silt. |
| Qnv | Burnley Basalt | Very high strength, dark grey, jointed, vesicular basalt. Typically, highly weathered over upper 2 - 3 m. |
| Qf | Fishermens Bend Silt (Upper) | Stiff to very stiff clay, silty clay and silt with some sand. Orange brown and grey mottled colour above RL -12 to -20 m. |
| Qf | Fishermens Bend Silt (Lower) | Medium dense to dense fine to medium grained sand, silty sand and clayey sand. Dark grey to black colour. |
| Qm | Moray Street Gravels | Dense to very dense, medium to coarse grained quartz sand with some gravels and some silt and clay. Organic material (tree remnants). |
| Qac | Princes Bridge Sediments | Basalt gravels and cobbles within matrix of sands, some clay. |
| Qlv | Swan Street Basalt | Extremely high strength, dark grey, massive olivine basalt, slightly weathered to fresh. |
| Qja | Punt Road Sands | Cobble to boulder sized clasts of siltstone or sandstone derived from the Melbourne Formation. Pore spaces between the clasts typically filled with finer clay, silt and sand. |
| S | Melbourne Formation | Predominantly low to medium strength siltstone with about 25% interbedded medium to high strength sandstone. Folded, faulted and jointed. Dark grey to black where slightly weathered to fresh becoming white to pale brown where extremely weathered. Intruded by Devonian age porphyritic dykes. |

# 3 SEA LEVEL CHANGES

## 3.1 QUATERNARY EUSTATIC SEA LEVELS

Estimates of sea level over time have been proposed by several authors using various techniques. In general, estimation of sea level change is more accurate for recent geology (since the last glacial maximum), where geomorphologic evidence is better preserved. Going further back in the geological record, estimation of sea level on a local scale becomes more difficult, and estimations are typically made on a global scale, using oxygen isotope ratios measured in deep sea sediments. The following lists various references of eustatic sea level, at global to local scale. These references have been used to compile the simplified sea level curve for the Melbourne/Port Phillip Bay area presented in Figure 3.

- Miller *et al.* (2005) present a sea level curve for the Phanerozoic, 543 Million years ago until present, at different scales, including global sea level curve for the last 3 million years.
- Murray-Wallace (2002) presents estimated sea level high stands over the past 860,000 years for southern Australia based on a study of inland strandlines in South Australia.
- Siddall *et al.* (2006) present a eustatic global sea level curve for the past 800,000 years compiled from sea level estimates based on oxygen isotope studies using 6 different analytical methods.
- Holdgate *et al.* (2001 and 2011) describe the marine geology of Port Phillip Bay and present local sea level curves for the past 140,000 years. Holdgate, 2011 presents evidence for Port Phillip Bay having dried up between 1,000 and 6,000 years ago.

## 3.2 CORRECTION FOR TECTONIC UPLIFT

The simplified eustatic sea level curve presented in Figure 3 is presented relative to current sea level. Assessment of the effects of sea level on the evolution of the Jolimont Valley requires an assessment of the sea level relative to the valley. This requires correction to account for tectonic uplift or subsidence.

Throughout the Quaternary, Southern Victoria has been subject to tectonic uplift as indicated by studies of coastal strandlines (Murray-Wallace 2002, Wallace *et al.* 2005). Various rates of Quaternary tectonic uplift for southern

Victoria are suggested: 0.07mm/year (Murray-Wallace, 2002), 0.06 mm/year (Shin, 2012), 0.04 mm/year (average Pliocene to Quaternary interpreted from Wallace 2005). Braun *et al*., 2009 estimate a current uplift rate of 0.01 to 0.05 mm/year based on earthquake data.

Port Phillip Bay is located within the Port Phillip Sunkland (Cupper *et al*., 2003). This sunken block is bound on the east by the Selwyn Fault and the west by the Rowsley Fault. The northern extent of the Sunkland is not as apparent, however, the 1:63,360 geological mapsheet of Melbourne suggests that the northern extent is represented by the Melbourne Warp, which is mapped about 1 km to the west of the mouth of the Jolimont Valley. There are few estimates of the rates of subsidence of the Port Phillip Sunkland. Bowler, 1966, based on paleontological evidence in the Bridgewater Formation, suggests 400 ft of subsidence during the Pleistocene, about 121 m in 2.5 million years or an average of 0.05 mm/year. Estimates of movement of the Selwyn Fault (Patterson, 2013) are of the order of 1,000 m over 50 million years, or 0.02 mm/year.

The Jolimont Valley is located on the northern periphery of the Port Phillip Sunkland. The eustatic sea level curve was corrected based on a uniform uplift rate of 0.05 mm/year and uniform subsidence rate of 0.05 mm/year. Upon doing so, it was immediately apparent that Jolimont Valley is likely to have been subject to uplift rather than subsidence. The Fishermens Bend Silt is described by Neilson, 1992, as a marine deposit at least 800,000 years old based on radiometric dating in the overlying Burnley Basalt. Marine deposition would not be possible assuming a subsidence model. With reference to Figure 2, the elevation of the top of the Fishermens Bend Silt in the Jolimont Valley is about -10 m AHD. At a rate of 0.05 mm/year of subsidence, eustatic sea level would have had to have been at least 40 m higher than its current level. This is not consistent with published eustatic sea level curves.

The sea level curve presented in this paper to assess evolution of the Jolimont Valley has been corrected for Quaternary Tectonic Uplift of 0.05 mm/year. The eustatic and corrected sea level curves are presented in Figure 3. The exercise in correlating material depositional periods with sea level undertaken here (Figure 3) suggests a non-uniform uplift rate of between 0.0 mm/year and 0.05 mm/year, which may have increased in the latter part of the Quaternary.

### 3.3 PERIODS OF EROSION, DEPOSITION AND WEATHERING IN THE JOLIMONT VALLEY

Figure 3 indicates periods of deposition and erosion within the Jolimont Valley based on the relative position of the sea level to valley elevation. The known elevations (Figure 2) of each geological unit encountered within the Jolimont Valley (Table 1) are superimposed over the sea level curve.

The only unit that has been radiometrically dated is the Burnley Basalt. Page, 1968 reports an age of 0.81 million years. The basalt infills a valley and is inferred to be a terrestrial emplacement. With reference to the sea level curve in Figure 3, this is consistent with a sea level low stand at about 800,000 years ago.

The absolute ages of other units are not known. A ‘best’ estimate of the age of deposition of each unit has been made based on its stratigraphic position and elevation with respect to the sea level curve. Also indicated is the feasible age range of deposition. Cross reference is made to Figure 4 which shows the valley evolution diagrammatically.

