Tasmanian Geological Survey
Record 2011/03

Landslide mapping and magnetic remanence of Paleogene basalt, Tamar Valley

by Clive R. Calver

Department of Infrastructure, Energy and Resources
Mineral Resources Tasmania

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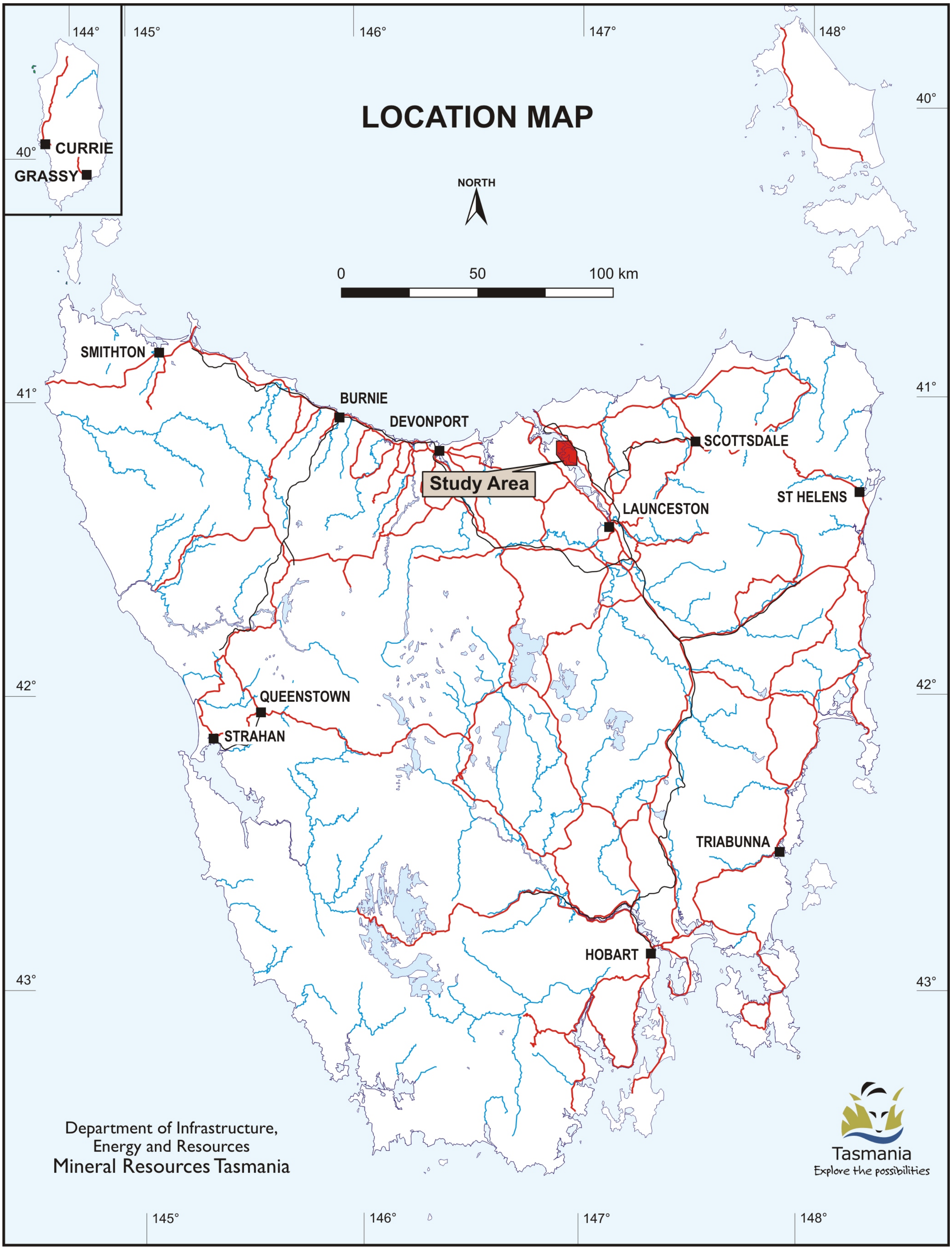

Mineral Resources Tasmania PO Box 56 Rosny Park Tasmania 7018

Phone: (03) 6233 8377 ● Fax: (03) 6233 8338

Email: info@mrt.tas.gov.au ● Internet: www.mrt.tas.gov.au

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Abstract

Direction and magnitude of natural remanent magnetism (NRM) were determined in 26 exposures of Paleogene basalt in the Rowella–Deviot–Craigburn area, to help distinguish outcrop from large rock masses displaced and rotated downslope. The 'known' outcrops nearly all have NRM directions consistent with the accepted mid-Paleogene pole position, while in most cases of suspected mass movement, the NRM has undergone an apparent rotation in accordance with expected landslide mechanisms. NRM intensities are 1 to 13 A/m and greatly exceed the induced component (Koenigsberger ratios typically between 4 and 15). Modelling of aeromagnetic anomalies shows that the 47 Ma Rowella basalt is a thick lens-shaped body mostly below sea level. The 33 Ma Batman Highway basalt fills a major (ancestral Tamar) channel, its base at or below sea level. A feeder probably underlies the Spring Bay nephelinite.

Introduction

Landslides in the Tamar Valley are found mainly on slopes underlain by poorly consolidated Paleogene sediments (e.g. Stevenson, 1975; Turner, 1975; Mazengarb, 2006). Basalt, overlying or interbedded with the sediments in many places, is often involved in mass movement, and contributes to slope instability through oversteepening. Mapping of the basalt, and differentiating transported basalt masses (topples, rafts) from in situ outcrop, are important in understanding the landslip hazards, geomorphology and Paleogene stratigraphy of the area.

In 2010, the writer reviewed existing geological maps in the Rowella–Deviot–Craigburn area, in preparation for a landslide susceptibility mapping project (see Mazengarb and Stevenson, 2010). The 1:25 000 scale geological coverage (Bell Bay and Beaconsfield digital geological maps) was based on work originally published at a scale of 1:63 360 (Gee and Legge, 1971). More detailed mapping of similar vintage was also available (Sutherland, 1971), as well as aeromagnetic imagery and radiometrics from a 200 m line spacing survey in 2001, and a 2010 airborne laser scanning (LiDAR) survey. Geochemistry, petrography and dating of the basalts have shown that a number of flows are present (Sutherland, 1969; 1971; Sutherland *et al*., 2006), of both normal and reversed magnetic polarity. The maps show extensive ridge-top basalt outcrop, and numerous, smaller, more or less isolated basalt areas in mid-slope and shoreline settings. Previous work (Sutherland, 1971; Stevenson, 1975; Turner, 1975) and current geomorphological mapping (M. Stevenson, pers. comm.) suggest that many of the mid to lower slope occurrences may be transported landslide blocks. Lack of outcrop, particularly of the weakly consolidated sedimentary sequence, means that the field relationships of most of these exposures are obscure. The aeromagnetic imagery is generally ambiguous, or lacking adequate resolution to be of much help.

