Notes on fault parametrisation in the FSM for the NSHA18

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This document is an amalgam of several other documents detailing fault parameterisation decisions for various domains.

Domain 1

Over much of neotectonic Domain 1 long term bedrock erosion rates are in the order of 0.2 - 5 m/Myr (Belton *et al.*, 2004; Bierman & Caffee, 2002; Chappell, 2006; Fujioka *et al.*, 2005; Quigley *et al.*, 2010b). This provides constraint on long-term fault uplift rates in that ranges are not being built in these essentially flat landscapes. Unless paleoseismic data is available, long term uplift rates have been set at the midpoint of this range. i.e. 3 m/Myr.

Unless data is available to suggest otherwise, a moderate dip angle of 45 degrees is assigned.

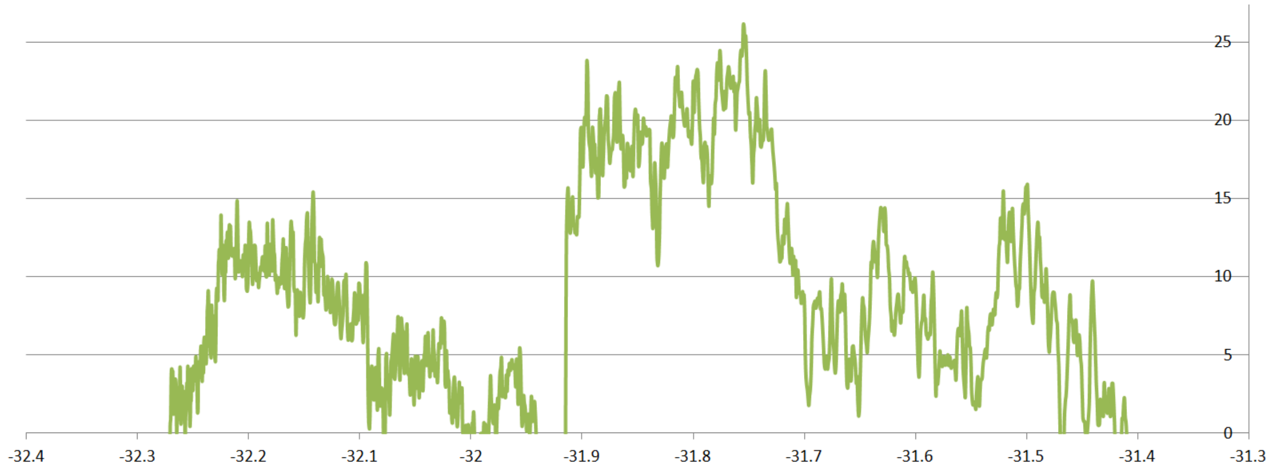
Faults with paleoseismic data include:
Dumbleyung (Estrada, 2009)
Tennant Creek (Crone *et al.*, 1997)
Meckering (Clark *et al.*, 2011b)
Hyden (Clark *et al.*, 2008)
Roderick River (Whitney *et al.*, 2015)
Roopena (Crone *et al.*, 2003)

Domain 3 (Nullarbor Faults, as imaged in 13GA-EG-1 seismic reflection data)

The 13GA-EG1 seismic reflection profile crosses a number of scarps on the Nullarbor Plain. While it cannot be certain that imaged faults several kilometres down coincide exactly with surface features, general relationships between dip, strike and structural trend can be gleaned. For example, The Forest Scarp intersects the line at roughly right angles, so a true dip might be imaged. The scarp is perpendicular to the crustal stress field, favouring reverse reactivation. The fault is 40 degrees west-dipping in the upper 7.5 km and shallows to ~20 degrees west-dipping below this level, before merging with other faults at ~15 km depth. The average dip in the seismogenic zone would then be ~30 degrees. A second set of faults that trend northeasterly might be expected to be steeper in dip (oblique slip - 40±10deg). However, the one fault with this orientation to cross the EG-1 seismic line (related to the Deakin Scarp) has a true dip of 30 degree in the top 10 km. The eastern Nullarbor hosts scarps which appear to reflect the reactivation of normal faults associated with the formation of the Denman Basin and the rifted margin of the Gawler Craton. These structures are likely to be steep at the surface, and listric at depth (50±10deg). In general, Nullarbor Plain scarps are much longer than would be expected from their scarp height. They are likely to reflect only a few large events on long pre-existing basement faults.

The time frame over which the observed slip has accrued is poorly constrained. Only the Madura scarp extends onto the ca. 2 Ma Roe Plain surface. The scarp splays into two and displaces this surface by approximately 10 m vertical (Clark *et al.*, 2012). Across the Nullarbor Plain surface the scarp averages ~20 m high (max 28 m). The scarp is essentially twice the height on the older surface (see below image). Allowing for some erosion, approximately consistent uplift rates are obtained if deformation accrued across the Nullarbor Plain towards the end of the interval surface from 10 - 5 Ma, when the current stress field was established (e.g. Sandiford *et al.*, 2004). Erosion rates derived from cosmogenic radionuclides are in the order of 4 m/Ma (Stone *et al.*, 1994). In order for relief to be preserved, average long term uplift rates are likely to be commensurate with, or slightly larger than this erosion rate. A minimum long term uplift rate of 4 m/Myr is hence set for relief preservation. As faults might be expected to build relief in a temporally clustered fashion (Clark *et al.*, 2015), uplift rate determination is not simply a matter of adding a rate based upon scarp height/activity period to the erosion rate.

Uplift rates from the Madura Scarp where it crosses the Roe Plain are in the order of 5 m/Myr, which might relate to a frequency of 2-3 large events per million years. In contrast, the longer Mundrabilla and Forrest Scarps show no evidence for fault activity for the last 2 Myr where they intersect the Roe Plain. These scarps are approximately 10 m high and more than 2 Myr old. The scarps might have been as much as ~18 m high when the Roe Plain emerged from the Southern Ocean. Uplift rates may be commensurate with, or greater than, the Madura Scarp. Unfortunately, for most scarps this information is unknown and the displacement across the Nullarbor surface is divided by 5 Myr to arrive at a minimum uplift rate. The greater of this number and 4 m/Myr is recorded as the long term slip rate.



Mundrabilla Scarp (note)

The great length over which the Mundrabilla scarp is straight suggests a steep dip. However, a steep dip is not favourable for reactivation in the current stress field. In addition, an uplift block associated with the Mundrabilla scarp that extends some 10-20 km east of the scarp suggests a more moderate dip. It is possible that a ~25-30 degree east-dipping reverse fault imaged in the seismic is responsible for the current scarp, and that the co-location with the magnetic lineament is a coincidence.

Domain 3 (scarps not developed on the Nullarbor Plain)

The Nullarbor Plain surface preserves a record of basement faulting from which uplift rates may be constrained across Domain 3, as the basement age and architecture is everywhere similar. For relief preservation a minimum long term uplift rate of 4 m/Myr is set. The only paleoseismic investigations within this domain are of the Lort River and Lake Edgar Faults. Three events in the last ca. 60 kyr are recorded for both faults (Clark *et al.*, 2011a; Estrada, 2009). These events were associated with 2.5-3 m of uplift on the moderately dipping (30deg) Lort River Fault and 8 m of uplift on the more steeply dipping (65-70 deg, Roberts *et al.*, 1975) Lake Edgar Fault. It's hard to envisage how the Roberts et al dip could be suitable for reactivation, so assume 50 degrees in bedrock.

It may not be strictly applicable everywhere, but if scarp height divided by 5 Myr obtains an uplift rate greater than the minimum then that is used for the long term uplift rate.

The D'aguillar ranges fault marks the boundary between the Proterozoic Tyenna Block, and the Tertiary Macquarie Graben, a sub-basin of the Sorell Basin. It might therefore be better related to an extended domain than to Domain 3.

Domain 2 (Flinders and Mt Lofty Ranges)

General note. The Mount Lofty and Flinders Ranges of South Australia are bound on the east and the west by reverse faults that thrust Proterozoic and/or Cambrian basement rocks over Quaternary sediment. These faults range from a few tens to almost one hundred kilometres in length, and tend to be spaced significantly less than a fault length apart. In the few instances where the thickness of overthrust sediment can be estimated, total neotectonic throws are in the order of 100-200 m (Sandiford, 2003b). Slip rates on individual faults range from 0.02-0.17 mm/a, with one unconfirmed estimate as high as 0.7 mm/a (Clark & McPherson, 2011; Quigley *et al.*, 2006; Sandiford, 2003b; Sheard & Bowman, 1996). Slip Rates on intramontane faults are largely unknown, but might be expected to be smaller than range bounding faults. In contrast to other parts of southeast Australia, the Mount Lofty/Flinders Ranges has experienced periods of relief generation throughout the Phanerozoic (Dyksterhuis *et al.*, 2005; Muller *et al.*, 2012). Taking into account the intermittent nature of faulting in Australia, it has been suggested that 30-50% of the present-day elevation of the Flinders and Mount Lofty Ranges relative to adjacent piedmonts has developed in the last 5 Ma. Uplifted last interglacial shorelines (ca. 120 ka) along the southern coastline of the Mount Lofty Ranges indicate that deformation is ongoing.