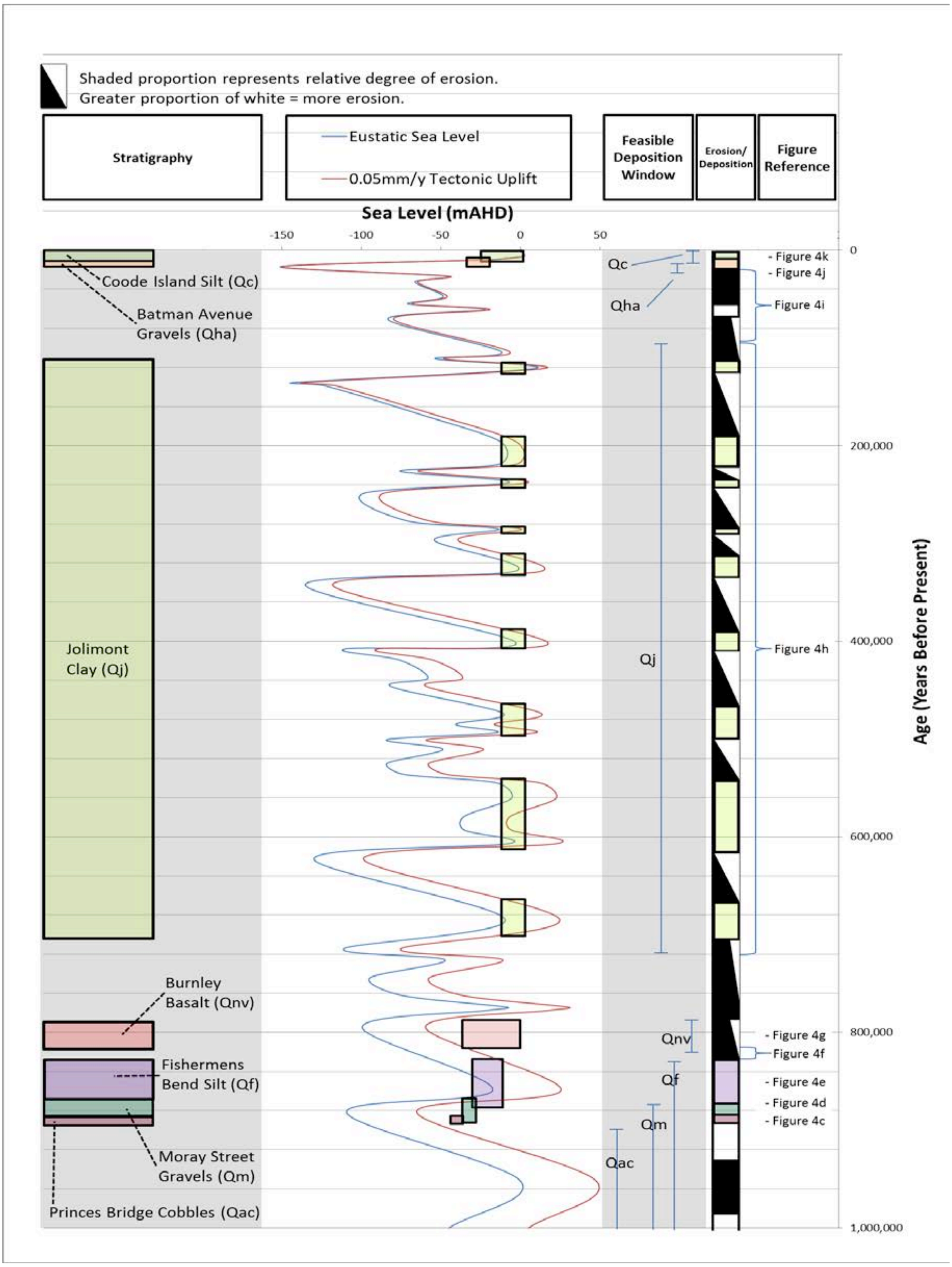

Figure 3: Quaternary sea level curve, based on compilation of previously publicised sea level curves (Holdgate *et al*. 2001 and 2011; Miller, 2005; Murray-Wallace, 2002; Siddall *et al*., 2005). Corrections shown for assumed uniform rate of tectonic uplift and subsidence of 0.05 mm/year. Periods of deposition and erosion based on sea level elevation relative to geological materials in Jolimont Valley are indicated.

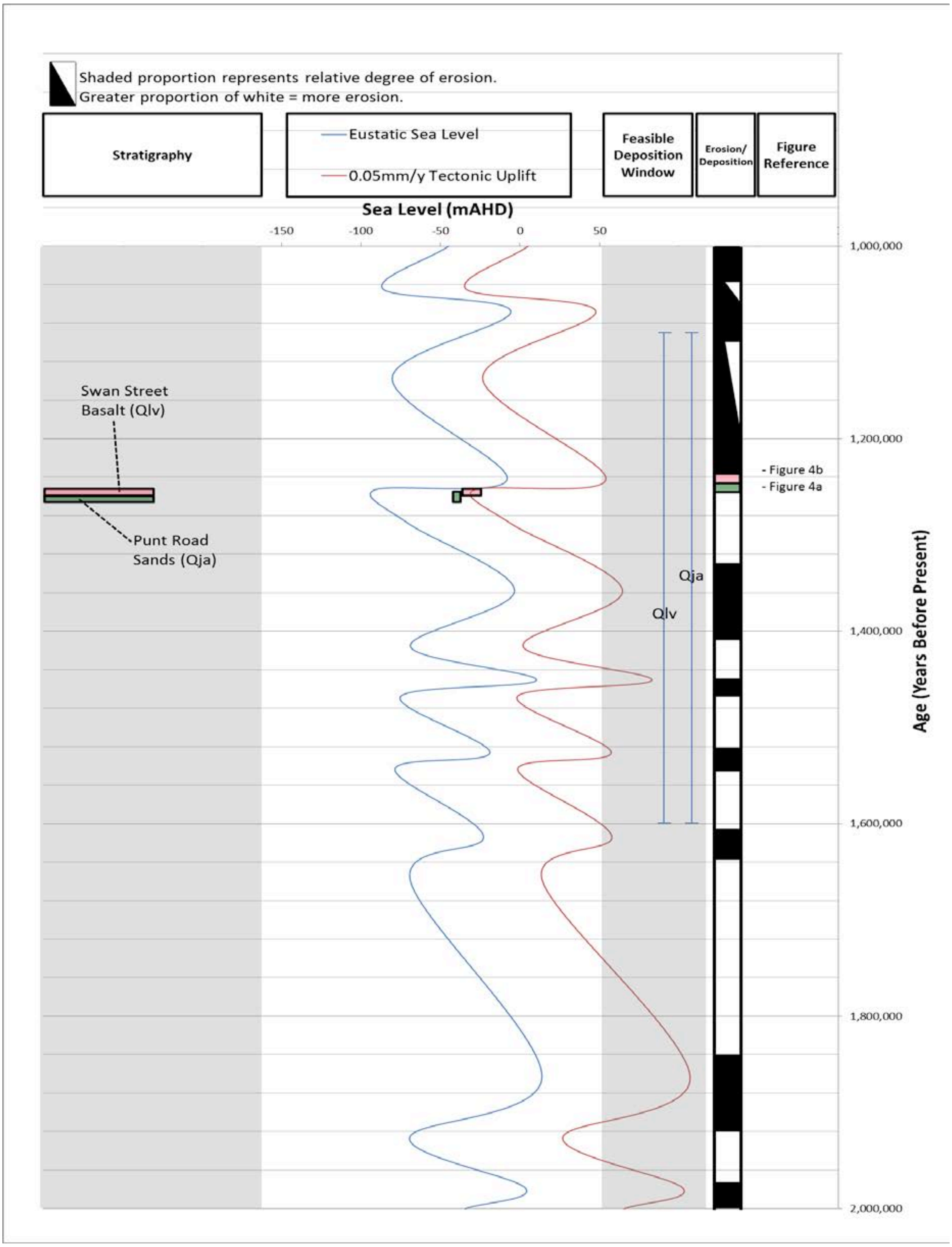

Figure 3 (continued): Quaternary sea level curve, based on compilation of previously publicised sea level curves (Holdgate *et al*., 2001 and 2011; Miller, 2005; Murray-Wallace, 2002; Siddall *et al*., 2005). Corrections shown for assumed uniform rate of tectonic uplift and subsidence of 0.05 mm/year. Periods of deposition and erosion based on sea level elevation relative to geological materials in Jolimont Valley are indicated.