Fieldwork undertaken by the writer in 2010 focussed on many of these problematic basalt exposures in the Rowella–Deviot–Craigburn area, particularly along the foreshore where exposure is relatively good. Structural data, lacking on previous maps, were obtained (orientation of jointing in basalts and bedding in the sediments). Directions of natural remanent magnetism (NRM) were determined from 26 orientated basalt samples to help distinguish in situ outcrop from basalt rotated by downslope mass-movement. Magnitudes of NRM and magnetic susceptibility were also determined to constrain analysis and modelling of aeromagnetic data and allow a better understanding of the subsurface distribution of the basalt.

The resulting geological map revision of the Rowella–Deviot–Craigburn area, incorporating the conclusions of this work, will be shown in the updated Beaconsfield and Bell Bay digital geological maps; a simplified version is shown as Figure 1. This revision also relies extensively on previous mapping, particularly Sutherland (1971), the aeromagnetic, radiometric and LiDAR surveys, current geomorphological mapping (Stevenson and Mazengarb, in prep.), and field observations by M. Stevenson and C. Mazengarb.

This report sets out the rationale, methodology and results of the palaeomagnetic work. The report is something of a pilot study, as to the writer's knowledge, this is a novel application of palaeomagnetism. Determining NRM directions is an imprecise way to constrain rotation, because of the broad possible range expected in any single outcrop due to the combined effects of secular variation and measurement error (see below). It will be shown that significant rotations can be demonstrated in interpreted landslide blocks, that are by and large consistent with expected landslide mechanisms, although a few results defy easy explanation.

All grid references in the text (and map grids) are GDA94 datum and are MGA co-ordinates in Zone 55, quoted in the form xxxxxx/yyyyyyy, where the first six numbers are metres east and the last seven numbers are metres north.

Geological setting

The northwest-trending Tamar Graben was produced by faulting in the Cretaceous to early Paleogene, in basement of predominantly Jurassic dolerite. The graben is filled by up to 300 m of poorly consolidated, lacustrine and fluvial clay, silt and sand, with minor lignite and conglomerate, of latest Cretaceous to Oligocene age, and a number of basalt flows of Eocene–Oligocene age (Sutherland, 1971; Forsyth, 1989; Sutherland *et al*., 2006). In the Rowella–Deviot–Craigburn area (fig. 1), the Tamar estuary meanders across the central, deepest part of the graben, which is about five kilometres wide. The floor of the graben (base of the sediments) is 250 m below sea level at Bell Bay, and most of the sediments below sea level there belong to the *M. diversus* Zone (Early Eocene) (Forsyth, 1989). Sediments at sea level in the Long Reach–East Arm area (fig. 1) belong to the Upper *M. diversus* to *P. asperopolus* Zone interval (Sutherland *et al*., 2006). Sediments onlap the southwest shoulder of the graben at Deviot, and the basal nonconformity of poorly consolidated lithic sandstone upon dolerite is exposed on the foreshore (494515/5434530), dipping gently northeast. In the area

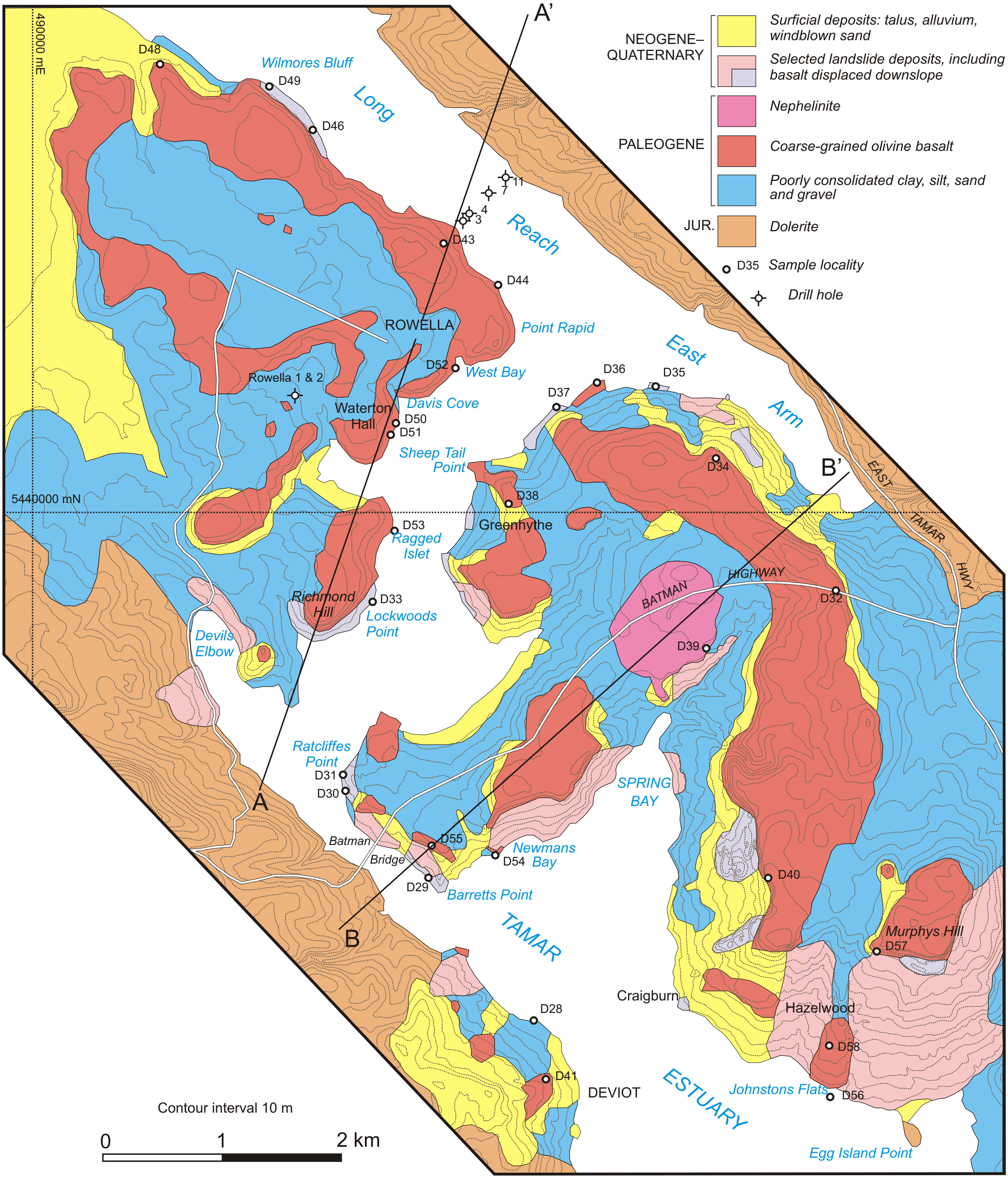

Figure 1

1:50 000 scale simplified geology and sample locations, Rowella–Deviot–Craigburn area, adapted from updated Beaconsfield and Bell Bay 1:25 000 scale geological maps.

mapped, sediments occur up to 120 m above sea level around Murphys Hill, where the uppermost unit is a dolerite cobble conglomerate.