Alma Fault

(Martin & Gerges, 1998)
The NNW-striking structure is an east dipping reverse fault that bounds the western side of the northern Mount Lofty Ranges. Neogene uplift along its length has formed a semi-continuous range up to 100 km long. Surface expression varies along its length, with a maximum observed topographic offset of approximately 40-50 m. Palaeoseismological investigations on the northern section of the fault near Hoyleton (75 km NNE of Adelaide) have revealed evidence for a 1.8 m single event slip across a 35 degree east dipping reverse fault. A caliche layer crossing the fault, presumably relating to airborne carbonate deposition during the last glacial maximum, is unbroken. An underlying unconformity surface, potentially relating to the last interglacial (an OSL sample from this unit returned a saturated age of >125 ka), is also apparently unfaulted. Borehole data from the SARIG website (https://sarig.pir.sa.gov.au/Map) indicates that that approximately 20 m of Tertiary and younger sediments overly bedrock on the western side of the fault near Hamley Bridge. Neotectonic throw might therefore be in the order of 50-70 m.

Length:	93 km
Dip:	Moderately east dipping reverse fault.
Slip Rate:	~25 m/Ma (minimum vertical slip rate), based upon the over thrust of Quaternary alluvium (max 2.7 Ma) by approximately 70 m at a location 5 km north of Hoyleton. Likely to be more due to erosion of hangingwall resulting in an underestimate of throw. Slip rate is less towards Hamley Bridge.

Ardrossan Fault

Fault controlling the SE margin of a Tertiary paleochannel (Drexel & Preiss, 1995). Tertiary sediments correlated to the North Maslin Sand (Middle Eocene) displaced by ~100m east side down (Drexel & Preiss, 1995).

Length: 111 km
Dip: unknown (moderately west dipping reverse fault?).
Slip Rate: >2.5 m/Myr (vertical slip rate), based upon estimate of 100 m of displacement of mid Eocene strata.

Bremer Fault

Bourman and Lindsay (1989) observe that the Morgan limestone has been uplifted >100 m across the Bremer Fault in the last 16 Ma. This accords with more recent investigations (Gibson, 2004; Gibson & Boston, 2008), which use a combination of drill hole data and AEM imagery to show that in the subsurface, the basal unconformity of the Murray Basin (overlain by Eocene sediments) is offset by up to 100 m.

Near to the middle of the scarp, the fault displaces Pliocene barrier dunes (2-3 Ma? (Bowler *et al.*, 2006), Fig. 6), with offset of ~25 m vertically on the tops of the dunes. Further south, a low relief landscape mantled with Quaternary longitudinal dunes is offset by about 10 m (east side up), with the displacement fading to the south. The varying offset of different age units shows that the fault has had a history of geologically recent movement spanning possibly back to the Early Tertiary, and continuing into the Quaternary, with approximate vertical movements of up to 75 m between Eocene and Pliocene, 15 m between Pliocene and the formation of the depositional surface (probably alluvial) on which modern longitudinal dunes have formed, and 10 m since formation of that surface (Gibson & Boston, 2008).

Length: 46 km
Dip: moderately east dipping reverse fault (Gibson et al interpret it as a west dipping normal fault, but it's not clear how this could be in the current stress condition).
Slip Rate: ~8-12.5 m/Myr (vertical slip rate), based upon estimate of 25 m of displacement of Pliocene dune crests.

Burra Fault

The structure aligns with the eastern range front of the southern Flinders Ranges. The fault exposure at World's End Creek is a west-dipping reverse fault with 3.8 m of slip thrusting Neoproterozoic Appila Tillite over Pleistocene Pooraka Formation alluvial sediments (>83 ka). Drillhole 77383, 3 km east of the southern mapped tip of the fault, encountered 52 m of alluvial sediment overlying Neoproterozoic basement. The drill log indicates that the upper 28 m, at least could be Quaternary in age (i.e. red clays). Somewhat tenuous to relate this to the fault though...

Length: 57.2 km
Dip: moderately west dipping reverse fault (36 degrees).
Slip Rate: >10 m/Myr (vertical slip rate), based upon guesstimate of ~30 m of overthrust of Quaternary section.

Coobowie Fault

10 m relief across a surface that may be a Pliocene marine planation surface. Speculative.
Length: 13 km
Dip: unknown (moderately to steeply west dipping reverse fault).
Slip Rate: 2-3 m/Myr (vertical slip rate), based upon guesstimate of 25 m of displacement across a 3-5 Ma surface.

Crystal Brook Fault

The Crystal Brook Fault is one of the major western range bounding faults of the southern Flinders Ranges. Approximately 250 m of relief at maximum offset across the fault (between Napperby and

Telowie). Near Baroota Reservoir, a drillhole (176532) at the footwall intersected ~40 m of Hindmarsh Clay (did not intersect lower section). This provides a minimum estimate of the overthrust Quaternary section.

Length: 64 km
Dip: steeply east dipping reverse fault.
Slip Rate: ~50 m/Myr (vertical slip rate), based upon guesstimate of 40 m of overthrust of 0.78 Ma Hindmarsh Clay.

Eden-Burnside Fault
The Eden-Burnside Fault is one of the major western range bounding faults of the Mt Lofty Ranges. It forms the main topographic expression of the western side of the Adelaide Hills, and defines the northwestern edge of the Eden Fault Block and the associated Noarlunga Embayment (Fairburn, 2000). The only suspected exposure of the fault is in a quarry at Highbury in Adelaide's eastern suburbs (Bourman *et al.*, 2010; Fairburn, 2004), where a steep westerly dipping contact separates Eocene Maslin Sand from Adelaidean bedrock. Fairburn (2004) suggests that, while the fault has deformed the Eocene Maslin Sand, Pleistocene deposits such as the Kurrajong Formation are undeformed, thus implying a mid-Pleistocene limit for significant activity on the structure. Bourman et al. (1999) note a 4 m elevation for the last interglacial shoreline at Port Stanvac, in the hanging wall of the fault. This suggests at least one uplift event in the last *ca.* 125 ka, which might relate to a short scarp (~10 km) evident in LiDAR DEM data which displaces the footwall fan of the Eden-Burnside fault between Kensington Park and Colonel Light Gardens. Long term slip rate is unknown. A coarse clastic component within the Pleistocene Kurrajong Formation led Fairburn (2004) to suggest that a major relief-building event occurred on the fault in the Plio-Pleistocene.

Length: 53 km
Dip: steeply east dipping reverse fault.
Slip Rate: >16 m/Myr (vertical slip rate), based upon 4 m level of the last interglacial shoreline (*ca.* 125 ka). No reason to believe that the long term slip rate is not similar to the Willunga Fault (50-80 m/Myr), given similar total displacement.

Encounter Bay Fault
Shell beds containing articulated Anadara shells are reported from 10 m above sea level (Watsons Gap: GDA94/MGA54 288055mE/6065080mN) and 6 m above sea level (Adare St: GDA94/MGA54 285199mE/6064179mN) at Victor harbour, whereas equivalent shell beds occur at 1 m below sea level near Hindmarsh Island Bridge (GDA94/MGA54 299001mE/6068373mN) (see also Bourman *et al.*, 1999). Though the inferred trace of the Encounter Bay Fault, based upon topographic relief, is several hundred metres west of the 10 m uplift site, it is thought by Bob Bourman that the apparent uplift might relate to the fault.

Length: 79 km
Dip: Moderately to steeply northwest dipping reverse fault.
Slip Rate: ~32 - 64 m/Ma (vertical slip rate), based upon 4-8 m of uplift of the last interglacial shoreline (*ca.* 125 ka).

Meadows Williamstown (Kitchener) Fault
The Meadows-Williamstown (also known as the Kitchener) Fault is a major crustal structure separating the Kanmantoo Trough to the east, from the Neoproterozoic Adelaidean succession to the west (Drexel *et al.*, 1993). The fault is mapped from north of Tarlee to the latitude of Sellicks Beach, a distance of over 130 km. Quaternary activity is only documented from the northern part of the fault. It bounds the eastern compartment of the Tertiary Barossa Basin, where late Miocene to Pliocene Rowland Flat sands are overthrust by ~80 m (Drexel *et al.*, 1993) (Fig 10.18).

Approximately 10 m of vertical displacement across the post-Tertiary section is observed in drainage at Bethel. Further south, the fault bounds the eastern margin of the Tertiary Meadows Basin. Marine taxa of Late Miocene to Pliocene age were described from Meadows Bore 1 from this basin (Liliana Stoian, DMITRE, AESC2014 abstract 04EV-P05). Maximum Pliocene flooding level in the adjacent Murray Basin was ~70 masl (Brown & Stephenson, 1991), suggesting ~250 m of uplift in the last 10-5 Ma (borehole collar is at elevation 319 m and marine taxa are described form 20 m depth and belonging to 20-60 m water depth facies). It is not clear by how much basement is overthrust over these Neogene sediments, so a rate on the Meadows Fault cannot at present be estimated. The uplift of the basin likely occurred on the hanging wall block of the Willunga Fault.

Length:	55 km (38 km) – length from northern rupture extent to southern extent of Tertiary Barossa Basin (length of Quaternary rupture).
Dip:	Moderately to steeply east dipping reverse fault.
Slip Rate:	~15 m/Ma (vertical slip rate) based upon 80 m displacement across the Pliocene Rowland Flat Sands.

Milendella Fault

The Milendella Fault is one of the major range-bounding faults on the eastern side of the Mt. Lofty Ranges, SA. It is approximately 55 km long and dips to the west, beneath the ranges. It is estimated to have a total post-Miocene throw of 60-90 m (Mills, 1965). At Cambrai, the Quaternary sequence is reported to have a thickness ~30 m (Mills, 1965). The exposure shows that the fault places basement above the entire Quaternary sequence(Bourman & Lindsay, 1989), implying a minimum displacement over the last ~1 million years of at least 30 m (Sandiford, 2003b).