## 4 VALLEY EVOLUTION

The block models in Figure 4 illustrate a suggested evolution of the Jolimont Valley. A commentary for the models and evolution of the Jolimont Valley is presented below. Figure 4 indicates the time represented by the model against the sea level curve.

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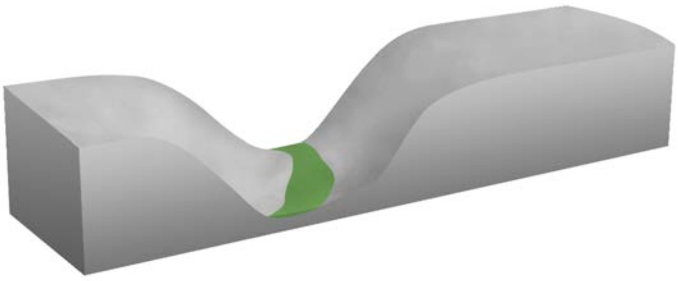
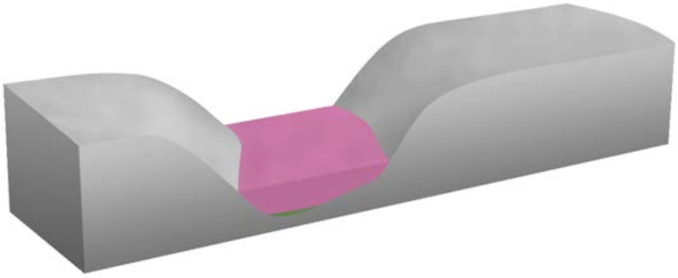
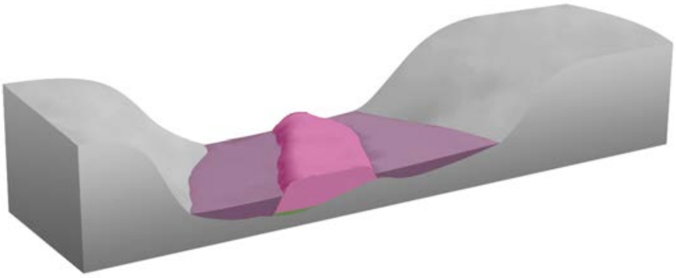
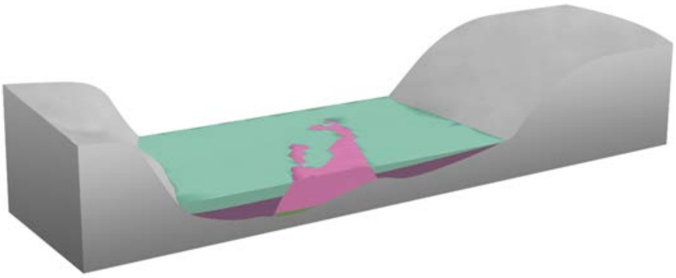
|---|---|
|  | Figure 4a - approx. 1.8 Ma to 1.3 Ma Period of deep down cutting into the Melbourne Formation during glacial sea level lows. Fast flowing rivers carved the Jolimont Valley (ancestral course of the Yarra River), Maribyrnong and the Moonee Ponds Creek Valleys. Colluvial and alluvial materials, boulders and gravels of siltstone, river gravels and sands were deposited on the valley walls and floors, depositing the Punt Road Sands. |
|  | Figure 4b - approx. 1.3 Ma Volcanic eruptions to the north of Melbourne caused lava to flow down the Jolimont Valley, emplacing the Swan Street Basalt. The basalt covered and preserved the Punt Road Sands at the base of the valley. |
|  | Figure 4c - 1.3 Ma and 0.9 Ma, the Swan Street Basalt was eroded. Aggressive periods of erosion occurred at around 1.1 Ma and 0.9 Ma during glacial minimums, removing much of the Swan Street Basalt, widening the valley and leading to the deposition of the Colluvium and Alluvium (Princes Bridge Sediments). |
|  | Figure 4d – 0.9 Ma to 0.85 Ma, during a period of low sea level, the Jolimont Valley further widened and Moray Street Gravels were deposited. |

Figure 4: Block models showing evolution of the Jolimont Valley, approximately 50 m to the east of Princes Bridge.

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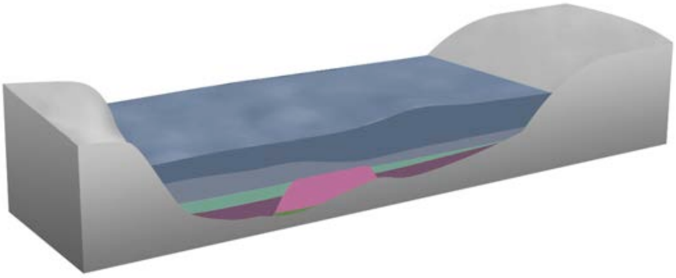
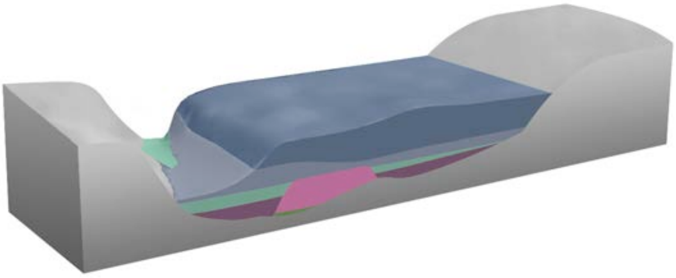
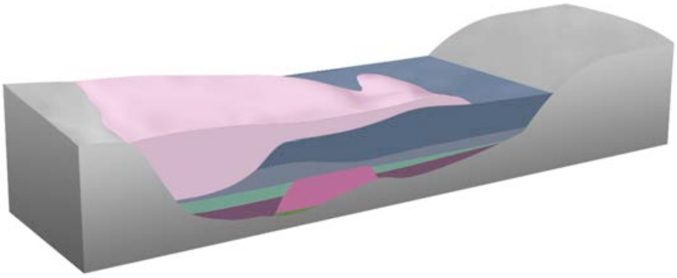
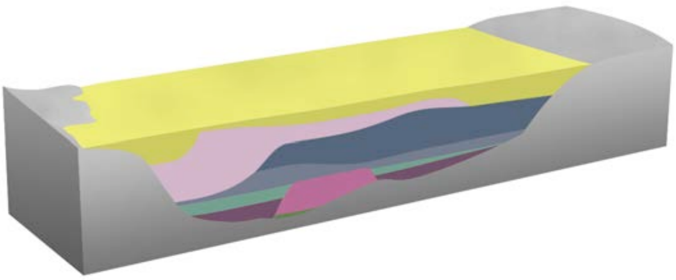
|  | Figure 4e - 0.85 – 0.83 Ma, the sea level rose rapidly flooding the Jolimont Valley and depositing marine sediment, the Fishermens Bend Silt. Coarse, sandy materials were deposited initially, which were overlain by finer clayey sediments as the sea deepened. |
|  | Figure 4f - 0.83 Ma years to about 0.81 Ma years ago sea level dropped, and the Fishermens Bend Silt was subject to a period of erosion, forming shallow channels in its surface and a main channel on the north side of the valley. The Fishermens Bend Silt was exposed to the atmosphere causing oxidation and orange staining through the upper 10 m to 15 m. The draining of this material induced consolidation, which stiffened it, and also lead to the development of fissures. |
|  | Figure 4g - 0.81Ma, a second lava flow flooded the Jolimont Valley (Burnley Basalt). Typically, the flow is at least 7 m to 8 m thick, which it may have needed to be, in order to retain sufficient heat to flow. At points of constriction in the valley, the lava overspilled, leaving thin lobes of basalt outside of the main channel. |
|  | Figure 4h – 0.81 Ma to 0.17 Ma - cycles of erosion and deposition occurred after the emplacement of the Burnley Basalt. Shallow channels eroded at the edge of the basalt, cutting into the softer siltstone. During one of the periods of high sea level, the Jolimont Clay was deposited. It is noted that elsewhere in the Yarra Delta, Fishermens Bend Silt is inferred to have been deposited during this period (Holdgate, 2001). Cupper *et al*. (2003) suggested that the Jolimont Clay was deposited as an almost continuous unit above the Fishermens Bend Silt and Burnley Basalt. Within the Jolimont Valley, the Jolimont Clay appears to be a channel infill, separated from the Burnley Basalt by a period of erosion. An early date would mean it has survived several erosion cycles. A more recent age of deposition is therefore proposed for the material within the valley, around 0.18 Ma. |