The oldest known basalt in the area is a coarse-grained hawaiite found at 25 to 134 m depth in DDH Rowella 1 and 2. It is dated at 47 1 Ma (early Middle Eocene) (K-Ar, whole rock) and is underlain and overlain by Upper *M. diversus–P. asperopolus* Zone sediments (Sutherland *et al.*, 2006). The location of these drill holes is uncertain (S. Forsyth, pers. comm.), but the dated basalt almost certainly corresponds to the reversely magnetised basalt in the Rowella area (fig. 1, 2). Massive coarse-grained olivine basalt, identical in field appearance to the Rowella hawaiite, is abundant throughout the mapped area (fig. 1), although much of it is significantly younger. The youngest may be that at Murphys Hill, a plateau remnant 140 m above sea level, overlying the dolerite cobble conglomerate. Sutherland *et al.* (2006) considered this to be the same flow as the hawaiite at the Batman Highway (near locality D32, fig. 1) dated at 32.5 0.7 Ma (Early Oligocene) (K-Ar, whole rock). No other basalts in the mapped area have yet been dated. Olivine nephelinite — a fine-grained basalt with lherzolite xenoliths — is found north of Spring Bay (fig. 1; Sutherland, 1971).

There are widespread, patchy developments of weakly consolidated siliceous gravel and sand, of probable Neogene age (not differentiated on Figure 1). Other surficial deposits include basalt-derived talus (float) and windblown sand. Landslide deposits, extensively developed on slopes underlain by the soft Paleogene sediments, have mainly been mapped from geomorphology (Stevenson and Mazengarb, in prep.). The identification of transported basalt masses is clear 1–2 km north of Craigburn and at Murphys Hill, where the masses are little removed from outcrop and transected by dilatational rifts parallel to slope. However it is difficult to distinguish outcrop from block slides or rotational landslides in the case of most mid slope and lower slope basalt occurrences. Consistency of jointing orientations suggests that some of these are coherent masses (or outcrop) several hundred metres in extent (e.g. Barretts Point: 493400/5436800). This is the problem that is specifically addressed in this report.

Methods

Magnitude and direction of NRM, and magnetic susceptibility, were determined following Breiner (1973). The method can give precisions of magnitude and direction of NRM of about 10% and 10° respectively (Leaman, 2002). Orientated samples, typically 400–1000 g, were hammered and sawn into approximate equidimensionality while preserving at least part of the marked (orientated) face. Three mutually orthogonal faces (one being the marked face) were created on each sample using a diamond saw or by building up with epoxy putty. A proton precession magnetometer sensor was aligned and fixed parallel to the Earth's magnetic field, in an outdoors location away from steep magnetic gradients. Each sample was positioned at a fixed distance above, and along the axis of the sensor, and rotated about an axis normal to the axis of the sensor. The distance from the magnetometer was at least five times the nominal diameter of the sample. Readings were taken at 45° increments on each of the three orthogonal faces, and of background (i.e. sample absent) at regular intervals. This procedure was facilitated by the construction of a supporting apparatus consisting of a long (1.5 m) wooden bar attached parallel to the sensor and support tube. A plywood plate, with a central brass pin and 45° divisions marked, supports the sample being rotated, and can be slid along the bar and fixed at desired distances above the sensor. A small hole, drilled in the centre of each of the orthogonal sample faces, fits onto the brass pin as the sample is being rotated. This apparatus allowed distance and orientation of samples to be accurately constrained.

Remanent magnetisation per unit volume, J_r (A/m), and magnetic susceptibility per unit volume, k (SI units), were obtained from the maximum, minimum and background readings (T_{max}, T_{min}, T_0), and sample diameter (D) and distance from sensor (r):

$$J_r = (3/2\ )(r/D)^3(T_{max}-T_{min})*10^3$$

$$k = (6/F)(r/D)^3(T_{max}+T_{min}-2T_0)$$

where F is the strength of the ambient magnetic field in gauss. J_r will be an underestimate in cases where the direction of NRM is not close to any of the orthogonal planes of rotation. Sample diameter was calculated from sample weight assuming a spherical shape and a density of 3.0. The Koenigsberger ratio (Q), the ratio of the remanent magnetisation to the induced magnetisation, is given by:

$$Q = J_r/(k*H)$$

where H is the local geomagnetic field (49.3 A/m); alternatively

$$Q = (T_{max}-T_{min})/(T_{max}+T_{min}-2T_0)$$

The results are tabulated in Table 1.

Direction of NRM was obtained using an embellishment of Breiner's method. Computations were carried out using Microsoft Excel. The method described here yields 24 readings for each sample (plus background readings). Six of these readings are effectively repeats of the same orientation relative to the magnetometer axis; these pairs of repeats were averaged, giving 18 readings corresponding to directions (vectors) symmetrically distributed in three dimensions about the sample centre. With background subtracted, each vector (in nT) is the sum of the perturbation due to magnetic susceptibility (which will be a constant and positive for all vectors) and the perturbation due to NRM (which will vary amongst vectors and be positive or negative). The perturbation due to magnetic susceptibility, $((T_{max}+T_{min})/2)-T_0$, is subtracted from each vector, leaving only the NRM component. Ideally there will then be nine positive vectors grouped in one hemisphere and nine negative vectors in the opposite hemisphere. 3D vector addition of positive and negative vectors (separately) gives two overall mutually opposed directions in 3D space. Polarity of the NRM, relative to sample co-ordinates, becomes apparent. Ideally the two summed vectors should be 180° apart, but because of measurement error and sample non-sphericity they deviate from 180° by a small angle, generally less than 5°. This angle ('vector deviation',