Length:	55 km
Dip:	Moderately west dipping reverse fault.
Slip Rate:	>30 m/Myr (vertical slip rate), based upon Sandiford (2003b)

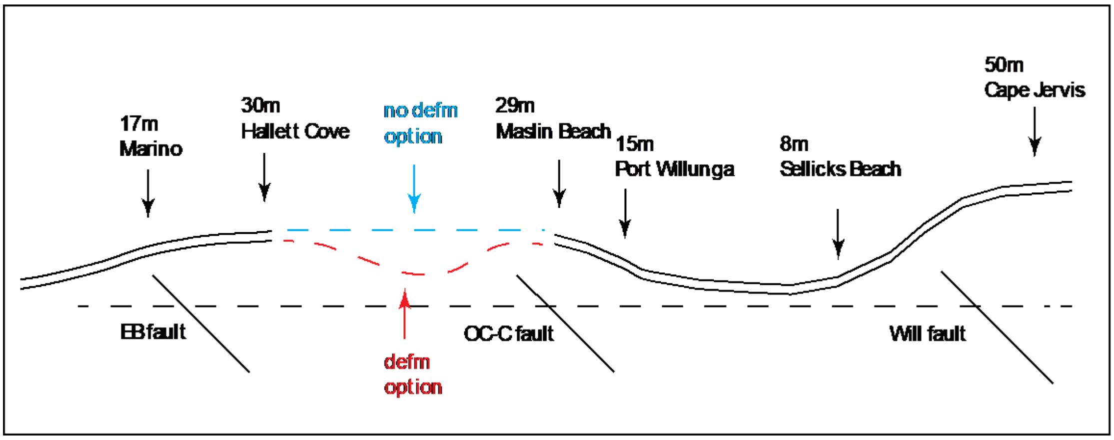
Morgan Fault

This fault was important in damming the Murray River to form Lake Bungunnia (McLaren *et al.*, 2011; Miranda *et al.*, 2009). 20-25m vertical displacement across Pliocene ridge crests (<5 Ma). 5 m across Quaternary strandplain (<2.7 Ma).

Length:	172 km
Dip:	Moderately west dipping reverse fault.
Slip Rate:	>1.9-5 m/Myr (vertical slip rate), based upon displaced Murray Basin strandlines.

Ochre Cove - Clarendon Fault

The structure forms the southern bounding margin of the Noarlunga Embayment, and is associated with a prominent escarpment. Gibson (1963) noted that the Ochre Cove-Clarendon Fault displays an east-dipping reverse habit where intersected by tunnelling operations during the construction of the Clarendon-Happy Valley pipeline. At the southern end of Moana Beach, Stuart (1969) identifies monoclinal flexing and drag as the cause of deformation in Late Eocene-Oligocene successions, which also exhibit depositional thinning of the sequence. The fault is reported to have been locked throughout the Quaternary (Bourman *et al.*, 1999), supported by a similar elevation of 29-30 m asl of Burnham Limestone on the hangingwall anticline crest of both the Eden-Burnside and Ochre Cove – Clarendon faults. However, differences in elevation between Burnham limestone (1.7 Ma) near the crest of the hangingwall anticline (29m @Maslin Beach), and on the hangingwall anticline backlimb (15 m @Port Willunga) potentially indicate post 1.7 Ma displacement on the fault.



Fairburn (2000) map Ochre Cove Formation sediments crossing the scarp at two locations. Topographic profiles indicate 30 – 50 m of elevation difference across the fault on this <1.1 Ma (Pillans & Bourman, 2001) unit. The unit is ~ 8 m thick, so a conservative upper bound displacement is 40 m.

Length:	33 km
Dip:	Moderately to steeply east dipping reverse fault.
Slip Rate:	~36 m/Ma (max vertical slip rate) based upon 30-40 m of uplift of Ochre Cove formation sediments.

Owen Fault
The Owen fault scarp displaces near surface clayey sediment (assume Hindmarsh Clay (~0.78 Ma)) by up to 50 m in the north, but closer to 25 m at the southern end of the scarp, where it might transfer deformation to, or link into, the Redbanks Fault.

Length:	24.1 km
Dip:	Moderately to steeply east dipping reverse fault.
Slip Rate:	~ 64 m/Ma (vertical slip rate), based upon 50 m of displacement of assumed Hindmarsh Clay.

Palmer Fault
Eastern range bounding fault of the Mt Lofty Ranges. Slightly offset to the Milendella Fault to the north. No specific information on fault displacement. However, near to the southern end of the scarp (west of Murray Bridge), the fault displaces Pliocene barrier dunes (2-3 Ma? (Bowler *et al.*, 2006), Fig. 6), with offset of ~60 m vertically on the tops of the dunes. These are the same dunes offset by the Bremer Fault further west.

Length:	42 km
Dip:	unknown (Moderately to steeply west dipping reverse fault).
Slip Rate:	20-30 m/Ma (vertical slip rate) based upon 60 m of displacement of Pliocene dunes.

Para Fault
The fault is associated with a scarp is 43 km long and up to 175 m high. The fault splays south of the Adelaide CBD (Sheard & Bowman, 1996), and is suggested to extend offshore to the SW (Cooper, 1985). Extensive drilling data obtained to define aquifers suggests that the base of the upper Pliocene to Pleistocene (5-3 Ma) Hallett Cove Sandstone has been displaced by up to 160 m vertically, and the base of the Upper Quaternary Hindmarsh Clay (<0.78 Ma) has been vertically displaced by up to ~120 m (Fairburn, 2004; Gerges, 2006; Sheard & Bowman, 1996). This implies non-regular slip on the fault. Selby & Lindsay (1982) attribute much of the deformation on the structure to the Early-Mid Pleistocene. The preliminary results of a trenching investigation by

Geoscience Australia across the fault trace near Gawler indicate a maximum of 0.5 m of vertical displacement of sediments inferred to be of last interglacial age (Pooraka formation).

Length:	43 km
Dip:	Moderately to steeply east dipping reverse fault.
Slip Rate:	~32 – 53 (150) m/Ma (vertical slip rate). Range based upon 160 m of displacement of Hallett Cove Sandstone (long term slip rate). Value in brackets based upon 120 m of displacement of the Hindmarsh Clay (active period slip rate?).

Redbanks Fault

The Redbanks fault scarp displaces Hindmarsh Clay (~0.78 Ma) at the surface by up to 25 m in the north, but closer to 10 m at the southern end of the scarp.

Length:	47 km
Dip:	Moderately to steeply east dipping reverse fault.
Slip Rate:	~ 32 m/Ma (vertical slip rate), based upon 25 m of displacement of Hindmarsh Clay.

Sandergrove Fault

Approximately 60 m of displacement across bedrock (Gibson, 2004). Associated with a 15 m high scarp developed in Quaternary sediment. AEM and drillholle information suggests two periods of activity, with Eocone –Miocene limestone deposited, faulted then eroded, then Quaternary deposited on top then faulted (Gibson, 2004; Gibson & Boston, 2008). The same data shows ~45 m displacement across the base of the Quaternary section.

Length:	43 km
Dip:	Moderately to steeply east dipping reverse fault.
Slip Rate:	~15 m/Ma (vertical slip rate) based upon 45 m displacement across the base of Quaternary sediment (Gibson & Boston, 2008) (figure 19).

Willunga Fault

The Willunga Fault is a steeply south-east dipping reverse fault, and one of the major western range-bounding faults of the southern Mt Lofty Ranges. A prominent wave cut bench of last interglacial age (ca. 125 ka) is incised into this sequence, and occurs at ~4-5 m above present sea level (May & Bourman, 1984; Sandiford, 2003b). Approximately 12 km further south at Normanville, along strike from the zone of greatest uplift in the hanging wall of the fault, subtidal sediments of last interglacial age are reported to occur up to 12 m above current sea level (Bourman *et al.*, 1999), suggesting a time averaged vertical slip rate of ~80 m/Myr. This estimate is independently corroborated by reported elevation differences of ~130 m in the Lower Pleistocene (ca 1.7 Ma) Burnham Limestone along the eastern margin of the St Vincents Basin (Belperio, 1995; Bourman *et al.*, 1999; Bourman *et al.*, 1997; Sandiford, 2003b). The differential elevation of the Port Willunga Formation between the Myponga Basin and the St Vincents Basin suggests a post-Early Miocene displacement of ~240 m (Tokarev *et al.*, 1999).

Length:	55 km
Dip:	Steeply southeast dipping reverse fault.
Slip Rate:	~80 m/Ma (maximum vertical slip rate), based upon displaced geologic units ranging in age from 0.125-1.7 Ma. Sandiford (2003b) puts a lower bound of 50 m/Myr on the fault.

Worlds End Fault

There is no borehole data to constrain the thickness of overthrust Quaternary sediment on this fault at the trench location. Boreholes in Worlds End Creek, 5 km south and between 700-1200m east of the fault line (6630-244; 6730-363), intersected 15 m of "gravelly red clay" which may be equated to the Quaternary section seen at the trench location. This section, in both boreholes, overlies 7-9 m of "yellow sandstone", which in turn overlies creek gravels to 25.6 m. The presence of river gravels beneath the yellow sandstone suggest that the sandstone is part of the Quaternary section, rather than a sandy facies of the Miocene Mannum Limestone.