Figure 4 (continued): Block models showing evolution of the Jolimont Valley, approximately 50 m to the east of Princes Bridge.

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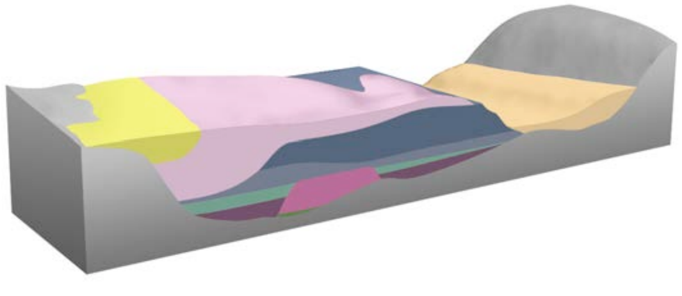
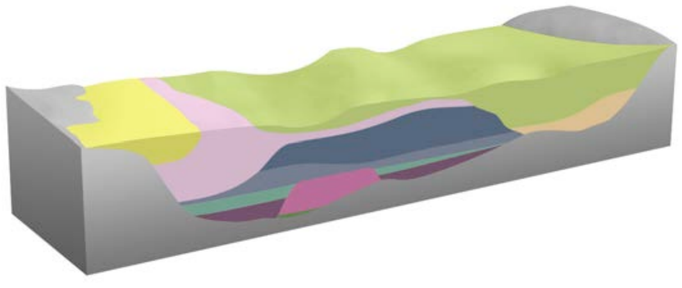
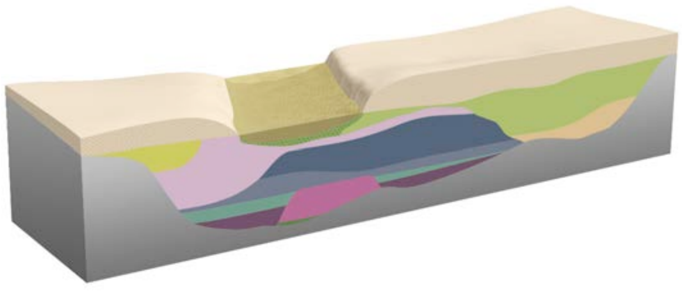
|  | Figure 4i - Between about 0.17 Ma ago and the peak of the glacial maximum, 18,000 years ago, there was an aggressive period of erosion associated with the last glacial minimum. The Jolimont Clay was drained, causing it to consolidate and stiffen. A deep valley was carved to the south of the Jolimont Valley, extending from the edge of the Burnley Basalt, down into the siltstone. Colluvial material was deposited on the sides and base of these valleys. |
|  | Figure 4j - Sea level rose between 18,000 years ago and the present. Initially, the Jolimont Valley filled with coarse material (Batman Avenue Gravels) and subsequently finer clayey material. This material, the Coode Island Silt, has never been significantly drained and remains normally to slightly overconsolidated. |
|  | Figure 4k - In the past 150 years, the landscape has been modified by man. This has included realignment of the Yarra River, deepening of the river channel and filling of low lying ground and some lowering of groundwater levels. |

Figure 4 (cont): Block models showing evolution of the Jolimont Valley, approximately 50 m to the east of Princes Bridge.

## 5 RELATIONSHIP BETWEEN STRESS HISTORY AND UNDRAINED SHEAR STRENGTH

Assuming they were deposited in a marine or a fully submerged environment, an approximate vertical effective stress history can be estimated for the Fishermens Bend Silt and Coode Island Silt within the Jolimont Valley. It is acknowledged that the sea level does not necessarily represent groundwater level. However, it is assumed here that during glacial minimums, where the sea level was up to 60 m below the base of the valley, the groundwater level dropped below the level of the valley and sediments within the valley were fully consolidated as a result. The oxidation (iron oxide staining) within the Fishermens Bend Silt and Jolimont Clay is consistent with this assumption.

Chandler, 2000 discussed relationships between the engineering properties of clay and their sedimentation and erosional history. This study, based on testing of different clays proposed an intrinsic relationship between void index, $I_v$ and vertical effective stress, $\mathbf{s}'_v$ for reconstituted clays consolidated from a slurry. This relationship is referred to as the Intrinsic Compression Line (ICL) and is defined as:

$$I_v = 2.6 - 1.475x + 0.075x^2 + 0.0055x^3 \quad \text{where } x = \log \mathbf{s}'_v \quad (1)$$

Void index, $I_v$ is a normalisation of the *in situ* void ratio $e_0$, against the oedometer compression at a vertical effective stress of 100 kPa. In Equation 2a, $e^*_{100}$ is the void ratio of a reconstituted sample compressed under a vertical effective stress of 100 kPa and $C^*_c$ is the compression index for compression between 100 kPa and 1,000 kPa. $I_v$ can be approximated using the *in situ* moisture content $w_0$, plastic limit $w_p$ and plasticity index $I_p$ as indicated in Equation 2b.

$$I_v = (e_0 - e^*_{100})/C^*_c \qquad (2a) \qquad\qquad I_v = 2.0(w_0 - w_p/I_p) - 1.0 \qquad (2b)$$

It is suggested by Chandler that for triaxial compression on a reconstituted sample, an intrinsic strength line (ISL) relating $I_v$ to the undrained shear strength of a reconstituted clay ($s^*_u$) can be approximated by Equation 3.

$$s^*_u = 0.33\mathbf{s}^*_{ve} \qquad (3)$$

where $\mathbf{s}^*_{ve}$ corresponds to the value of effective vertical stress on the ICL at the *in situ* void ratio (or using Equation 2b, the *in situ* moisture content). The ISL and ICL as presented by Chandler are reproduced in Figure 5. Also shown in Figure 5 are properties of Fishermens Bend Silt and Coode Island Silt measured on samples recovered within the Jolimont Valley. The estimated Void Index $I_v$ and *in situ* vertical effective stress, $\mathbf{s'}_{v0}$ are set out in Tables 2 and 3.