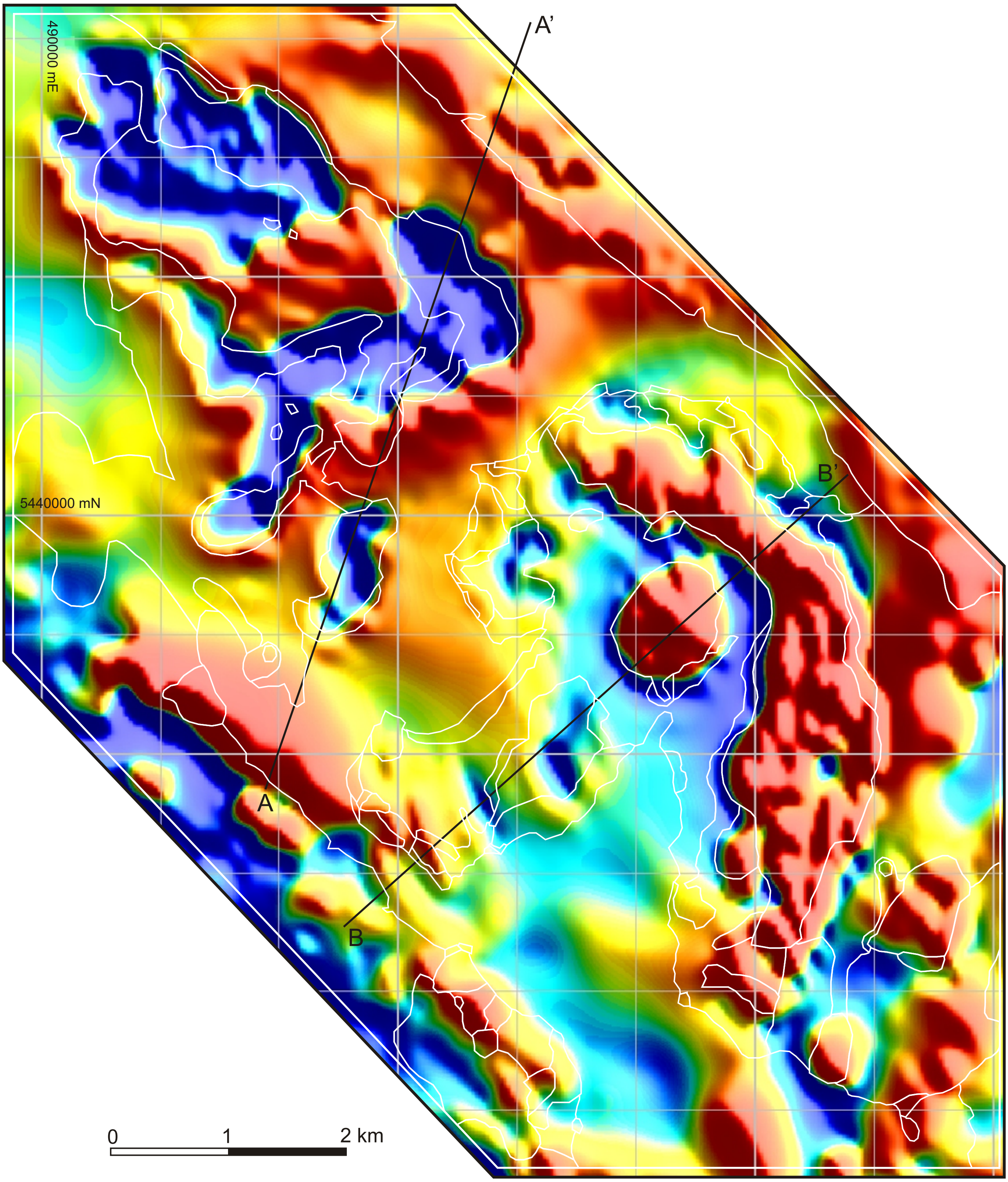

Figure 2

TMI image of area shown in Figure 1; white lines — geological boundaries; black lines — modelled sections.

Table 1

GDA co-ordinates, magnetic parameters and interpretation of samples.

Field no.	Reg. no.	Locality	mE (GDA)	mN (GDA)	J_r (A/m)	k (SI)	k' (SI)	Q	Inclination	Declination	Polarity	Vect dev	Interpretation
D28	R15826	Deviot foreshore	494235	5435725	2.710	0.013	0.016	4.2	64	209	nor	3.9	outcrop
D29	R15827	Barretts Point	493332.547	5436925.396	2.128	0.005	0.001	8.1	27	138	nor	2.5	blockslide or topple
D30	R15828	Ratcliffes Point	492643.613	5437657.143	1.060	0.004	0.003	5.3	31	227	nor	3.5	rotational landslide
D31	R15829	Ratcliffes Point	492623.745	5437786.351	3.028	0.004		14.9	76	312	nor	1.2	rotational landslide?
D32	R15830	Cutting on Batman Highway	496755.882	5439340.723	2.249	0.006		7.6	76	191	nor	4.8	outcrop: interpreted
D33	R15831	Lockwoods Point	492873.12	5439229.168	5.046	0.008	0.007	12.6	13	101	rev	4.4	rotational landslide
D34	R15832	Near top hill, above East Arm	495748.282	5440444.542	2.422	0.011	0.003	4.3	48	129	nor	1.3	outcrop: interpreted
D35	R15833	Shoreline west of East Arm	495238.132	5441056.691	4.259	0.009	0.005	9.2	56	41	nor	0.6	raft or blockslide
D36	R15834	Shoreline west of East Arm	494758.619	5441081.244	1.491	0.006		4.8	48	216	nor	2.9	outcrop?
D37	R15835	Shoreline west of East Arm	494408.89	5440876.591	2.655	0.005		11.5	48	113	rev	7.4	raft or blockslide
D38	R15836	Greenhythe	494027.842	5440045.185	7.357	0.015		10.1	42	94	nor	3.1	topple
D39	R15837	North of Spring Bay	495704.145	5438833.949	5.151	0.007		16.0	unorientated				
D40	R15838	Outcrop above Craigburn Rocks	496181.217	5436940.807	4.800	0.006	0.007	15.2	87	285	nor	3.4	outcrop: interpreted
D41	R15839	Outcrop at Deviot	494324.289	5435240.39	12.724	0.001		205.1	61	186	nor	6	outcrop: interpreted
D43	R15840	Rowella NE ridge	493472.412	5442251.416	3.309	0.001	0.003	50.6	51	218	nor	8	outcrop: interpreted
D44	R15841	Rowella NE foreshore	493917.995	5441900.026	4.295	0.011	0.008	8.2	25	156	nor	7.6	landslide
D45	R15842	Rowella N ridge	493096.51	5442029.24	3.243	0.007	0.004	9.0	unorientated				
D46	R15843	Rowella N foreshore	492363.669	5443208.521	8.257	0.023	0.012	7.4	53	45	rev	5	rotational landslide
D47	R15844	Westwood Road	490346.946	5443661.584	2.849	0.009	0.010	6.7	unorientated				
D48	R15845	Rowella N ridge	491074.121	5443751.79	4.447	0.013	0.013	6.9	68	195	rev	6.9	outcrop: interpreted
D49	R15846	Rowella far N shore	491986.171	5443567.986	4.117	0.029		2.9	47	75	rev	2.5	rotational landslide
D50	R15847	Waterton shore	493057.179	5440736.59	3.275	0.011		6.0	24	257	rev	4.7	?
D51	R15848	Waterton shore	493019.296	5440648.845	3.590	0.011	0.007	6.7	24	77	rev	1.7	rotated?
D52	R15849	West Bay shore	493561.107	5441201.269	4.884	0.020		5.0	62	122	rev	3.9	outcrop: interpreted
D53	R15850	Ragged Islet	493033.849	5439844.041	13.063	0.003		105.2	17	132	rev	3.7	rotational landslide
D54	R15851	Newmans Bay	493885.848	5437123.269	1.437	0.004		7.5	83	105	rev	4.5	outcrop
D55	R15852	Ridge above Barretts Point	493371.711	5437179.497	5.107	0.006	0.002	17.5	64	175	nor	3.3	outcrop: interpreted
D56	R15853	Johnstons Flats shore	496700.092	5435072.911	3.938	0.000	0.009	497.2	50	259	rev	0.7	blockslide
D57	R15854	Murphys Hill	497092.033	5436299.727	2.654	0.012	0.010	4.6	unorientated				
D58	R15855	Hazelwood ridge	496710.861	5435506.811	3.665	0.013	0.004	5.9	74	295	nor	7.5	outcrop: interpreted
B8	R15856	North of Bradleys Beach	494313.775	5440693.306	1.089	0.004	0.004	5.0	unorientated				
B17	R15857	Newmans Bay	493787.41	5436930.128	0.918	0.003		6.3	unorientated				

k': magnetic susceptibility measured with handheld meter;
vect dev: vector deviation (see text).

Table 1) is given as an indicator of the integrity of the procedure for each sample.

A final 3D summation of these two vectors provides the best estimate of the direction of NRM relative to the co-ordinate system represented by the orthogonal sample faces. This direction was then translated into an azimuth and inclination in true space (keeping track of the polarity) using a manual stereonet. Repeat determinations of NRM directions on the same sample were within a few degrees of each other. Precision (including measurement error of orientation in the field) is estimated to be 10°.