Length:	30 km
Dip:	moderately west dipping reverse fault (48 degrees).
Slip Rate:	~10-15 m/Myr (vertical slip rate), based upon guesstimate of 30 m of overthrust of Quaternary section.

Yorketown scarp

25 m relief across a surface that may be a Pliocene marine planation surface. Speculative.

Length:	23 km
Dip:	unknown (moderately to steeply east dipping reverse fault).
Slip Rate:	5-8 m/Myr (vertical slip rate), based upon guesstimate of 25 m of displacement across a 3-5 Ma surface.

Domain 4 Faults (not in the eastern highlands)

Constraint on the uplift rates of faults in the western parts of neotectonic Domain 4 is provided by the Pliocene strandline system of the Murray Basin. These <6 Ma strandlines (McLaren et al.) are preserved on the crests of folds, suggesting very low erosion rates (<<5m/Myr?). Bishop (1985) suggests Tertiary denudation rates of the Murray-Darling Basin have been in the order of 1-3 mm/Myr. The highpoint of 3m/Myr has been used for a threshold uplift rate for relief preservation.

The Iona, Neckarboo and Danyo ridges overly ‘steeply’ west dipping reverse faults. Sandiford (2003b) estimates 10-15 m/Myr slip rates (~5-10 m/Myr uplift rates). Given the faults are perpendicular to Shmax it seems unlikely that they dip ‘steeply’ (40±10 degrees seems reasonable).

The northeast trending faults in the SW of the domain are associated with greater neotectonic uplift than the more northerly trending faults of the Lachlan Fold Belt further east and south. Relative orientation compared to the NW-SE trending Shmax may control activity rates. For example, the slightly east of north striking Cadell Fault is associated with greater surface expression (and subsurface expression) than the slightly west of north trending Avonmore fault. The WNW trending Whitelaw and Sebastian faults are associated with yet more subtle expression in the Murray Basin sediments. It is reasonable to expect that these misaligned faults may be steeper (50±10 degrees)

Surface displacements are divided by 5 Myr to arrive at an uplift rate. This number reflects the establishment age for the current stress field and roughly the age of the older Murray Basin surfaces.

Domain 4 Faults (eastern highlands)

The faults of the eastern highlands are often associated with significant topographic expression – up to several hundred metres. In terms of their activity rates they are mostly poorly characterised. The main concentration of faults with the greatest relief occurs where the Shmax is perpendicular.

Snowy Hydro records indicate significant thicknesses of alluvial sediments are overthrust by basement rocks on both the Tawonga and Khancoban-Yellow Bog Faults. Both Fault are also associated with significant changes in plateau height elevation, ~200 m in the case of the Tawonga

Fault. While the age of the overthrust sediments is not known, a range of ages from Quaternary to Eocene is possible. Several other faults impound lakes or are associated with gorge sections, sometimes bearing strath terraces.

Recent work on the Lake George fault indicates that 250 m of uplift has occurred on this fault in the last 4 Myr. Average long term uplift rates are in the order of 60 m/Myr, with active period slip rates being ~10 x this rate. By analogy with the Lake George Fault, uplift rates on similarly oriented faults are conservatively taken as the scarp height divided by 5 Myr.

Fault dips at seismogenic depth are not known. Surface dips tend to be shallow to moderate, say 40±10. A few oblique faults are also associated with relief, but might be expected to have a significant lateral component to motion (e.g. Dunns Fault, Morass Creek Fault, Kiewa Thrust).

Domain 5 (Gippsland and east of Melbourne)

General note. The neotectonic faults within the onshore Gippland Basin are typically normal faults reactivated in compression. In most cases fault dip at depth is not known, but can be assumed to be in the range of 50±10 degrees, given their genesis as normal faults. Faults at the surface may be significantly steeper (reflecting listric geometry of the parent fault) or shallower (reflecting the development of footwall shortcut thrusts during reactivation) in dip. Faults dip beneath related topography (e.g. the Narracan Block), and are predominently associated with fault propagation folds (monoclines and hangingwall anticlines and domes) rather than discrete fault displacements at the surface. The regional stress direction is ~SE-NW (Sandiford *et al.*, 2004). This suggests that the major basin bounding faults (e.g. Rosedale Fault) may accommodate a significant component of strike slip motion, whereas intrabasin faults (e.g. Morwell), and the NE set in the Paleozoic basement (e.g. Waratah Fault) may be closer to pure dip slip reactivation. These faults may be shallower in dip than the more easterly trending basin faults (~40±10 degrees).

The age of onset of uplift, as evidenced by the development of a regionally significant unconformity surface, is constrained to the interval between 4-8 Ma in the Gippsland Basin (Dickinson *et al.*, 2002; Sandiford *et al.*, 2004). A regionally extensive sheet of alluvium, known as the Haunted Hills Formation (HHF), overlies the unconformity surface. This alluvium is related to renewed erosion of the rejuvinated landscape. The basal parts of the HHF at several location contain pollen of Myrtaceidites lipsis, which constrains deposition above the unconformity to the Pliocene (<4 Ma: http://www.ga.gov.au/corporate_data/76687/Chart_40_Gippsland_Basin.pdf). Several Cosmogenic Radionuclide burial/exposure age determinations ranging from ~0.5-2.5 Ma) on HHF gravels (Clark *et al.*, 2011c; Gardner *et al.*, 2009; McPherson *et al.*, 2009) indicate that the unit is diachrononous.

Long-term slip rate estimates for the Gippsland Basin are subject to the same uncertainty as those in the Otway Basin (Paine *et al.*, 2004; Sandiford, 2003a), stemming from apparent episodic pulses of regional deformation (Clark *et al.*, 2012; Quigley *et al.*, 2010a). In the eastern onshore Gippsland Basin an angular unconformity between the Jemmy's Point formation (Pliocene) and the overlying Haunted Hill Formation (Late Pliocene to Quaternary) implies a significant pulse of post-3 Ma deformation (Holdgate *et al.*, 2003). Seismic reflection evidence combined with palynological age constraint suggests that a major episode of deformation involving folding ceased at 1.0 Ma in the offshore Gippsland Basin while continuing onshore until approximately 0.2–0.25 Ma (Holdgate *et al.*, 2003).

Bass/Almurta Fault
Northern bounding fault of the Narracan Block. Geomophically continuous with the Yarragon monocline to the east. Lakes Oil seismic section GKG05-08 shows Strzelecki Group sedimentary rocks are folded in the hanging wall of the fault with an amplitude commensurate with the surface

expression of the scarp of ~150-200 m. No Haunted Hills Formation (HHF) occurs on the upthrown side of the fault. Jorgensen (2004) state a vertical slippage rate of 10 m/Ma. They do not support this number.

Length: 57.6 km
Dip: Moderately to steeply south dipping reverse-oblique fault (50±10 degrees).
Slip Rate: ~10 - 50 m/Ma (maximum vertical slip rate), based upon the range between Jorgensen's estimate and 200 m of uplift in the last ~4-8 Ma.

Beaumaris Monocline
Small intrabasin fault within the Sorrento Graben.

Length: 12.7 km (as mapped – likely to be longer).
Dip: Unknown (likely to be a moderately northwest dipping reverse fault 40±10 degrees).
Slip Rate: ~4-8 m/Myr (minimum), based upon a 35 m amplitude monocline developed in 5-8 Ma Black Rock Sandstone (Mallett & Holdgate, 1985). Could deform younger units by this amount.

Budgeree Fault
Northern bounding fault of the Balook Block. Geomophically continuous with the Rosedale Fault to the east.

Length: 25 km (likely links into the Rosedale Fault system)
Dip: likely to be moderately to steeply southeast dipping (50±10 degrees).
Slip Rate: ~20 m/Myr (maximum vertical slip rate) from Jorgensen (2004). I think they made this up. Relief is larger than the geomorphically contiguous Rosedale Fault (300-400m), suggesting that values of **50-80 m/Ma** might not be unreasonable. No HFF or Thorpdale Volcanics exposed on upthrown side - only Cretaceous Strzelecki Group rocks.

Clarkefield Scarp
Length: 23.4 km
Dip: Unknown (likely to be a moderately west dipping reverse fault, 40±10 degrees).
Slip Rate: ~6 m/Ma (maximum), based upon a maximum 10 m high scarp developed in Newer Volcanics flows dated at ~1.66 Ma (Gibson, 2007).

Carrajung Monocline
Northern bounding fault of the Balook Block, offset from the Budgeree Fault by the Balook Fault, but part of the same system. Strzelecki Group rocks exposed on the upthrown side. No HHF on the upthrown side. Approximately 400 m of relief across Older Volcanics (~55 Ma Carrajung Volcanics?) between Mt Tassie and Calignee. There may be another unmapped structure contributing to this elevation difference as the monocline itself is associated with a ~200 m step in Strzelecki Gp rocks (assumed to be commensurate with post 4-8 Ma deformation.

Length: 22.7 km
Dip: Unknown (likely moderately to steeply S dipping 50±10 degrees).
Slip Rate: >7-25 m/Myr (minimum vertical slip rate), based upon approximately 400 m of vertical displacement of the Carrajung Volcanics (lower bound), and 200 m of displacement of the Strzelecki Gp (assuming 4 - 8 Ma and younger deformation). Jorgensen (2004) states 5 m/Myr slip rate. Could be substantially higher (See Budgeree Fault). Likely influenced by ruptures on the Budgeree and Yarram Faults.