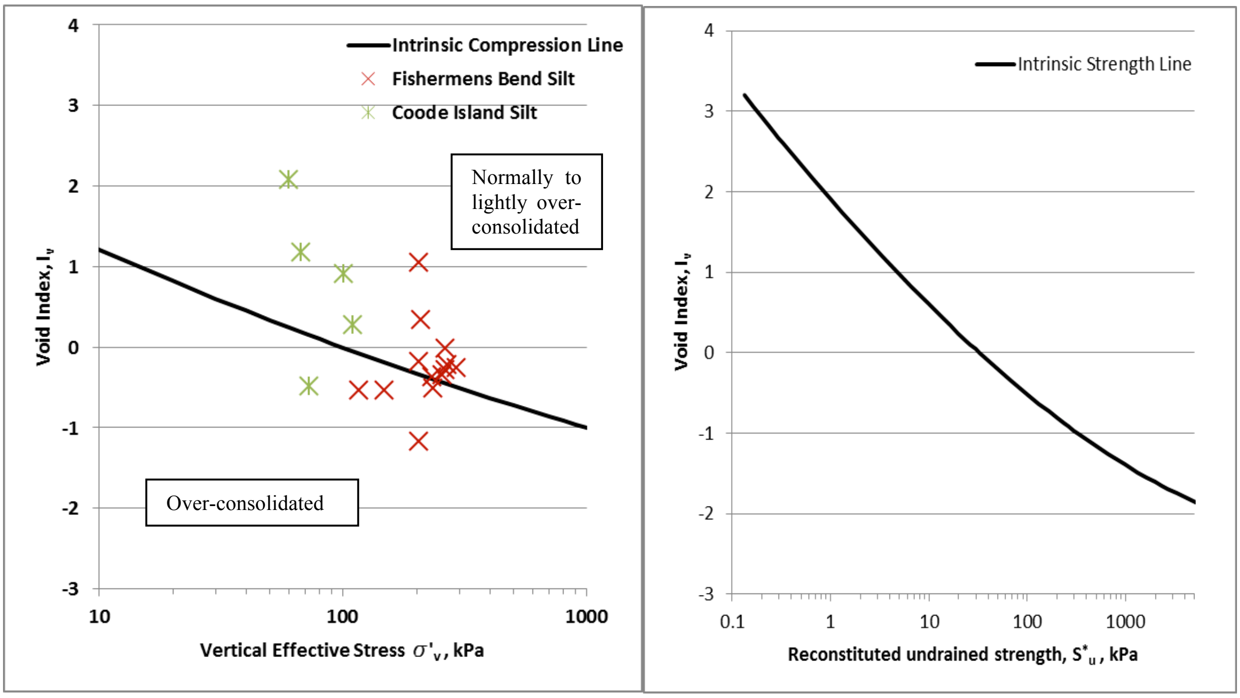


Figure 5: ICL and ISL (Chandler, 2000) showing $I_v$ estimated based on laboratory testing in Fishermens Bend Silt and Coode Island Silt. Data is presented in Tables 2 and 3.

Chandler, 2000 presents the results of compression testing on various clay soils which indicate that stiff, over-consolidated soils typically plot to the left of the ICL and soft, normally to lightly consolidated soils typically plot to the right of the ICL. Although there is some scatter in the results presented here, Figure 5 suggests that the both the Fishermens Bend Silt and Coode Island Silt are lightly over- consolidated with *in situ* state generally to the right of the ICL. This is consistent with the geological stress history as subsequently described. Whilst the Fishermens Bend Silt has been over consolidated due to it being drained and re-saturated, neither material has been heavily consolidated due to stress relief associated with erosion of overlying materials.

Chandler suggests that the undrained shear strength of soils which lie to the right of the ICL may be approximated by Equation (4):

$$s_u = \mathbf{s'}_{vy}(s^*_u/\mathbf{s}^*_{ve}) \qquad (4)$$

where $\mathbf{s'}_{vy}$ is the yield stress in oedometer compression. This is analogous to the pre-consolidation stress or maximum effective stress to which a soil has been subject during its geological history. However, Chandler notes that $\mathbf{s'}_{vy}$ measured in the laboratory is usually always higher than the pre-consolidation stress estimated based on the 'geological' yield stress, attributing the difference to diagenesis and development of internal structural strength within clays during burial. For the assessment undertaken here, we have adopted the lower bound assumption that $\mathbf{s'}_{vy}$ is equivalent to the estimated maximum stress to which the soil has been subject since its deposition.

## 5.1 STRESS HISTORY

Figures 6 and 7 present the estimated effective vertical stress ($\mathbf{s'}_v$) vs. time at various elevations within the Fishermens Bend and Coode Island Silt. These have been adapted from the sea level curve and depositional history presented in Figure 3. Bulk densities of 2.00 and 1.75 t/m$^3$, have been assumed for the Fishermens Bend Silt and Coode Island Silt respectively based on the average of the measured moisture contents set out in Table 2 and assuming a particle density of 2.65 t/m$^3$. A bulk density of 2.7 t/m$^3$ has been assumed for the Burnley Basalt (applicable where this overlies the Fishermens Bend Silt). The pre-consolidation pressure ($\mathbf{s'}_{vy}$) (maximum historical effective vertical stress) and current stress ($\mathbf{s'}_{v0}$) (stress at '0' time) may be estimated from these curves.