Modern palaeomagnetic studies generally employ thermal or alternating-field demagnetisation procedures to remove low coercivity components from the NRM in order to arrive at a more accurate determination of original remanence directions (e.g. Butler, 1992). These procedures were not done. Early studies on Cenozoic basalts and Jurassic dolerite in South East Australia show that their magnetisation directions have remained stable and meaningful results can be obtained from un-demagnetised samples (Irving, 1956; Green and Irving, 1957).

Six determinations of NRM directions were also made of NQ drill core basalt samples from Rowella-2 and Windermere-2. Results were inconsistent and probably influenced by remagnetisation during drilling.

Dating of basalts in the area gave ages of 47 Ma and 33 Ma (Sutherland *et al*., 2006). These dates lie in a slow-moving part of the Australian apparent polar wander path in which the south pole was at approximately 66°S, 120°E in present day co-ordinates (Idnurm, 1985, 1994), which corresponds to a geomagnetic field in northern Tasmania of inclination 74°, declination 202°, assuming a geocentric axial dipole (Butler, 1992). Individual observations of the direction of NRM from basalt outcrop may be expected to lie within about 30° of this direction, because of the combined effects of measurement error (c. 10°) and dispersion due to secular variation (c. 20°: Butler, 1992). This distribution is indicated as a shaded small circle ('expected outcrop NRM directions') on the stereonet (fig. 3).

Results

NRM directions

Nine of the orientated samples were collected from sites that were interpreted with some confidence in the field as in situ outcrop (designated 'outcrop: interpreted' in Table 1). Outcrop was generally identified as such by two or more of:

(1) physical continuity over several metres or more;

(2) ridge top position; and

(3) subvertical columnar jointing.

Eight of the nine NRM directions lie within the zone of expected outcrop NRM directions (fig. 3). Polarities were all consistent with associated aeromagnetic anomalies except for sample D43 (of normal polarity, within a negative aeromagnetic anomaly; but see below).

Interpretations of the remaining 17 NRM directions, from problematic basalt exposures, are given below in approximate north to south order. All locations are shown on Figure 1.

Wilmores Bluff area

In situ outcrop inland of Wilmores Bluff has NRM with a steep southerly inclination and reversed polarity (sample D48), in accord with the extensive associated negative aeromagnetic anomaly. A narrow (80 m) bench extends along the coast at the foot of the basalt escarpment for about one kilometre southeast of Wilmores Bluff, and local back-tilting at the landward side suggests this bench is part of a complex of rotational landslides. There are coherent exposures of basalt and sediments dipping 8° to 40° SW along the shore. Two basalt NRM determinations (D46, D49) show moderate inclinations to the northeast and reversed polarity, suggesting rotation of outcrop by c. 50° (30°) about a southeast-trending axis, consistent with the interpretation of this bench as a rotational landslide partly covered by the estuary.

Point Rapid

Semi-continuous shoreline exposures of basalt, on a small headland 500 m north of Point Rapid, have a consistent dip of platy jointing to the northeast over a distance of about 70 metres. The NRM (sample D44) is inclined at only 25° to the southeast and is of normal polarity, suggesting substantial rotation relative to upslope outcrop that is expected to be of reversed polarity from the regional negative aeromagnetic anomaly.

Waterton Hall

Waterton Hall is situated on a promontory that is part of an area that is weakly positively anomalous on the aeromagnetic image, in contrast to the strong regional negative anomalies to the north and south. The promontory is underlain by similar coarse-grained olivine basalt to the areas to north and south. Coastal exposures of basalt (samples D50 and D51), within the positive anomaly, display columnar jointing plunging northeast at 40° to 60°. Further north, a basal contact of this basalt is poorly exposed, dipping southwest at 20° to 40° (see also Sutherland, 1971, pp. 31–32). The basalt has a weathered, fine-grained vesicular margin and sits on poorly exposed clay and lithic sandstone. Further north again, on the north side of Davis Cove, basalt is well exposed with columnar jointing plunging north at 45° to 65°.

The outcrop on the northern side of Davis Cove is at the southern limit of the negatively anomalous area associated with the Rowella basalt. These exposures could be interpreted as a southwest-dipping sequence of basalt–sediment–basalt, with columnar jointing normal to contacts. Samples D50 and D51 have NRM directions with shallow inclinations (25°) to the southwest and northeast respectively (both reversely magnetised). Sample D51 appears to have been rotated in rough accord with the dip of bedding and the plunge of columnar jointing (assuming the latter was originally vertical). However there is no ready explanation for the direction of the apparent rotation of this area, as the trend of the modern channel is SW–NE.