Darnum Monocline

Splays off the Bass/Almurta Fault. HHF uplifted by ~60-70 m across the monocline.

Length:	25.3 km (as mapped).
Dip:	Unknown (likely moderately northwest dipping reverse-oblique fault 40±10 degrees).
Slip Rate:	~8-18 m/Myr (minimum vertical slip rate), based upon ~60-70 m of uplift across 4-8 Ma HHF. HHF may be as young as ca. 0.5 Ma, based upon cosmo results in the Latrobe valley to the east (Clark *et al.*, 2011c; McPherson *et al.*, 2009), so slip rate could be much higher.

Darriman Monocline

Roughly E-W striking structure displacing Pliocene Haunted Hills Formation fluvial deposits (~70 m+) and Pleistocene dune and alluvial deposits (30 m vertical) nearer the coast to the east (VandenBerg, 1997). Continues offshore to the east and is a notable boundary fault to the offshore Gippsland Basin.

Length:	34.2 km
Dip:	Unknown (likely to be a moderately to steeply north dipping reverse fault, 50±10 degrees).
Slip Rate:	~28-38 m/Myr (minimum vertical slip rate), based upon a displacement across 1.8-2.5 Ma HHF ages from the southern side of the Balook Block as per Gardner et al. (2009). Could be less if HHF is 4-8 Ma, and 2 x this rate if displaced Pleistocene deposits are younger than assumed.

Doomburrin Fault

Isolated remnant of HHF near Fish Creek uplifted 80 m across this fault relative to the downthrown side to the NW. Nearby age estimates of the HHF are 1.9-2.5 Ma (Gardner *et al.*, 2009).

Length:	28.1 km (as mapped, but likely to be much longer – goes offshore and likely extends to the SW beyond the mapped extent ~15 km)
Dip:	unknown (likely moderately to steeply SE dipping, 50±10 degrees).
Slip Rate:	32 – 42 m/Myr (maximum vertical slip rate), based upon approximately 80 m of vertical displacement of 1.9-2.5 Ma HHF. Could be half this is HHF is older.

Geliondale Monocline

Gelliondale Block, bounded on the south by the Gelliondale/Toora Fault, uplifted by ~200 m over the last 4-8 Ma (Webb *et al.*, 2011).

Length:	22.3 km (plus perhaps the length of the Toora Fault).
Dip:	Unknown (likely to be a moderately to steeply north dipping reverse-oblique fault, 50±10 degrees).
Slip Rate:	~25-50 m/Myr (maximum vertical slip rate), based upon approximately 200 m of uplift in the last 4-8 Ma (Webb *et al.*, 2011). Could be twice this rate if HHF is ~ 2 Ma, as suggested by results from the nearby Waratah Fault (Gardner *et al.*, 2009).

Haunted Hills fault

The Haunted Hills Fault is mapped as a N-S oriented W-dipping structure in Lower Cretaceous Strzelecki Group sedimentary rocks (Beavis 1959; Barton 1971; VandenBerg 1971, 1997) with prominent landscape expression in the form of a 50-70 m high monoclinal ridge developed in HHF. Dickinson *et al.* (2002) present evidence to suggest that the monocline underlain at depth by a 70 degree west dipping reverse fault (their Figure 15). While this dip seems too steep to be suitable for reactivation, the fault perhaps links into the Morwell Fault at depth. Guy Holdgate suggested (pers comm, 2011) that a ~1m step in the landscape existed where the fault intersected in drilling projected to the surface.

Length: 19 km
Dip: 70 degrees west.
Slip Rate: ~17.5 m/Myr (maximum vertical slip rate), based upon approximately 70 m of uplift in the last 4 Ma (estimate for basal HHF from Dickinson (2002)).

Heath Hill Fault
Eastern bounding fault of Western Port Bay. 150 m vertical displacement across Eocene to Miocene Older Volcanics (http://vro.depi.vic.gov.au/dpi/vro/portregn.nsf/pages/port_lf_sig_sites_99). Baxter Formation (late Miocene to Pliocene) is also displaced across the fault. Warragul 250k sheet shows HHF being uplifted across the fault (~60-100 m).

Length: 50.3 km
Dip: Unknown (likely to be a moderately southeast dipping reverse fault, 40±10 degrees).
Slip Rate: ~15-25 m/Myr (minimum), based upon HHF being <4 Ma, and Baxter Formation being folded by the same amount as Older Volcanics. Could be significantly lower.

Kongwak Monocline
Southern bounding fault of the Narracan Block. Shown in Holdgate (2003) as a steeply north-dipping reverse fault (reactivated normal fault). East of the mapped part of the fault, near Leongatha, ca. 39.9 Ma volcanics are displaced by ~100m vertical. No HHF on the top. 100-150 m of maximum relief.

Length: 32.8 km (as mapped). Appears in SRTM DEM to be continuous with the Hallston Fault, which would extend the Kongwak fault another ~7 km, bringing the total potential rupture length to ~40 km.
Dip: Unknown (likely steeply north-dipping reverse-oblique fault, 50±10 degrees).
Slip Rate: 10-50 m/Myr (maximum vertical slip rate), based upon analogy with the Bass/Almurta Fault on the northern side of the Narracan Block.

Koorooman Fault
Western bounding fault of an uplifted block of Strzelecki Group rocks between the Balook and Narracan Blocks. Approximately 60 m of relief across the block relative to neighbouring lowlands. Southern extension of the Morwell Fault forms the eastern Margin of the Block, requiring a significant neotectonic slip rate on the Tarwin Fault. No good displacement-time indicators.

Length: 31.8 km
Dip: unknown (likely moderately to steeply north, 40±10 degrees).
Slip Rate: 7.5-15 m/Myr (min) based upon 60 m displacement in the last 4-8 Ma.

Morwell Monocline
Length: 29.7 km, up to 44.7 km possible. Well defined topographic scarp over 29.7 km transitions to the SW into a lineament (valley) which links into the Tarwin Fault.
Dip: Unknown (likely to be a moderately to steeply west dipping reverse-oblique fault, 50±10 degrees).
Slip Rate: ~43-55 m/Myr (average vertical slip rate), based upon an average ~50 m high scarp developed in Haunted Hills Formation gravels obtaining a cosmogenic radionuclide exposure age of ~1.2 Ma (Clark *et al.*, 2011c). Max scarp height is locally ~65 m (~55 m/Myr uplift rate).

Napier Monocline

Short splay that links the Yarram and Darrimun Faults. Likely to rupture influenced by these faults. 50-100m of relief developed in HHF, though HHF not exposed on the downthrown side.

Length:	12 km.
Dip:	Unknown (likely moderately to steeply northwest, 50±10 degrees).
Slip Rate:	~25-50 m/Myr (maximum vertical slip rate) depending upon local age of HHF – 2-4 Ma (Dickinson *et al.*, 2002; Gardner *et al.*, 2009).

Rosedale Monocline

Northern bounding fault of the Balook Block (Strzelecki Ranges). The Baragwanath anticline (e.g. Holdgate *et al.*, 2003) is here considered to be related to deformation on the fault underlying the Rosedale Monocline, and so is not considered separately.

Length:	77.8 km (onshore portion associated with a prominent scarp – continues offshore to the east for at least twice this distance to the continental shelf).
Dip:	Moderately to steeply south (as imaged in offshore petroleum seismic sections).
Slip Rate:	~50-80 m/Myr (maximum vertical slip rate), calculated for the near offshore in the interval 1.5-0.25 Ma by (Holdgate *et al.*, 2003). Equates to <105 m/Myr on a 50 deg dipping fault, or ~88 m/My slip rate if the uplift is averaged over the last 1.5 Myr.

Selwyn Fault

Length:	97 km
Dip:	Unknown. Uplifted beach gravels on the eastern side of the fault, and east side-up displacement of the Pleistocene Bridgewater Formation, suggest that the currently active fault is east dipping (40±10 degrees).
Slip Rate:	~50 m/Myr (Janssen, 2001), based upon displacement of the Pleistocene Bridgewater Formation (Mallett & Holdgate, 1985).

Snake Ridge Monocline

Topographic evidence suggests the fault continues further west than its mapped position (250k geology) across the Latrobe River to at least Flynn Creek. It is possible that the underlying fault also continues across the northern edge of the Loy Yang Dome.

Length:	36.8 km, up to ~50 km possible.
Dip:	Unknown. Likely to be moderately to steeply SSE, 50±10 degrees.
Slip Rate:	~50-95 m/Myr (average vertical slip rate), based upon an average ~30 m high scarp developed in Haunted Hills Formation gravels obtaining a cosmogenic radionuclide exposure age of ~0.53-0.63 Ma (Clark *et al.*, 2011c). Max scarp height is locally ~60 m (~95 m/Myr uplift rates).

Tap Tap Fault – northern side of the Gelliondale Block, uplifted 200 m in 4-8 Ma. Not clear how to separate out a slip rate for this 13.6 km fault, which locally bounds the northern margin of the Gelliondale Block.

Tarwin Fault

Southern bounding fault of an uplifted block of Strzelecki Group rocks between the Balook and Narracan Blocks. Approximately 100 m of relief across the block relative to neighbouring lowlands. Southern extension of the Morwell Fault forms the eastern Margin of the Block, requiring a significant neotectonic slip rate on the Tarwin Fault. No good displacement-time indicators.