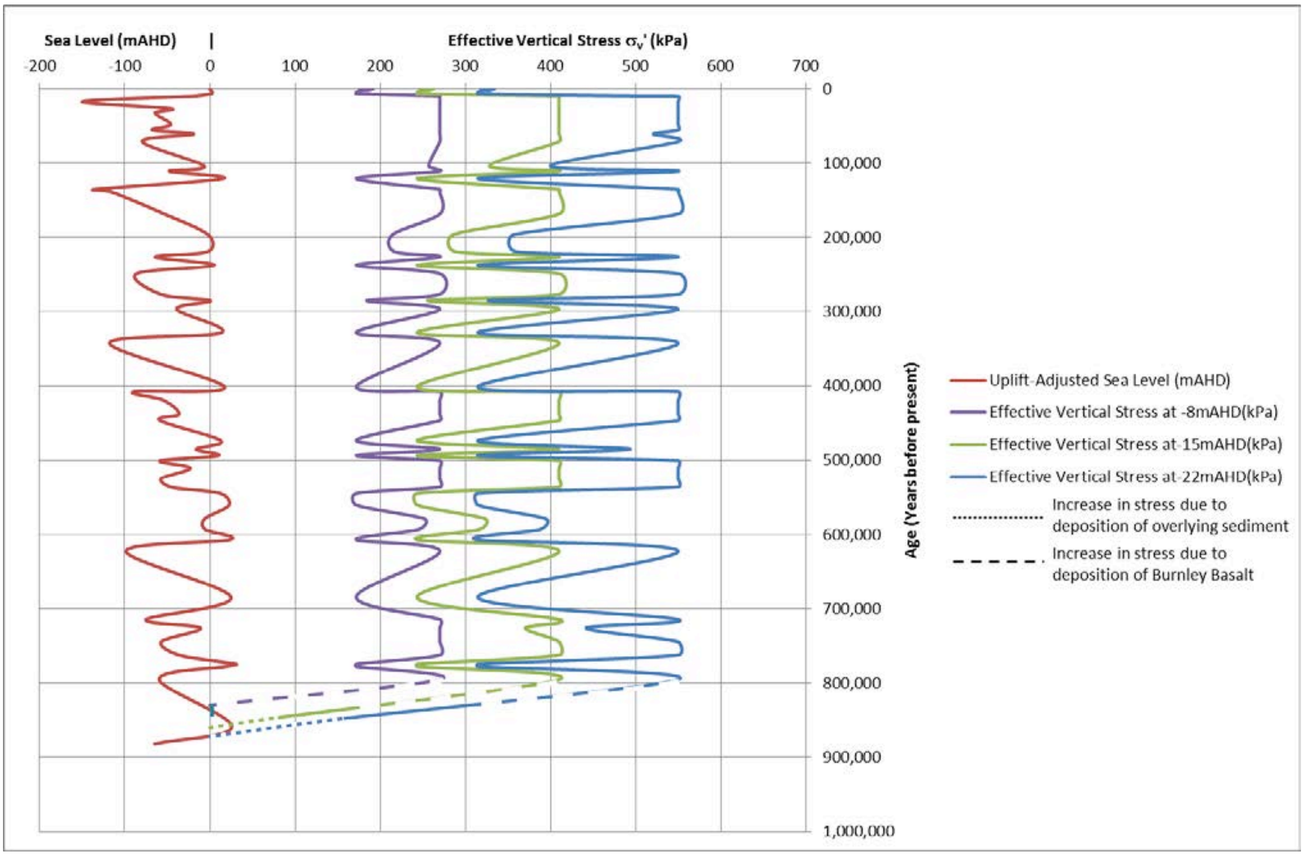


Figure 6: Estimated effective stress in Fishermens Bend Silt versus time.

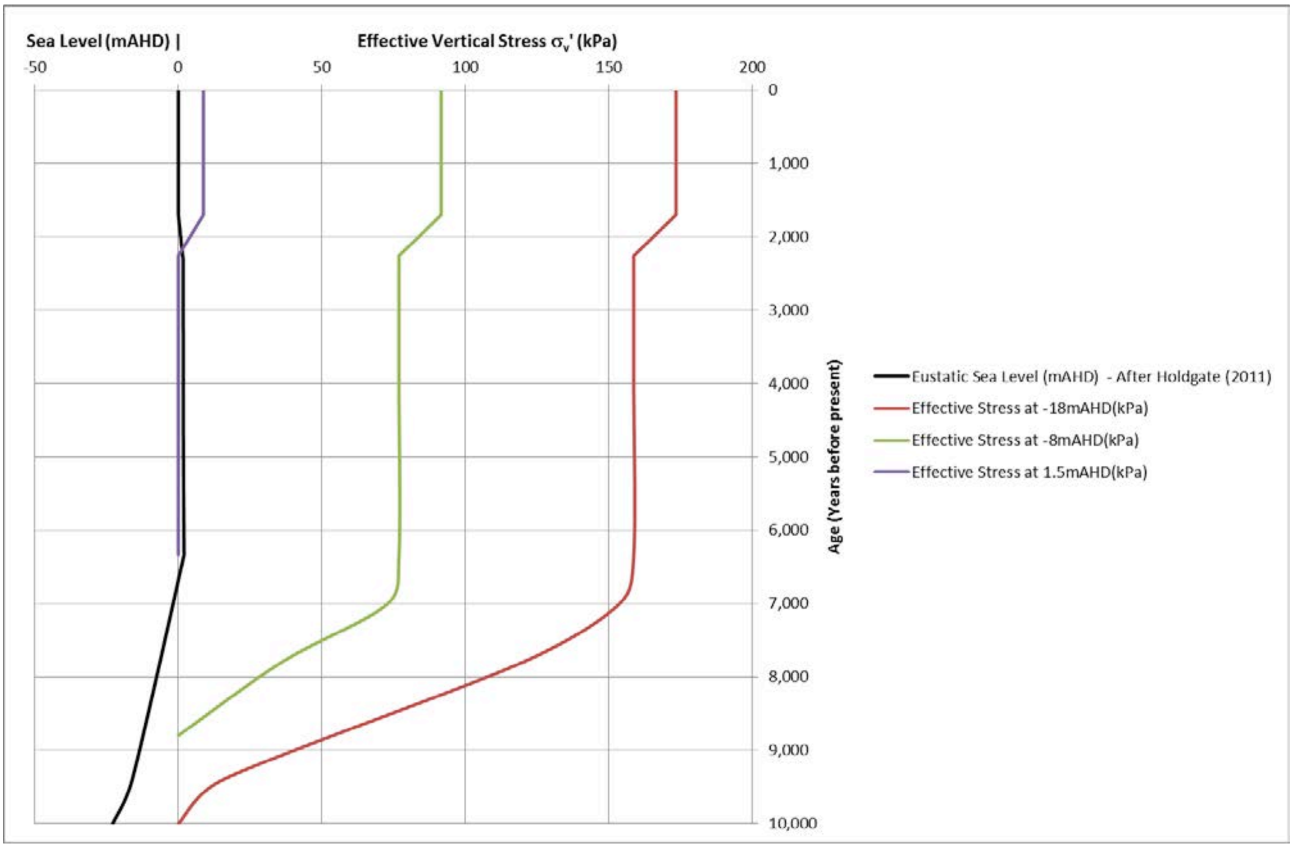


Figure 7: Estimated effective vertical stress in Coode Island Silt versus time.

## 5.2 ESTIMATION OF SHEAR STRENGTH BASED ON GEOLOGICAL HISTORY

Atterberg Limit and moisture content testing undertaken on samples obtained from investigations in the Jolimont Valley are summarised in Table 2 along with the estimated void index ($I_v$) based on Equation 2b. The corresponding $s^*_{ve}$, based on solving Equation 1, and $s^*_u$ based on Equation 3 are also presented. The estimated *in situ* and maximum geological stresses, $s'_{v0}$ and $s'_{vy}$ are taken from Figures 6 and 7 for the corresponding elevation. $I_v$ and $s'_{v0}$ are also plotted on Figure 5.