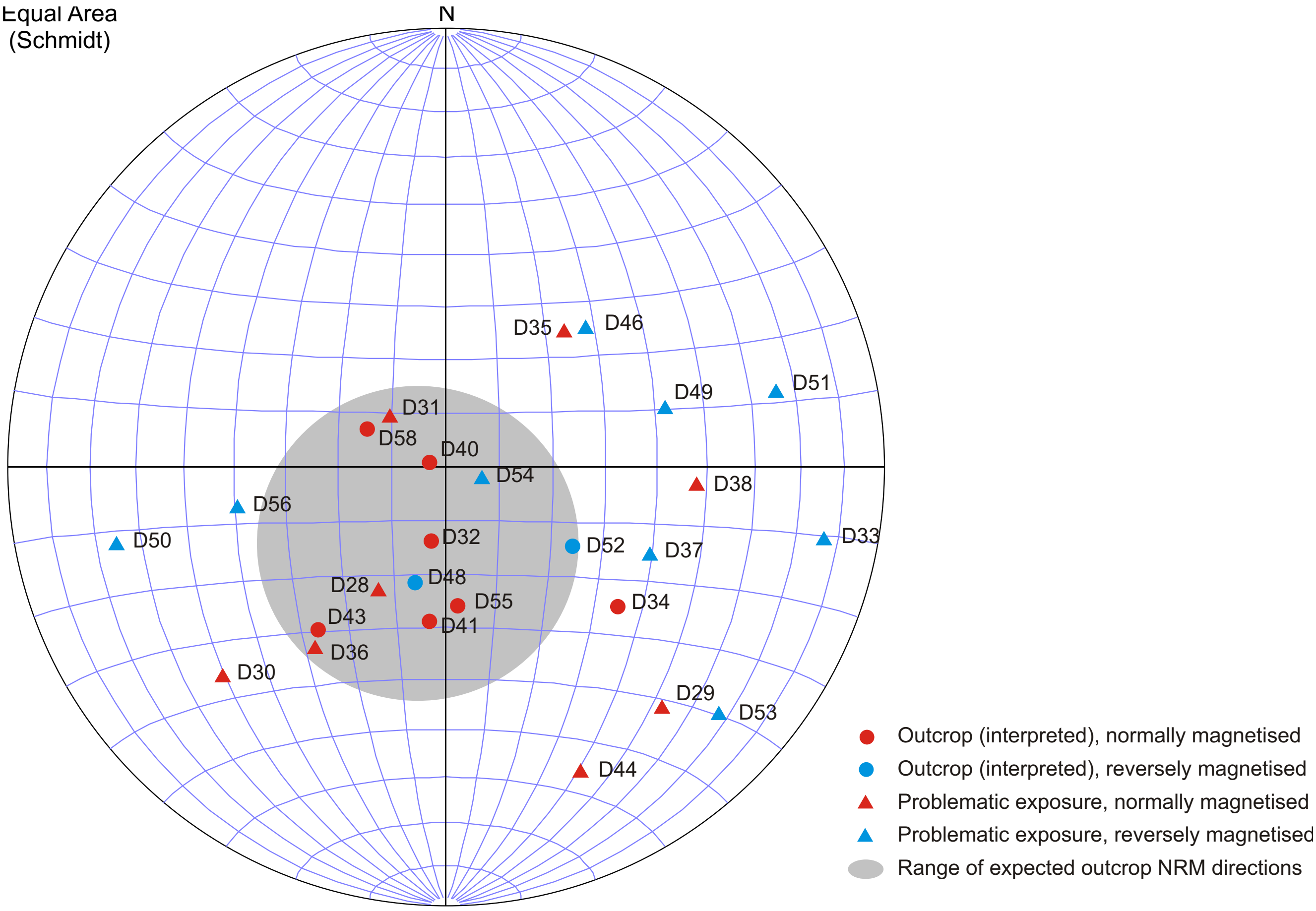

Figure 3

Lower hemisphere equal-area stereonet showing NRM directions.
Shaded area: expected distribution of NRM directions of in situ outcrop.

The direction of NRM in sample D50 cannot be readily explained. Nonetheless, the shallow inclinations of NRM can explain the weak positive anomalism of the area, as the effective magnetic contrast will largely be due to the relatively weak induced component (magnetic susceptibility).

Ragged Islet

Ragged Islet is a coastal stack separated from the steep basalt escarpment by a low-lying intertidal area. The exposure has subvertical, northeast-striking platy jointing. NRM of sample D53 plunges 17° to 132°, suggesting substantial rotation (c. 60° 30°) of an originally steep southerly plunge about a SW–NE axis, consistent with the stack being part of a rotational landslide now largely covered by the estuary.

Lockwoods Point

Lockwoods Point has shoreline exposure of basalt with well-developed columnar jointing plunging about 30° to the east (fig. 4). Intermittent exposure over about 130 m of shoreline shows similar jointing orientations. The exposures lie at the seaward edge of a bench backed by a steep north-trending escarpment of basalt which is reversely magnetised (fig. 2). The bench and coastal exposures have been interpreted as part of a rotational landslide on geomorphic evidence (M. Stevenson, pers. comm., 2011). Alternatively, the coastal outcrops could be in situ, with the columnar jointing normal to a steep eastern boundary of the basalt. NRM of sample D33 plunges 13° to 101° (reversed), strongly supporting the landslide interpretation. Rotation of about 80° (30°) about a N–S axis is indicated, consistent with the observed columnar jointing being originally subvertical.

East Arm area

A small promontory (at 495230/5441060) consists of a coastal basalt exposure about 40 m wide and 5 m high, with columnar jointing plunging northwest at about 35°. Within 200 m to the east and west, bedded clays crop out that dip c. 20° to the southwest. NRM of the basalt (sample D35) plunges northeast, well outside the zone of expected outcrop directions (fig. 3). This occurrence is probably a raft.

Basalt forms a larger promontory about 500 m to the west. Here, columnar jointing plunges steeply (70°) to the northwest over at least 160 m of continuous shoreline exposure. Sample D36 is normally magnetised and the direction of NRM lies within the range expected of outcrop. This observation, and the extensive, near-vertical columnar jointing, suggest that this exposure is in situ, although a large block slide cannot be ruled out.

Discontinuous basalt exposures are found further west along 400 m of shoreline (494300/5440750). This is at the diffuse northwestern extremity of a major elongate positive aeromagnetic anomaly (c. 6 1 km) that may represent a

Figure 4
Intertidal basalt exposure at Lockwoods Point with columnar jointing plunging gently east (towards the viewer); note also the platy joint set normal to columnar jointing. NRM direction here is subparallel to the columnar jointing, indicating that this basalt has been significantly rotated.

basalt-filled channel extending to below sea level (see next section). These exposures could be outcrop near the base of the channel. However jointing directions are variable along this section, and sample D37 has NRM plunging east (reversed), outside the zone of expected outcrop directions, observations that do not support an interpretation of outcrop.

Greenhythe

A small ridge of basalt extends northwards from near Greenhythe Road to Sheep Tail Point. There is no obvious associated aeromagnetic anomaly. Exposure on the western side of this ridge (sample D38) has NRM plunging 42° east, well outside the zone of expected outcrop directions (fig. 3). The sampled exposure may be a small topple, rotated westwards by about 50°, derived from normally magnetised outcrop.

Ratcliffes Point

About 500 m north of the eastern abutment of the Batman Bridge, shoreline outcrop of soft claystone and siltstone dips moderately (23°, 60°) northeast, and is apparently overlain (contact not exposed) by basalt, exposed upslope and along the shore to the north, with northeast-dipping platy jointing and in places, southeast-plunging columnar jointing (presumably perpendicular to the contact). Jointing directions are consistent over at least 100 metres. Sample D30 has an NRM plunging 31° southwest, suggesting significant rotation (50° 30°) about a northwest-trending axis, more or less consistent with the dip of the underlying bedding. The area is probably part of a large rotational landslide.

About 100 m north, an area about 40 m wide has columnar jointing plunging steeply (62°) north. Sample D31 has NRM plunging steeply (76°) northwest, just within the zone of expected outcrop directions (fig. 3), but also consistent with the small amount of rotation suggested by the plunging columns (if they were originally vertical).

Barretts Point

Exposures of basalt on Barretts Point, extending 300 m northwest alongshore towards the eastern abutment of Batman Bridge, form coherent masses up to 40 m long and have a roughly constant dip of platy jointing, at about 60° to the ENE, over the 300 m extent. Basalt crops out some distance upslope on the ridge to the northeast. The shoreline exposures are interpreted as part of a landslide, possibly a block slide or topple, on geomorphic evidence (M. Stevenson, pers. comm.). A weak positive magnetic anomaly underlies the area.

A sample from the outcrop on the ridge is normally magnetised and in situ (D55). A sample from the shoreline exposure (D29) has NRM plunging 27° to 138°. This could be interpreted as an outwardly rotated topple or block slide (as distinct from an inwardly rotated, rotational landslide), although the inferred northeast-trending axis of rotation is at odds with the overall northwest-trending slope.

Newmans Bay

Shoreline exposures of basalt at Newmans Bay lie at the southern edge of an elongate, northwest-trending negative aeromagnetic anomaly. Outcrop occurs on the ridge 300 m to the north, within the negative anomaly. The shoreline exposures lie at the western edge of an area mapped as a large, complex landslide (M. Stevenson, pers. comm.). The basalt on the shoreline conformably overlies poorly consolidated, cross-bedded lithic sandstone and granule conglomerate, dipping 39° to the northeast (fig. 5). Columnar jointing in the basalt plunges southwest, normal to the contact. There is extensive shoreline exposure of basalt with subvertical columnar jointing forty metres to the

Figure 5
Basalt overlying cross-bedded sandstone, with contact dipping 39° NE, Newmans Bay. NRM direction in the basalt indicates no significant rotation, suggesting dip of bedding may be due to deformation accompanying emplacement of the basalt.

northeast. Some of these joints are filled with sandy clay to form dilatational neptunean dykes up to 300 mm wide.

