Sedimentology of the late Palaeozoic Cape Jervis Formation, Troubridge Basin, South Australia

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Verity J. Normington,
Steven M. Hill,
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David Giles

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Department for Energy and Mining

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Verity J Normington[1,2], Steven M Hill[3], Caroline J Tiddy[1,4] and David Giles[1,4]

1 Deep Exploration Technologies Cooperative Research Centre (DET CRC)

2 Department of Earth Sciences, University of Adelaide, South Australia (currently at Northern Territory Geological Survey, Alice Springs NT)

3 Geological Survey of South Australia, Department for Energy and Mining

4 Future Industries Institute, University of South Australia

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Department for Energy and Mining
Level 4, 11 Waymouth Street, Adelaide
GPO Box 320, Adelaide SA 5001
Phone +61 8 8463 3000
Email dem.minerals@sa.gov.au
dem.petroleum@sa.gov.au
www.energymining.sa.gov.au

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FOREWORD

This report presents the results of the sedimentology of the sedimentary rocks carried out on five measured sections of the Cape Jervis Formation in the Troubridge Basin. Measured sections were systematically logged and sampled by the author and Dr Steve Hill during field trips between July 2010 and February 2012. Analytical methods include observations of the physical characteristics of the sedimentary rocks including detailed petrology and mineralogy. Petrological analysis was conducted by the author at Adelaide Microscopy at the University of Adelaide using thin sections prepared by Pontifex and Associated Pty Ltd in Adelaide. Mineralogical (spectroscopic) analysis and data processing was conducted by Georgina Gordon using the Hylogger^{TM} 3-3 at the Glenside Drill Core Storage Facility in Adelaide.

This report builds on research initially conducted by Ludbrook (1967) and expanded upon by Alley and Bourman (1984) and Bourman and Alley (1990, 1995, 1999) which focused on the millimetre- to centimetre-scale sedimentology as well as the depositional setting of the sedimentary rocks of the Cape Jervis Formation. These are duly referenced throughout this report. The depositional settings of the glacigene sedimentary rocks of the Troubridge Basin; based on the sedimentology are presented herein.

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Sedimentology of the late Palaeozoic Cape Jervis Formation, Troubridge Basin, South Australia

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ABSTRACT

The late Palaeozoic Cape Jervis Formation of the Troubridge Basin in southern South Australia provides a sedimentological record of the glacial environment during the Permo-Carboniferous glaciation. The sedimentary sequence is divided into five informal units that comprise the Cape Jervis Formation, and preserve sedimentological features that have been used to constrain the glacial setting and associated depositional mechanisms during this time. Landscape features such as glaciated pavements and the presence of lodgement till diamictite suggest that the glacial setting was a wet-based, continental icesheet with ice tongue glaciers at the front margin of the icesheet. The icesheet advanced in a north to northwest direction forming glaciated bedrock surfaces and depositing lodgement till. The fluviolacustrine beds suggest that the icesheet was then stagnant, which facilitated the formation of glacial lakes and meltwater streams. The icesheet then began to decay and retreat southward. Ablation of the ice resulted in deposition of a flow till complex, and caused a eustatic rise that resulted in a marine transgression and subsequent deposition of glaciomarine sedimentary rocks.

INTRODUCTION

Palaeogeographic reconstructions of Australia during the late Carboniferous to earliest Permian, supported by palaeomagnetic data (Creer 1968, Embleton and Valencio 1977, Embleton and Schmidt 1977, Isbell et al. 2012) and numerous lines of geological evidence (e.g. Crowell and Frakes 1971b, Martin 1981, Archbold 1982, Caputo and Crowell 1982, Ireland et al. 1998, Scheffler et al. 2003, Foden et al. 2006, Veevers 2006); consistently place Australia and Antarctica in an amalgamated high-latitude southerly configuration; as part of the supercontinent Gondwana. There is consensus amongst researchers that a large continental ice mass grew over Antarctica and spread across southern Australia as Gondwana drifted across the South Pole (Crowell and Frakes 1971a, Alley et al. 1995). The Australian portion of the ice mass is suggested to have developed by the end of the Carboniferous and reached its greatest extent by the earliest Permian, after which it rapidly decayed (Alley et al. 1995).

The most definitive evidence for the late Palaeozoic glaciation in South Australia is preserved within the sedimentary rocks of the Cape Jervis Formation. The Cape Jervis Formation is exposed across most of the Fleurieu Peninsula, the southeastern coastal cliffs of the Yorke Peninsula and eastern Kangaroo Island in a geographic area first referred to by Wopfner (1972) as the Troubridge Basin (Fig. 1a). Glaciated pavements are extensive throughout the Fleurieu Peninsula (Fig. 1b), and glacially-derived sedimentary rocks have been observed across most of the basin. It is likely that the Troubridge Basin and the other now disconnected basins are remnants of a much larger glacial system.