Table 2: Shear strength estimation based on Atterberg Limit and moisture content testing.

| Unit | Sample Elevation (AHD) | $w_o$ (%) | $w_p$ (%) | $I_p$ (%) | $I_v$ | $s^*_{ve}$ (kPa) | $s^*_u$ (kPa) | $s'_{v0}$ (kPa) | $s'_{vy}$ (kPa) | $s_u$ (kPa) |
|---|---|---|---|---|---|---|---|---|---|---|
| Coode Island Silt | -3.2 | 29.9 | 13 | 11 | 2.07 | 2 | 1 | 60 | 60 | 16 |
| | -4.1 | 51 | 26 | 23 | 1.17 | 11 | 3 | 67 | 67 | 18 |
| | -4.9 | 35.9 | 23 | 50 | -0.48 | 283 | 93 | 73 | 73 | 20 |
| | -8.6 | 62.5 | 29 | 35 | 0.91 | 17 | 6 | 101 | 101 | 27 |
| Fishermens Bend Silt | -3.7 | 30.3 | 20 | 45 | -0.54 | 323 | 107 | 116 | 153 | 50 |
| | -6.8 | 28.3 | 18 | 45 | -0.54 | 323 | 107 | 148 | 215 | 70 |
| | -9.2 | 29.3 | 17 | 12 | 1.05 | 13 | 4 | 204 | 294 | 100 |
| | -9.3 | 18.9 | 21 | 24 | -1.18 | 1599 | 528 | 204 | 296 | 97 |
| | -9.32 | 22.1 | 16 | 15 | -0.19 | 146 | 48 | 205 | 296 | 97 |
| | -9.7 | 25.4 | 14 | 17 | 0.34 | 50 | 16 | 209 | 304 | 100 |
| | -12.0 | 20.1 | 16 | 13 | -0.37 | 218 | 72 | 232 | 350 | 114 |
| | -12.2 | 27 | 20 | 29 | -0.52 | 305 | 101 | 234 | 354 | 115 |
| | -14.3 | 23.5 | 17 | 20 | -0.35 | 209 | 69 | 256 | 396 | 128 |
| | -15.0 | 18.4 | 13 | 15 | -0.28 | 179 | 59 | 263 | 410 | 133 |
| | -15.1 | 22.4 | 17 | 11 | -0.018 | 103 | 34 | 264 | 412 | 133 |
| | -15.5 | 24.2 | 16 | 21 | -0.22 | 157 | 52 | 268 | 420 | 136 |
| | -18.0 | 24.3 | 18 | 17 | -0.26 | 171 | 56 | 293 | 470 | 151 |

In addition, an oedometer test was undertaken within the Coode Island Silt on a sample obtained from an elevation of -13.6 m AHD, from within the valley to the south of the Yarra River (Figure 2). The void index $I_v$ estimated using Equation 2a is shown in Table 3.

Table 3: Shear strength estimation based on Oedometer test.

| Unit | Sample Elevation (AHD) | $e_o$ | $e^*_{100}$ | $C^*_c$ | $I_v$ | $s^*_{ve}$ (kPa) | $s^*_u$ (kPa) | $s'_{v0}$ (kPa) | $s'_{vy}$ (kPa) | $s_u$ (kPa) |
|---|---|---|---|---|---|---|---|---|---|---|
| Coode Island Silt | -13.6 | 1.272 | 1.192 | 0.282 | 0.28 | 56 | 18 | 110 | 110 | 36 |

## 5.3 COMPARISON OF SHEAR STRENGTH ESTIMATED BASED ON STRESS HISTORY WITH CPT AND LABORATORY TESTS

Figures 8a and 8b compare the undrained shear strengths ($s_u$) estimated based on geological history (Tables 2 and 3) with those measured during investigations using CPT and triaxial testing. $S_u$ has been estimated from CPT tests using Equations 5 and 6 as outlined by Robertson et al. (2010) and applied to Yarra Delta sediments by Ramsey *et al.* (2013). The estimation of $s_u$ from CPT data, where pore pressure measurements are available, is described by Equation (5):

$$s_u = q_{net}/N_{kt} \qquad (5)$$

where:

$N_{kt}$ = Empirical conversion factor [Taken as 18 for Coode Island Silt and 14 for the Fishermens Bend Silt]
$q_{net}$ = Net cone resistance [Function of total cone resistance, $\alpha$, $\beta$ and $\mu$ and $p_o$]
$\alpha$ = Cone correction factor [Equal to 0.59 for a 15cm$^2$ cone]
$\beta$ = Function of pore pressure measurement location on the cone [Taken as 1.0 for the cone used]
$\mu$ = Water pressure
$p_o$ = Overburden pressure

Where pore pressure measurements are not available, the following Equation (6) was used:

$$s_u = (q_t - \sigma_v)/N_{kt} \quad (6)$$

where:

$\sigma_v$ = Total overburden stress
$q_t$ = Total cone resistance
$N_{kt}$ = Empirical conversion factor [Taken as 18 for Coode Island Silt and 14 for the Fishermens Bend Silt]

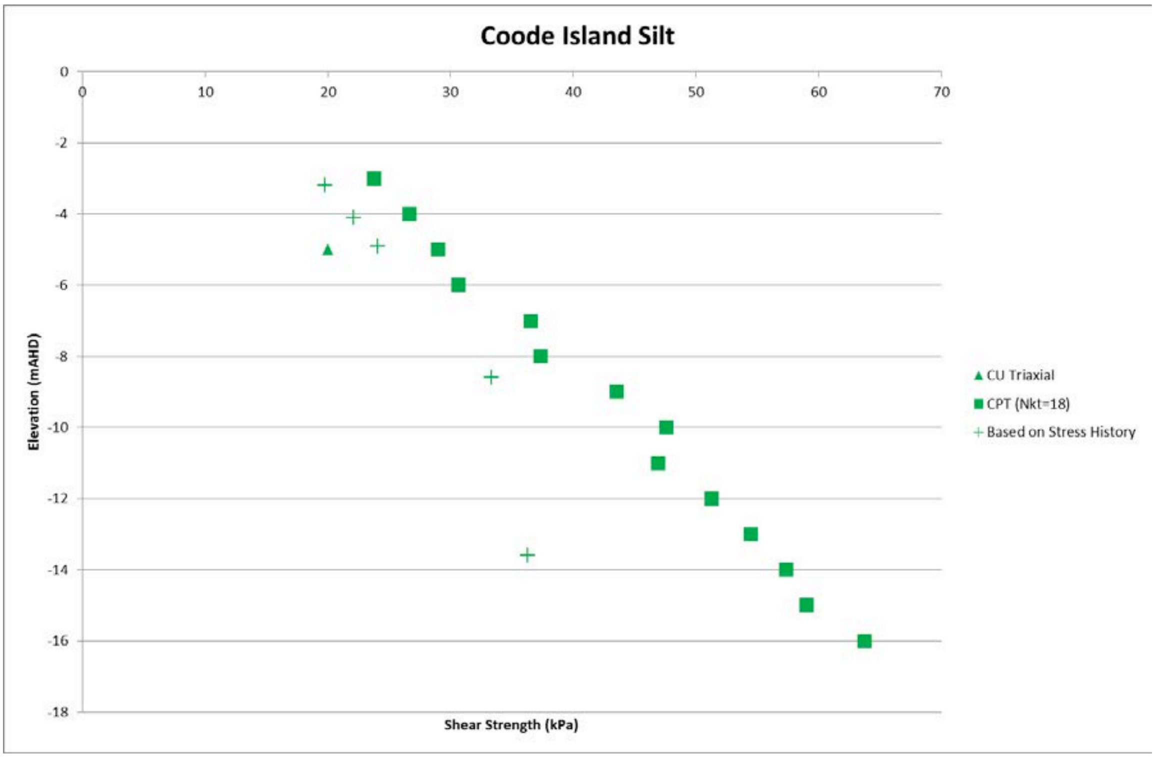


Figure 8a: Undrained shear strength $s_u$ estimated from from CPT data plotted with $s_u$ estimated from stress history for Coode Island Silt.