Sample D54, from one metre above the northeast-dipping basal contact, is reversely magnetised, consistent with the aeromagnetic anomaly, and its NRM direction is consistent with outcrop; the sample does not appear to have been significantly rotated in the manner suggested by the dip of the underlying bedding. The dip of bedding here can be attributed to deformation associated with emplacement of the basalt.

Hazelwood area

Basalt on the south slope of Murphys Hill around *Hazelwood* is flanked by extensive landslide areas mainly developed on sediments, and from geomorphological considerations alone the basalt itself could be a large (0.6 km) block slide (M. Stevenson, pers. comm.). The associated strong positive aeromagnetic anomaly suggests considerable depth to this basalt, and a probable feeder. A 20 m wide exposure was sampled (D58), with the NRM direction being normally magnetised and consistent with outcrop.

A low coastal stack nearby lies just outside the positive aeromagnetic anomaly, and consists of exposures of basalt up to eight metres wide. NRM direction of sample D56, collected here, lies just outside the expected range of outcrop orientations and is reversed. Thus, the exposures forming the stack are probably not in situ.

Deviot

The ridge of coarse olivine basalt outcrop above Deviot is in situ and normally magnetised (sample D41). On the foreshore, 300 m north of the jetty, there is a 40 m wide exposure of closely-jointed, fine-grained basalt with common lherzolite xenoliths, similar to the Spring Bay nephelinite. Contacts are not exposed. Intertidal exposures 100 m back towards the jetty show sediments dipping 60°S, probably disturbed by landslide movement. However sample D28, of the fine-grained basalt, has NRM within the expected range of outcrop orientations and is normally magnetised (like the Spring Bay nephelinite). The exposure could be a small feeder. None of the basalts at Deviot is sufficiently voluminous to show on the aeromagnetic image, which is dominated by features attributable to Jurassic dolerite that shallowly underlies the Deviot area.

NRM intensities and modelling

Calculated intensities of NRM and magnetic susceptibilities of the basalts are given in Table 1. NRM ranges from 1 to 13 A/m. Repeat determinations suggest a precision of within 10%, but values determined for the relatively weak induced component (magnetic susceptibility, k) are probably of much lower precision. Magnetic susceptibilities determined with a hand-held meter are included for comparison. Koenigsberger ratios typically lie between 4 and 15. With both NRM directions and the present field steeply inclined, the aeromagnetic anomalies are therefore largely the result of remanence rather than magnetic susceptibility. The 'effective magnetisation' causing the anomalies is approximately the vector sum of the induced and remanent components.

The 'effective magnetic susceptibilities' (Leaman, 2002) of normally magnetised coarse olivine basalt ((Q+1)*k) average 0.09 0.06 SI units; and of reversely magnetised coarse olivine basalt ((Q-1)*k), -0.07 SI 0.06. The two determinations of normally magnetised nephelinite (average 0.09) are not significantly different from the coarse olivine basalt. These values are used here as a guide to modelling the anomalies, allowing semi-quantitative estimates of volumes to be made.

Leaman (2002) found that the average magnetic contrast of Jurassic dolerite is equivalent to a susceptibility of about

0.07 SI, and that lower parts of a sill may be significantly lower, averaging 0.03 SI.

Two sections modelled using Modelvision show a subsurface interpretation of several of the basalt units discussed above (fig. 6). Only shallow (<250 m) anomalies were modelled. Solutions are non-unique. An attempt has been made to achieve solutions that are as simple as possible within the constraints of the magnetic anomalies, magnetic properties of the rocks and known geology.

Section A–A'

This section extends across the central graben in a NNE direction through the reversely magnetised Rowella basalt (fig. 1).

The model suggests that the Jurassic dolerite at the southern end of this section has subvertical faults downthrowing towards the graben, and the upper surface of the dolerite is a sloping nonconformity where the fault scarps were eroded and onlapped as the graben filled with sediment. Reversely magnetised basalt, its base above sea level, forms Richmond Hill and descends below sea level further north (in accord with mapping). Around Waterton Hall, the basalt with gently inclined NRM (giving rise to a low positive effective magnetisation) can be modelled as a lenticular body partly overlapping and overlying the main Rowella basalt to the north.

The basal depth of the basalt in the Rowella-2 drill hole (134 m) is taken as an approximate constraint on the thickness of the main mass of the Rowella basalt. At this thickness, the magnitude of the negative anomaly requires a strongly negative effective magnetisation (-0.125 SI) for this body, suggesting an NRM intensity somewhat greater than the average, but well within the range observed for the coarse olivine basalts. Short wavelength anomalies in this area can be attributed to irregularities in the upper surface of the basalt. The broadly trough-shaped lower contact may reflect an oblique section through a channel filled by the basalt. This basalt has been dated at 47 Ma (Sutherland *et al.*, 2006).

The northern limit of this strongly reversely magnetised unit at the surface does not coincide with the coastal escarpment, but is set back from it by about 150 metres. There is plentiful exposure of basalt on the coastal escarpment and shoreline, and an outcrop sample on the coastal escarpment here (D43) is normally magnetised (Table 1). Drilling nearby shows that the basalt pinches out into sediments, about 150 m offshore to the north and 30 m below sea level (between BH3 and BH4, MRT plan 1903). Within these constraints, a small wedge of normally magnetised basalt, that overlies and partly overlaps the Rowella basalt, can be modelled (fig. 6).

Faulted dolerite forms the northeastern edge of the graben, and like the southern end of the section, the upper surface of the dolerite here slopes under the onlapping Paleogene sediments. A line of drill holes nearby gives good control on the southwesterly dip of the top of the dolerite in the subsurface under the eastern side of Long Reach; about 20° between BH7 and BH11 (see MRT plan 1903).

Section B–B'

This section extends from the west side of the graben just south of the Batman Bridge in a northeast direction across to East Arm (fig. 1).

Configuration of dolerite basement at either end of the section is similar to section A–A', except that the volumes are much smaller at the southern end. Normally magnetised basalt fills a small channel underlying the escarpment east of Whirlpool Reach. Further east, reversely magnetised basalt forms a thin tabular flow along the top of the ridge and fills two similar small channels that extend down to just below sea level, the more westerly coinciding with shoreline outcrop observed at Newmans Bay (see previous section). The Spring Bay nephelinite is associated with a high amplitude subcircular positive anomaly (fig. 2). The modelled effective magnetisation (0.11 SI) is the same as that determined from a sample of the nephelinite (D39), and the central peak (800 nT) can be resolved by postulating a subsurface vertical feeder beneath a tabular flow about 70 m thick (fig. 6).

The basalt forming the main ridge southwest of East Arm (Batman Highway basalt) is also associated with a large (600 nT) positive anomaly. This basalt has been dated at 33 Ma (Sutherland *et al.*, 2006). The amplitude of the anomaly requires significant thickness to this body and it is modelled as the fill of a substantial channel, with a floor below sea level. Consistent with this, in map view the anomaly is elongate, arcuate and truncated at either end by the modern estuary (fig. 2). The steepness of the modelled channel margins may be in part due to subsidence of dense lava into poorly consolidated sediments. The negative anomalies flanking the Spring Bay and Batman Highway basalts can be explained by the dipole effects at the margins of these bodies.