Length: 31.8 km
Dip: unknown (likely moderately to steeply north).
Slip Rate: 12.5-25 m/Myr (min) based upon 100 m displacement in the last 4-8 Ma.

Toora Fault
Geomophically continuous with the Gelliondale Monocline.

Length: 14.2 km
Dip: unknown (likely steeply north).
Slip Rate: see Gelliondale Monocline.

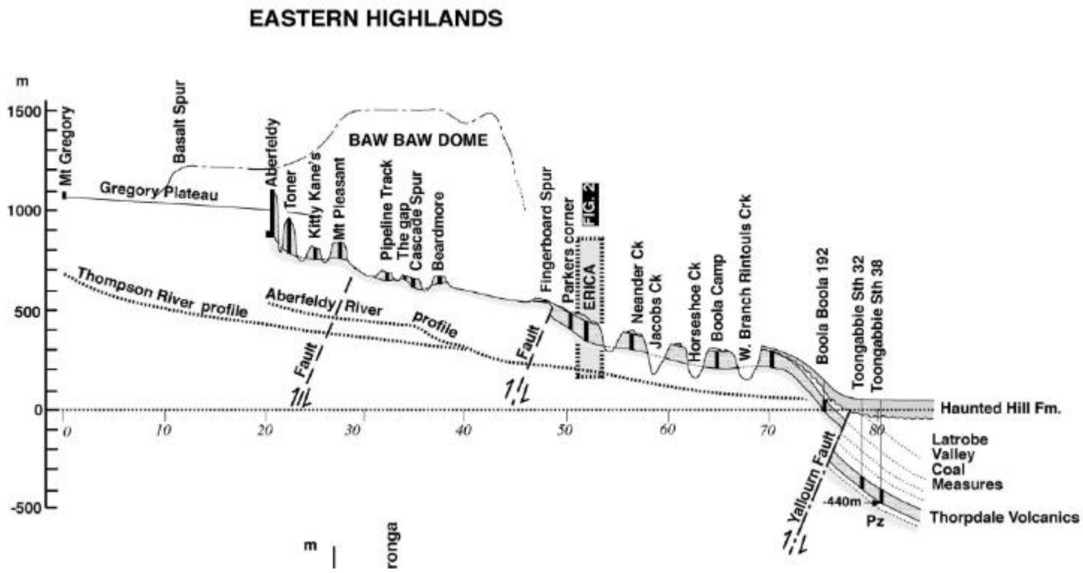
Waratah Fault
Length: 37.2 km
Dip: moderately to steeply northwest (40±10 degrees)
Slip Rate: ~10-40 m/Myr (maximum vertical slip rate), based upon uplifted marine terraces ranging in age from 125 ka to 1-2 Ma (Gardner *et al.*, 2009).

Wonwron Monocline
Topographically subdued (no Strzelecki group at the surface) eastern extension of the Balook Block – links into the Yarram Monocline. Up to 50 – 80 m of vertical offset across the HHF, decreasing to the east. Gardner et al. (2009) obtain cosmogenic radionuclide ages for the HHF on the southern side of the Balook Block further west (near Waratah Bay) of ~ 2 Ma.

Length: 29.5 km
Dip: Unknown (likely to be a moderately north dipping reverse fault).
Slip Rate: ~20 – 40 m/Myr m/Ma (maximum vertical slip rate), based upon a maximum 80 m high scarp developed in HHF ranging from 2-4 Ma.

Yallourn Monocline
Main fault separating the Gippsland Basin from the eastern highlands. The base of the Haunted Hills Formation gravels is seen to be vertically displaced by ~30 m across the Yallourn Monocline near to where it links into the Haunted Hills Fault (Dickinson *et al.*, 2002, Figure 14). The age of the upper part of the folded Haunted Hills Formation is not known from this site. The mid to basal parts are Pliocene (<4 Ma), based upon microfauna (Dickinson *et al.*, 2002). Displacement increases to the east. Haunted Hills Formation gravels at Matthews Quarry are vertically displaced by up to 240 m relative to Tyers. A low-confidence cosmogenic radionuclide burial age of >0.86 Ma was obtained on the base of these sediments in the Matthews Quarry (GA unpublished data). Remnants of Haunted Hills Formation gravels occur up to ~400 m above their level within the Latrobe Valley (Holdgate *et al.*, 2011).

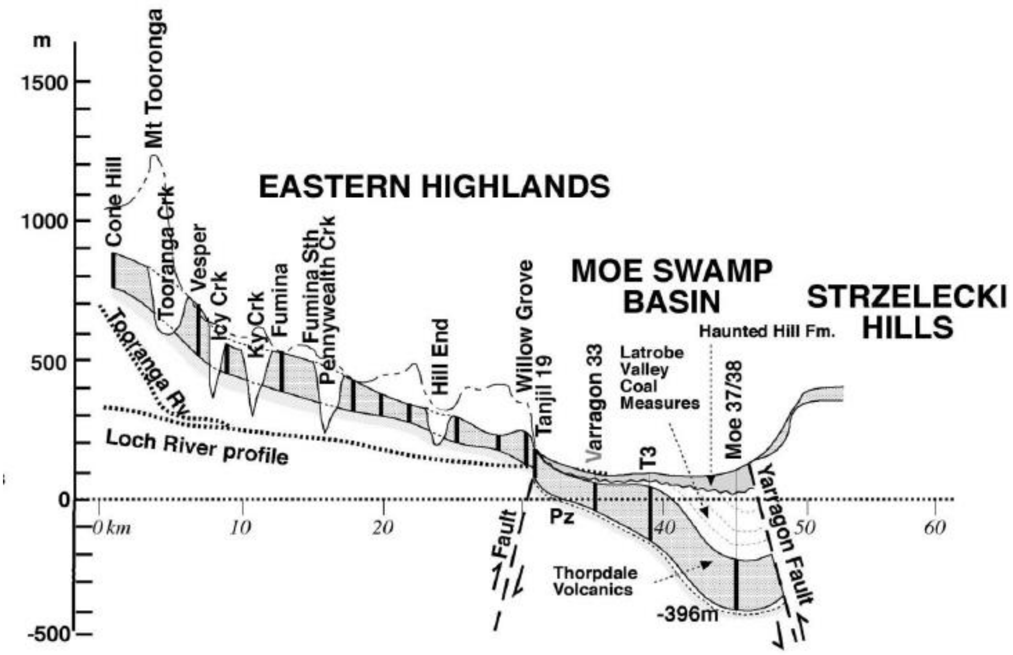
Length: 63.6 km
Dip: mainly a monoclinal fold, but expect the underlying fault dips moderately to the north from prior exposure of synthetic faults in coal workings (Gloe, 1960). 40±10 degrees
Slip Rate: ~60-100 m/Myr (vertical slip rate), assuming a maximum HHF unit age of 4 Ma (after Dickinson *et al.*, 2002). The maximum vertical displacement of ~400m is adopted, together with the 4 Ma age, a rate of 100 m/Myr is obtained. A perhaps unrealistic rate of 280 m/Myr is obtained using the CRN age at Matthews Quarry (Clark et al. 2011).



Yarragon Monocline

19-26 Ma Thorpdale volcanics have been displaced by ~700m across the fault (including a significant folding component), which forms the northern bounding fault of the Narracan Block. There is no Haunted Hills Formation on the uplifted southern side of this fault (this unit has been removed by erosion). By analogy with the Yallourn Monocline, where the displacement of the Haunted hills Formation closely tracks the folding in the hangingwall anticline of the fault, the post-4Ma displacement might be as large as 300-350 m.

Length:	32.4 km (as mapped). Appears in SRTM DEM to be continuous with the Bass/Almurta Fault system
Dip:	Unknown (depicted as a moderately to steeply south dipping reverse fault in Holdgate et al. (2011)). 50±10 degrees
Slip Rate:	~25 – 90 m/Myr (vertical slip rate), minimum based upon 700 m of uplift of Thorpdale volcanics. Maximum based upon ~300-350 m of uplift since 4-8 Ma (cf. Dickinson *et al.*, 2002).



Yarram Monocline
Southern bounding fault of the Balook Block. Approximately 400-450 m of relief compared to the adjacent coastal plane.

Length:	53 km
Dip:	Unknown (likely moderately to steeply NNW dipping, 50±10 degrees).
Slip Rate:	>56-112 m/Myr (minimum vertical slip rate), based upon approximately 400-450 m (measured by SRTM) of uplift of the Balook Block across the fault in the last 4-8 Ma (Webb *et al.*, 2011).

Domain 5 (Otway Ranges and west of Melbourne)

This data is an updated version of data compiled for a report to GNS in 2009 on the Otways CCS site, based upon which the following paper was published:

Stirling, M., Litchfield, N., Gerstenberger, M., Clark, D., Bradley, B., Beavan, J., McVerry, G., Van Dissen, R., Nicol, A. & Wallace, L. 2011. Preliminary probabilistic seismic hazard analysis of the CO2CRC Otway Project Site, Victoria, Australia. Bulletin of the Seismological Society of America, 101(6): 2726-2736.

The faults below occur in two geological contexts. The first are faults within the Otway Basin. These faults formed as listric normal faults. They have been reactivated in compression in the last 5-10 Ma. These faults might be expected to be steeper than typical reverse faults because of their origins as normal faults (40-60 deg). Sandiford (2003a) constrains the timing of major deformation to 2-1 Ma based upon relationships evident on the western flanks of the Otway Ranges. The second setting is the Lachlan Fold Belt. Faults here relate to large reverse fault systems active during the assembly of the Tasmanides. As such, faults might assume orientations typical of reverse faults and thrust faults (30-50 deg). In some cases, fault dips are known from direct observation.