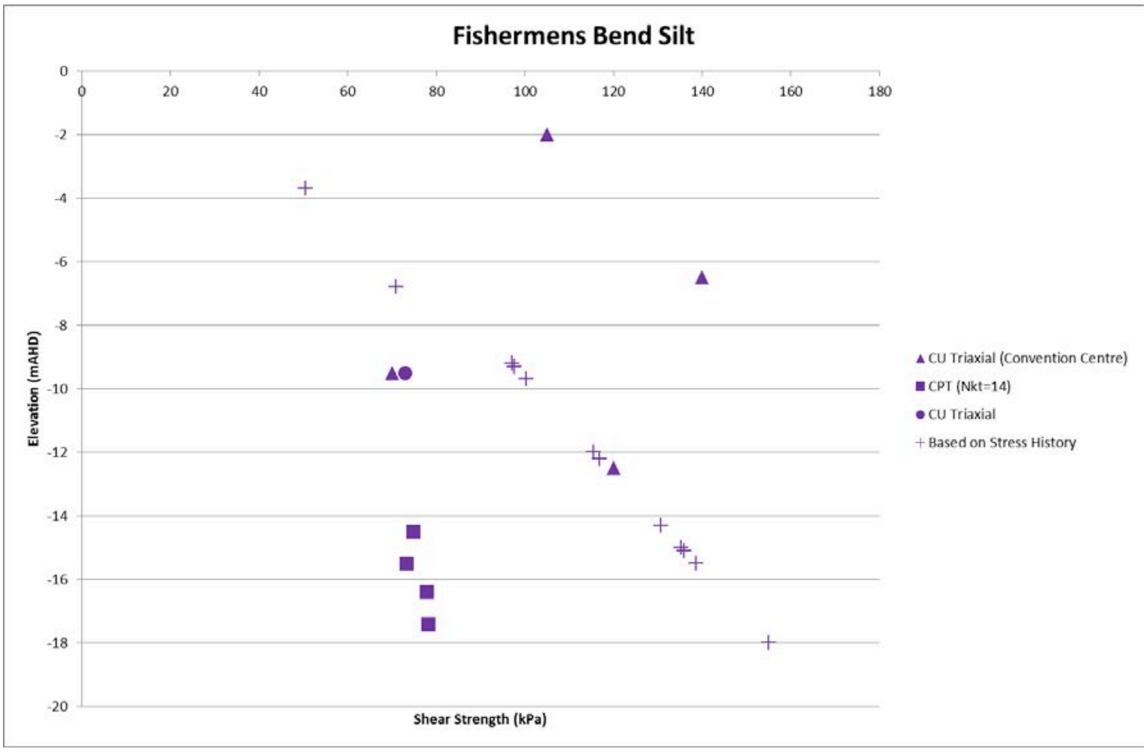


Figure 8b: Undrained shear strength $s_u$ estimated from from CPT data plotted with $s_u$ estimated from stress history for Fishermens Bend Silt.

# 6 DISCUSSION

The evolutionary model presented here raises a number of discussion points, summarised below.

## 6.1 DEPOSITION AND EROSION OF FISHERMENS BEND SILT

It has been previously noted that the Fishermens Bend Silt is a variable deposit both in terms of its engineering properties and composition, for example (Ervin, 1992). Furthermore, the age of deposition of this material is uncertain. For example, Holdgate (2001) suggests it has been deposited in the Yarra Delta as recently as 110,000 years ago whilst Cupper *et al*. (2003) suggests it was deposited around 800,000 years ago prior to the deposition of the Burnley Basalt, with the overlying Jolimont Clay representing later deposition of the same material.

The sea level curve presented, indicates the sea level was high enough to flood the Jolimont Valley as many as 9 times between the two extreme age estimations for deposition of the Fishermens Bend Silt, 800,000 years ago to 110,000 years ago). If this was the case, there could have been repeated cycles of erosion and deposition, the remnants of which are now identified as the Fishermens Bend Silt and Jolimont Clay. The possibility is raised that the variability within this unit is the result of remnant materials deposited during different sea level high stands over a 700,000 year period and subject to different periods of erosion and deposition.

The estimated shear strengths in Figure 8, based on the stress history of a clay material fully consolidated through draining seems to be central to the measured shear strengths within this unit and may provide a reasonable estimate. However, more field measurements, in particular of Fishermens Bend Silt from below the basalt for which depositional age is reasonably well known are needed to further investigate this. The stress history suggests that irrespective of age within the 700,000 year depositional window, the Fishermens Bend Silt/Jolimont Clay has been fully drained. The variability in these materials could be attributed to effects of differing degrees of sub-aerial weathering, differing composition, mineralogy and diagenesis depending on the time of deposition and subsequent erosional cycles to which the material at any particular location has been exposed. Sample disturbance may also affect the measured engineering properties in this material.

It is possible that the valley remained below sea level, but was not flooded. This could be the case if calcarenite deposits (Bridgewater Formation) blocked the entrance to Port Phillip Bay. However, if this had occurred for long periods, fresh water or lacustrine sediments corresponding to high sea level stands might be expected within the Jolimont Valley. No evidence for this has been observed.

Whilst the estimation of undrained shear strength using stress history can only be considered approximate at best, it may provide a useful check against measured properties.

## 6.2 COODE ISLAND SILT

Undrained shear strength estimated based on stress history for the Coode Island Silt appears to be reasonably consistent with measurements, albeit the measurements are slightly higher. This might be attributed to consolidation induced by recent depressurisation of the Coode Island Silt (for example the nearby Arts Centre and CityLink Burnley Tunnel projects), recent stress increase through fill placement or diagenesis (cementation and development of internal structure). Undrained shear strength estimation based on stress history appears to present a useful check against field or laboratory measurements for this material.

## 6.3 RATE OF TECTONIC UPLIFT

Correlation between sea level and periods of erosion and deposition in the Jolimont Valley appear to suggest that the Jolimont Valley has been subjected to a period of uplift through the Quaternary. This rate of uplift appears to be consistent with estimations using other methods and is estimated to be an average of 0.03 mm/year to 0.05mm/year at the Jolimont Valley.

# 7 CONCLUSIONS

Investigation within the Jolimont Valley has allowed a ground model to be developed and evolutionary model to be proposed. The model proposed suggests the valley has been formed through multiple phases of erosion and deposition. Geological units such as the Fishermens Bend Silt and Jolimont Clay, may be the remnants of multiple phases of deposition, erosion and weathering. An estimation of engineering properties of clay materials within the Jolimont Valley, including Fishermens Bend Silt and Coode Island Silt can be made based on its stress history. However, such estimations can only be considered approximate and should only be used as a check against measured properties or for preliminary estimates. In particular, due to its variable depositional history, measured properties within the Fishermens Bend Silt and Jolimont Clay can differ significantly from predicted properties.

Correlation between the materials encountered in the Jolimont Valley and published eustatic sea level curves suggests tectonic uplift rates within the vicinity of the Jolimont Valley of between 0.03 and 0.05 mm/year.

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