There is no clear field evidence for the age of the Spring Bay nephelinite relative to the Batman Highway basalt, which has been dated at 33 Ma (Sutherland *et al.*, 2006). Sutherland (1971) considered the nephelinite to be older, as the lateritic surface on its northern flank appears to dip under the Batman Highway basalt. The model (fig. 6) supports this interpretation, as the nephelinite spreads out, presumably as a flow, at a lower elevation than the (now eroded) shoulders of the channel harbouring the Batman Highway basalt. In map view, the Batman Highway basalt channel wraps around the Spring Bay nephelinite, although slightly separated from it (fig. 2), suggesting that at a higher erosional level the nephelinite may have been slightly more extensive than its present mapped extent, and the Late Eocene–Early Oligocene River Tamar was deflected around it.

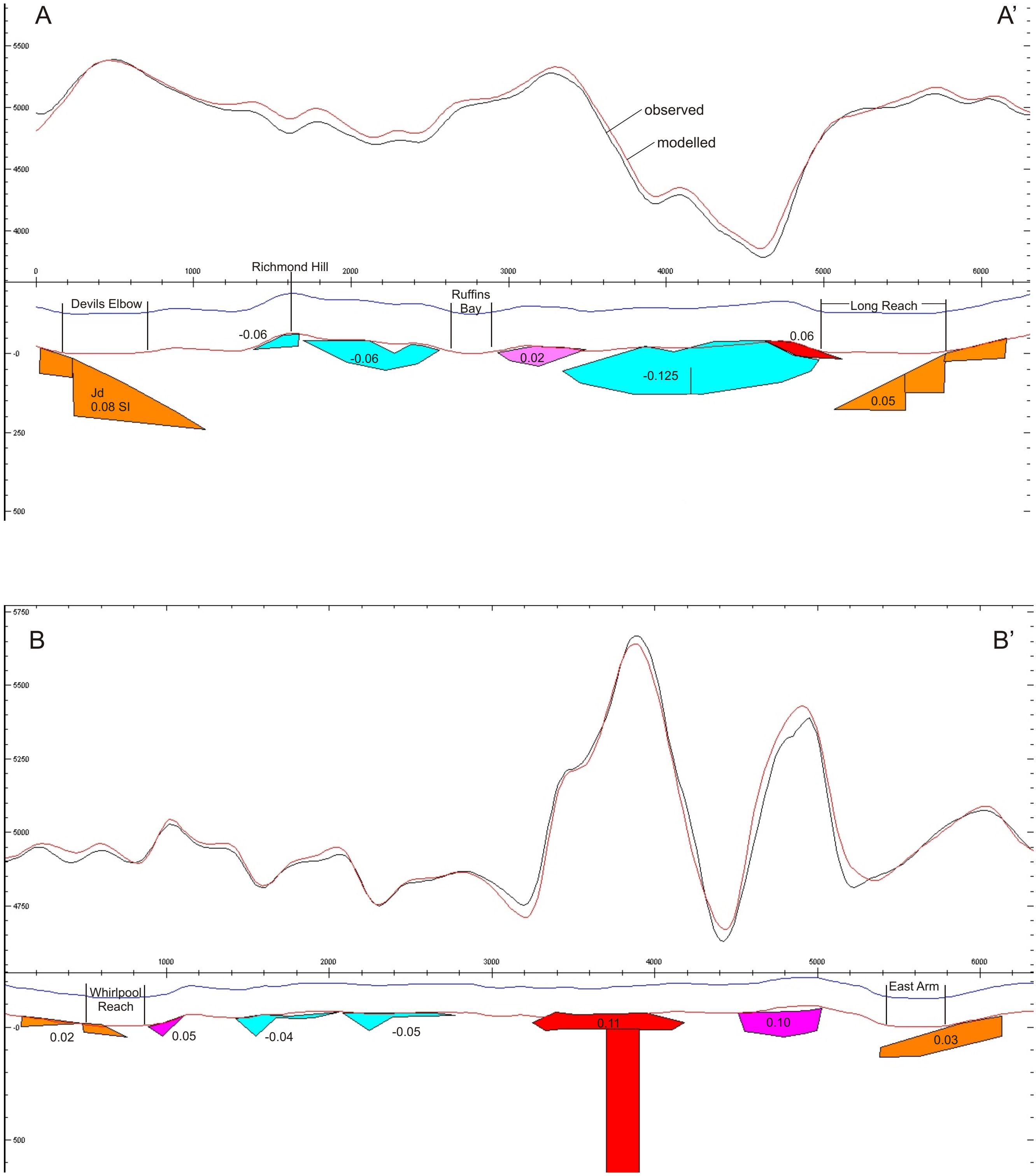

Figure 6

Modelled sections A–A’ and B–B’, magnetic units only shown.
Approximately 2   vertical exaggeration
(see Figures 1 and 2 for section locations).

Conclusions

Determination of NRM directions, using the relatively simple method of Breiner (1973), is shown to be a useful way of constraining rotation in Paleogene basalt and thereby helping to differentiate transported basalt from outcrop, and elucidating landslide mechanisms. Eight out of nine 'known' basalt outcrops have NRM directions consistent with the accepted mid-Paleogene pole position, making allowance for secular variation and measurement error. Basalt exposures south of Wilmores Bluff, at Ragged Islet, Lockwoods Point and Ratcliffes Point are rotational landslides. Exposures at Barretts Point and near Greenhythe are interpreted to be topples. A foreshore exposure near Point Rapid, two near East Arm and one near Johnstons Flats all appear to be transported (significantly rotated) although no particular landslide mechanism can be inferred. One other exposure near East Arm, one at Deviot, one at Newmans Bay and one at Hazelwood are interpreted as outcrop, supported in the latter two cases by aeromagnetic interpretation. Two samples near Davis Cove are significantly rotated, one in apparent accord with dip of bedding and columnar jointing, but there is no obvious landslip mechanism evident from modern topography.

There are many other problematic basalt occurrences in the Tamar Valley where this method could be used. Within the mapped area (fig. 1), many enigmatic coastal exposures between East Arm and Craigburn remain untested.

Determination of NRM intensities and magnetic susceptibilities allows the effective magnetic contrast of the basalts to be determined (Leaman, 2002), supporting forward modelling of aeromagnetic anomalies and constraining subsurface volumes of the basalts. The 47 Ma Rowella hawaiite is broadly lenticular and probably extends to at least 150 m below present day sea level. The samples with low inclinations near Davis Cove lie in an area of weak positive anomalism and a relatively shallow body of low effective magnetic contrast is inferred. The 33 Ma Batman Highway hawaiite fills a major (ancestral Tamar) channel, floored at or just below sea level, extending from Craigburn to East Arm. The base of the Spring Bay nephelinite flow is below the now eroded shoulder of the Batman Highway basalt channel, implying the nephelinite pre-dates the Batman Highway basalt. A large positive anomaly central to the nephelinite is modelled as a subvertical feeder pipe. Numerous other smaller flow remnants are present in the area, nearly all of coarse olivine basalt similar to the hawaiites, and of normal and reversed polarity. Some of these fill narrow (tributary) channels incised to below present day sea level.

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