Avalon Fault

Length:	23.4 km
Dip:	Unknown (likely to be a moderately west dipping reverse fault, 40±10 degrees).
Slip Rate:	~6 m/Ma (maximum), based upon a maximum 10 m high scarp developed in Newer Volcanics flows dated at ~1.66 Ma (Gibson, 2007).

***Avoca fault* -** Quaternary sediments covering the fault trace show no evidence for surface rupture. Potentially not active in current stress field (Michael Jorgensen pers com.).

Bambra Fault Zone
While mapped as the Bambra Fault, this section is topographically continuous with the Colac Fault, and so may rupture with it.

Length:	33 km
Dip:	Unknown (likely to be a moderately to steeply southeast dipping 50 ±10 degrees).
Slip Rate:	~4-25 m/Ma. Minimum based upon a maximum 40 m high scarp developed in Mid to Late Miocene Gellibrand Marl (Tickell et al, 2007). Maximum relates to the rate for the Colac fault, which appears topographically continuous with this segment of the Bambra Fault.

Bambra Fault Zone 2
This fault is mapped as continuous with the Bambra Fault, though it seems more likely based upon topography that the eastern segment links into the Colac Fault.

Length: 52 km (topography suggests it may extend a further 26 km to the SW to the coast, at least).
Dip: Unknown (likely to be a moderately to steeply southeast dipping 50 ±10 degrees).
Slip Rate: ~4 - 20 m/Ma. Minimum estimate based upon a maximum 40 m high scarp developed in Mid to Late Miocene Gellibrand Marl (Tickell et al, 2007). Maximum estimate pertains if the deformation int eh Otway Ranges is <2 Ma (Sandiford, 2003a)

Barabool Fault

The Barrabool fault is a prominent linear scarp 17.7-24.5 km long that terminates at the Winchelsea Scarp (Mt Pollock Monocline).

Length: 17.7-24.5 km (given the height of the scarp, it perhaps ruptures with the Colac/Bambra Fault system with the Mt Pollock Monocline as a step-over).
Dip: Unknown (likely to be a moderately to steeply south dipping reverse-oblique reactivated normal fault, say 50 ±10 degrees).
Slip Rate: ~20-30 m/Ma (maximum vertical slip rate), based upon 60 m of uplift in SRTM across 2-3 Ma basalts (Bernie Joyce pers. Comm.).

Bellarine Fault - Most displacement accumulated prior to lower Eocene. Potentially not active in current stresss field (Holdgate et al., 2002).

Bet Bet Fault – some indication of activity in the Pliocene on this 15 km long structure in geophysical data (Jeremy James Pers. Com. 2006).

Castle Cove Fault

A prominent break in slope on the northwest flank of the Otway Ranges at ~230-280 m elevation is interpreted to be a Pliocene shoreline (Sandiford, 2003b). As depicted on the Port Campbell 1:100,000 Geology sheet, much of this uplift might be associated with the Johanna and Castle Cove Faults. The above observation that much of the total reverse throw across the Ferguson Hill anticline is Miocene and younger, suggests that offsets across Cretaceous markers are ball-park indicative of neotectonic displacements. However, the Johanna and Castle Cove Faults are developed in Cretaceous strata with no prominent marker horizons. Enveloping surfaces constructed by joining the high points of the landscape along a section (in SRTM data), have been used to estimate neotectonic throw, as a proxy. Dislocations in the enveloping surfaces can be considered to significantly underestimate slip due to the prominent folds associated with deformation (e.g. the Crowes Anticline in the hanging wall of the Johanna Fault), and to erosion focusing on the uplifted blocks.

Length: 22 km (as mapped, but likely to be much longer – goes offshore and likely extends to the NE beyond the mapped extent)
Dip: Steeply NW dipping (Port Campbell 1:100k geological sheet 50 ±10 degrees).
Slip Rate: 6.0 -30 m/Ma (minimum vertical slip rate), based upon approximately 60 m of vertical displacement of the landscape enveloping surface in SRTM data. The minimum bound assumes that surface is 5-10 Ma. The maximum bound relates to the conclusion of Sandiford (2003a) that deformation started at 2Ma.

Colac Fault

Length: 51 km (as mapped). Appears in SRTM DEM to be continuous with the 33 km long Bambra Fault, bringing the total potential rupture length to 84 km
Dip: Unknown (likely to be a steeply southeast dipping 50 ±10 degrees).

Slip Rate: ~10-25 m/Ma (maximum vertical slip rate), based upon ~50 m of uplift of Pliocene strandlines (2-5 Ma, probably towards the younger end) (Sandiford, 2003; Wallace et al., 2005). SRTM suggest 40-45 m of uplift is more typical, although Tickell et al. (1992) suggest a value of 30 m.

Cooriejong Monocline

Length: 11.3 km

Dip: steeply northeast (appears to form part of some sort of accommodation zone between larger NE-striking features).

Slip Rate: ~4.9 m/Ma (maximum vertical slip rate), based upon approximately 78 m of uplift across Mid Miocene Gellibrand Marl (Tickell et al., 1992). There are several parallel structures of similar length and topographic expression to the southwest that are likely to have similar slip rates.

Curdie Monocline

Length: 23.8 km

Dip: steeply southeast (50 ±10 degrees).

Slip Rate: ~10-20 m/Ma (maximum vertical slip rate), based upon approximately 100-120 m of uplift across the base of the Mid to Late Miocene Port Campbell Limestone (Tickell et al., 1992). Topographic expression across the structure is not obvious.

Curlewis Monocline

Length: 17.2 km

Dip: Unknown (likely to be a moderately to steeply south dipping reverse-oblique fault).

Slip Rate: ~3.6 m/Ma (maximum vertical slip rate), based upon approximately 80 m of uplift across 22.5 Ma basalts (Gibson, 2007).

Enfield fault

Aeromagnetics was used to map the fault, which appears on the Rokewood and Mercer 1:50 000 geological sheets (and appears to extend beyond these, but is not mapped). The geophysics indicated 150m of uplift in the last 3-4 Ma. The Karoonda surface dips at 8 degrees here. (Dave Taylor & Martin Hughes pers com, 2005). There is no obvious fault trace or scarp evident in the SRTM DEM, though the lineament marks a break of slope. The fault is also mentioned in Hughes et al. (1998). Not clear why this structure is active when it is at such a high angle to the nearby active faults.

Length: >44.6 km

Dip: Unknown.

Slip Rate: ~37.5-50 m/Ma (maximum vertical slip rate), based upon approximately 150 m of uplift in the last 3-4 Ma (Hughes Pers Com.).

Woolsthorpe Scarp

Prominent linear scarp 26.7 km long. It is not mapped as a fault on 250 000 geology sheets, nor has it been ground checked.

Length: 26.7 km (given the height of the scarp, it perhaps ruptures with the Barabool Fault with the Mt Pollock Monocline as a step-over).

Dip: Unknown (west dipping?)

Slip Rate: ~5-10 m/Ma (maximum vertical slip rate), based upon 10 m of uplift in SRTM across ~1-2 Ma basalts (Gibson, 2007).

Fault 7

Fault 7 is a prominent linear feature 19.7 km long. It is partly manifest as a southeast facing scarp, and part as a linear section of stream channel. It is not mapped as a fault on 250 000 geology sheets, nor has it been ground checked.

Length: 19.7 km
Dip: Unknown (potentially steeply northeast dipping, linking in with the Simpson Structure of Colac Fault).
Slip Rate: ~5-12.5 m/Ma (maximum vertical slip rate), based upon 25 m of uplift in SRTM across Pliocene strandlines.

Ferguson Hill Anticline
Length: 39 km
Dip: Steeply NW dipping (Port Campbell 1:100k geological sheet, say 50±10 deg).
Slip Rate: ~30-58 m/Ma (maximum vertical slip rate), based upon approximately 115 m of uplift across Pliocene strandlines identified in digital elevation data. Sandiford, (2003a) argues that deformation occurred <2 Ma. Underlying Cretaceous units have been displaced by ~130 m vertically, suggesting much of the deformation across the structure postdates the Miocene. Tickell et al (1992) suggest a smaller displacement of 60 m the Pliocene Hanson Plain Sand across the fault.

Johanna Fault
A prominent break in slope on the northwest flank of the Otway Ranges at ~230-280 m elevation is interpreted to be a Pliocene shoreline (Sandiford, 2003b). As depicted on the Port Campbell 1:100,000 Geology sheet, much of this uplift might be associated with the Johanna and Castle Cove Faults. The above observation that much of the total reverse throw across the Ferguson Hill anticline is Miocene and younger, suggests that offsets across Cretaceous markers are ball-park indicative of neotectonic displacements. However, the Johanna and Castle Cove Faults are developed in Cretaceous strata with no prominent marker horizons. Enveloping surfaces constructed by joining the high points of the landscape along a section (in SRTM data), have been used to estimate neotectonic throw, as a proxy. Dislocations in the enveloping surfaces can be considered to significantly underestimate slip due to the prominent folds associated with deformation (e.g. the Crowes Anticline in the hanging wall of the Johanna Fault), and to erosion focusing on the uplifted blocks.

Length: 44 km (as mapped, but perhaps up to 77 km long onshore, plus extends offshore to the SW)
Dip: Steeply NW dipping (Port Campbell 1:100k geological sheet, 50±10 degrees).
Slip Rate: 6.5 -33 m/Ma (minimum vertical slip rate), based upon approximately 65 m of vertical displacement of the landscape enveloping surface in SRTM data The minimum bound assumes that surface is 5-10 Ma. The maximum bound relates to the conclusion of Sandiford (2003a) that deformation started at 2Ma.

Love Creek Monocline – landscape indicates Pliocene to recent uplift (also Tickell et al. 1992) but can't get a consistent displacement or displacement sense.

Lovely Banks Monocline
Length: 30.6 km
Dip: Unknown (likely to be a moderately west dipping reverse fault, say 40±10 degrees).
Slip Rate: ~35 m/Ma (maximum vertical slip rate), based upon a maximum 70 m high scarp developed in Newer Volcanics flows dated at ~1.91-2.17 Ma (Gibson, 2007).

Mt Ararat/Stawell Fault

Martin Hughes, an expert on the geology of Victoria, has found evidence for uplift of late Tertiary sediments along these faults. Further details are not available. The faults are not separated here as they are parallel to the regional geologic grain and occur along strike from one another - hence they may represent the same fault system. There is no topographic expression associated with the faults apparent on the SRTM 90m DEM, with the exception of the range including Mt Ararat, at the southern end of the Mt Ararat Fault. This suggests either that the slip rate is very low, or that the Tertiary sediments truncated by fault movement predate the current stress field, and the fault is currently inactive.

Muckleford Fault

Near Guildford, late Cainozoic sub-basaltic gravels are displaced by up to 50 m across the Muckleford Fault [Cherry & Wilkinson (1994) in Kotsonis & Joyce (2003)]. Northwest of Guildford, the Muckleford Fault has displaced an auriferous lead by 20 m, and the overlying basalts by 15m (Kotsonis & Joyce 2003).

Length: 116 km
Dip: Unknown (likely to be a moderately west dipping reverse fault).
Slip Rate: ≤5 m/Ma (maximum vertical slip rate over the last 3 Ma), based upon a maximum 15 m vertical displacement of the Guildford Plateau lavas (Kotsonis & Joyce 2003).

Pirron Yallock Monocline
Length: 35.7 km
Dip: Unknown (likely to be a moderate to steeply south-dipping reverse reactivated normal fault, say 50±10 deg).
Slip Rate: 5-12.5 m/Ma (maximum), based upon vertical displacement of 25 m of marine bench upon which regressive Pliocene strandlines were deposited.

Rowsley Fault
Length: 70 km
Dip: Unknown (likely to be a moderately to steeply west dipping reverse fault, so say 40±10 deg).
Slip Rate: >55 m/Ma (maximum), based upon a 110 m high scarp developed in Newer Volcanics flows dated at ~2.0 Ma (Gibson, 2007). Scarp increases in height to ~250m towards the north, but Newer Volcanics only occur on the footwall, so slip rate maximum cannot be determined.

Selwyn Fault
Length: 97 km
Dip: Unknown (most likely formed as a steeply west dipping normal fault, but uplifted beach gravels on the eastern side of the fault, and east side-up displacement of the Pleistocene Bridgewater Formation, suggest that the currently active fault is east dipping).
Slip Rate: ~50 m/Ma (Janssen, 2001), based upon displacement of the Pleistocene Bridgewater Formation (Mallett & Holdgate, 1985).

Simpson Anticline
The Simpson Anticline is a prominent linear feature 26.9 km long associated with a prominent southeast facing scarp. It is likely to link into the Colac fault to the northeast.

Length: 26.9 km

Dip: Unknown (potentially steeply northeast dipping, linking in with the Colac Fault, say 50±10 degrees).
Slip Rate: ~5-12.5 m/Ma (maximum vertical slip rate), based upon 25 m of uplift in SRTM across Pliocene strandlines (assuming 2 Ma activity start of Sandiford, 2003a).

Winchelsea Scarp
Likely to be a hard-link between the Barrabool Fault and the Colac Monocline. An easterly dipping reverse fault has broken through to the surface, displacing late Tertiary fluvial sediments (Moorabool Viaduct Member) and a lava flow estimated to be 2-3 Ma (E. B. Joyce, University of Melbourne, Written Communication, 2006). The total displacement across the fault is not known, but the associated scarp (monoclinal fold?) is approximately 15 m high further SW of the Winchelsea exposure.

Length: 16.6 km
Dip: 30 (moderately east dipping at surface).
Slip Rate: ~5-7.5 m/Myr (maximum vertical slip rate), based upon 15 m of uplift in SRTM across 2-3 Ma basalt.

Domain 6 Faults (western extended)

Quaternary strandline systems up to several hundred thousand years old (Tamala Limestone) are well preserved along the WA coastline. Fossil strandlines of presumably greater antiquity (Miocene to Pliocene) are preserved near Kalbarri. These observations suggest relatively low erosion rates on the coastal plane. Cl36 CRN determinations of erosion rate from uplifted parts of the Cape Range average 6 m/Myr (Clark *et al.*, 2011b). It might be expected that denudation rates on lower relief terrain will be lower than this value. Where data is not present, uplift is divided by 5 Myr to obtain an uplift rate. A minimum uplift rate of 4m/Myr is assigned to preserve relief.

McPherson et al (2013) document a strain gradient from the Carnarvon Basin (30-50 m/Myr) into the Craton (<5m/Myr).

Most faults formed as normal faults in a basin setting and so might be expected to be relatively steep, say 50±10 degrees.

Further north, on the Northwest Shelf, the Western Australia Shear Zone (WASZ) is a system of active faults and folds that extend along the reactivated passive margin of Australia through the Browse, Roebuck, and Carnarvon Basins (Whitney and Hengesh, 2013). The WASZ reoccupies older rift related structures that initially formed during periods of continental-scale fragmentation in the Paleozoic and Mesozoic Eras. These faults are currently undergoing reactivation with a dominant lateral component to motion. Normal (e.g. Barrow Island) and reverse (e.g. Cape Range) components to motion are also observed (Hengesh & Whitney, 2016; Hengesh & Whitney, 2015; Whitney *et al.*, 2016a; Whitney & Hengesh, 2014; Whitney & Hengesh, 2015a; Whitney & Hengesh, 2015b). These authors identify an inner and outer shelf fault zone, and an inner basin fault zone. Where slip rates are available, they are reported in the below table. The value for Quaternary slip rate was used where available.

The inner basin fault zone is a dense zone of seafloor faulting 50 km wide and 100 km long between the Inner and Outer Shelf Fault zones. It is represented in the FSM as a single fault in the centre with the slip rate across the entire zone from Base Pliocene displacements (from Hengesh & Whitney 2016). The Sholl Island, Flinders and Long Islands Faults are assigned slip rates intermediate between the Cape Range and Giralia Faults (Whitney *et al.*, 2016a; Whitney *et al.*, 2016b)

From Hengesh & Whitney (2016)

Table 5. Estimated Vertical Displacements and Slip Rate Values From Selected Seismic Lines

					Throw (s TWT)		Displacement (m)		Period of Activity (Ma)		Estimated Fault Slip Rate (mm/yr)	
Fault Zone/Seismic Line	Figure	Shot Point Range	Horizon	Zone of Deformation	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Inner Basin fault zone (seismic line BBHR-11)	Figure 9	3125–4600	Inferred Quaternary unconformity	Entire fault zone	0.080	0.150	64	120	0.50	1.00	0.06	0.24
	Figure 9	3125–4600	Base Pliocene	Entire fault zone	0.300	0.325	240	260	1.00	3.00	0.08	0.26
	Figure 10	4410–4450	Seafloor	Individual fault strand	0.006	0.007	5	5	0.13	0.25	0.02	0.04
	Figure 10	4410–4450	Inferred Quaternary unconformity	Individual fault strand	0.019	0.028	15	22	0.50	1.00	0.02	0.04
Outer Shelf fault zone—north section (seismic line BBHR-01)	Figure 12	5250–5175	Seafloor	Fault on east side of east verging anticline	0.025	0.040	19	31	0.13	0.25	0.08	0.25
Outer Shelf fault—south section (seismic line jn.jn.87_15)	Figure 13c	NA	Late Miocene fault offset	Entire fault zone	0.17	0.30	136	240	1.00	3.00	0.05	0.24
Inner Shelf fault zone (north) (seismic line BBHR-04)	Figure 15	5540–5700	Seafloor	Individual fault strand	0.010	0.025	8	19	0.13	0.25	0.03	0.15
	Figure 15	5540–5700	Late Miocene fold amplitude	Individual fault strand	0.040	0.045	32	36	1.00	3.00	0.01	0.04
	Figure 15	5540–5700	Late Miocene fault offset	Individual fault strand	0.010	0.025	8	20	1.00	3.00	0.003	0.02
Inner Shelf fault zone (south) (seismic line s136_136_24_mig_time)	Figure 17	5640–5950	500 ka	Entire fault zone	0.015	0.018	12	14	0.50	0.50	0.02	0.03
	Figure 17	5650–5950	1.0 Ma	Entire fault zone	0.039	0.041	31	32	1.00	1.00	0.03	0.03
	Figures 16 and 17	5600–5975	Late Miocene	Entire fault zone	0.150	0.180	120	144	1.00	3.00	0.04	0.14

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