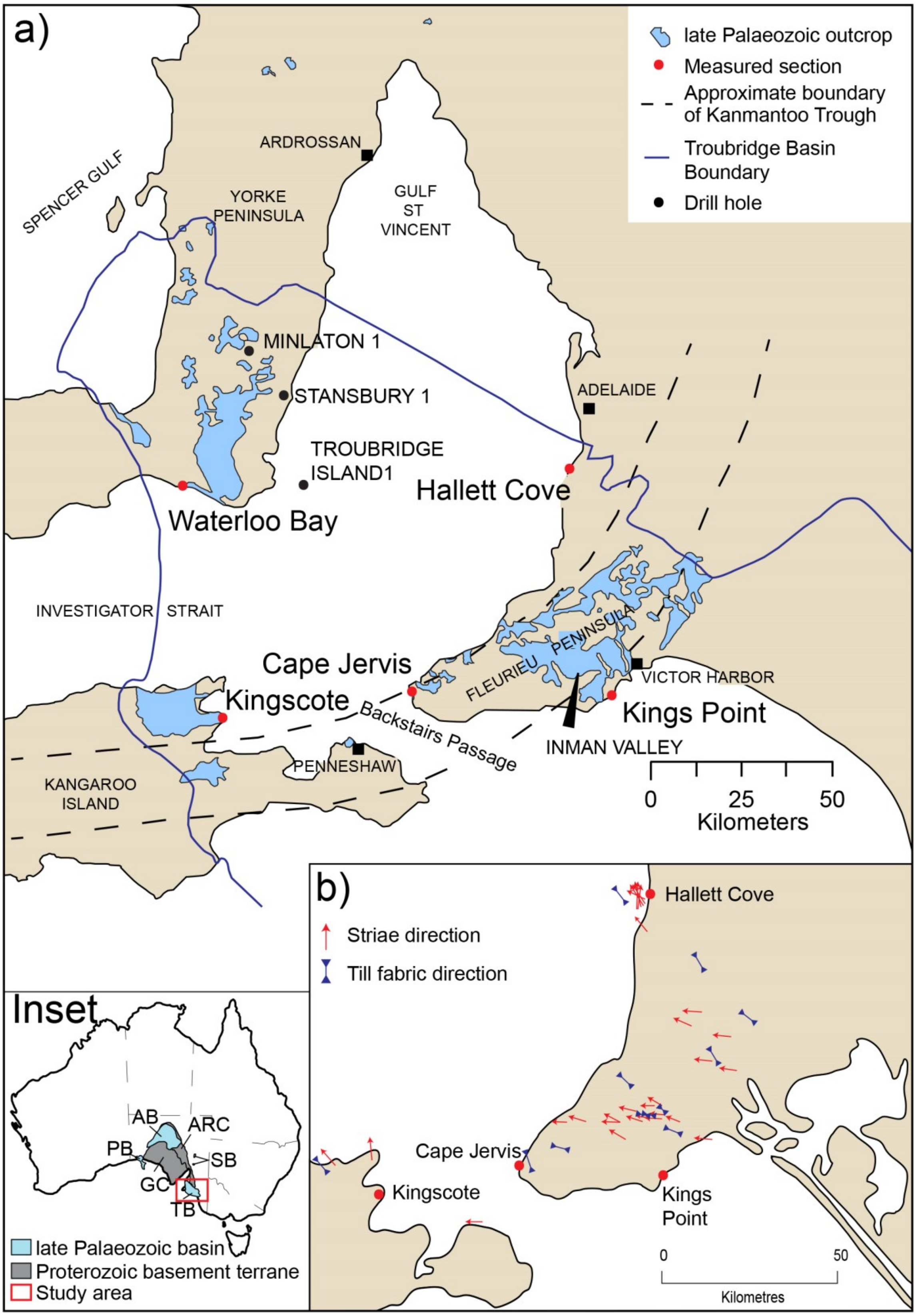

Figure 1. a) Approximate limits of the Troubridge Basin adapted from Alley and Bourman (1995), showing exposures of the late Palaeozoic Cape Jervis Formation adapted from Thompson and Horwitz (1962), Crawford (1960) and Fairclough (2007). Key locations and drillholes are also shown; b) Ice movement direction in the Troubridge Basin based in till fabrics and striae orientations adapted from Bourman and Alley (1990). Inset: location of study area (red box) in relation to Australia and significant basement terranes (grey) and late Palaeozoic basins (blue). AB: Arckaringa Basin; ARC: Adelaide Rift Complex; GC: Gawler Craton; PB: Polda Basin; SB: Springfield Basin; TB: Troubridge Basin.

Small-scale depositional models localised around key sections of the Cape Jervis Formation have been derived from sedimentological studies (e.g. Alley and Bourman 1984, Bourman and Alley 1990, 1995, 1999). Basin- to continental-scale models that interpret the evolution of glaciation have also been developed (e.g. Crowell and Frakes 1971b, Embleton and Valencio 1977, Veevers 2006). Further definition of the depositional setting of the sedimentary rocks of the Cape Jervis Formation requires correlation of the sedimentology across the basin, identification of differences between units at the key sections, as well as differences within the same unit across the basin. The widespread and extensive exposure of the Cape Jervis Formation provides an opportunity for such an investigation.

The composition and mineralogy of the sedimentary rocks would provide a greater insight to the glacial environment as well as the degree of transport and post-depositional alteration the sedimentary rocks have undergone. This would provide information relevant to which sedimentary rocks could be targeted for geochemical analysis to provide the most accurate representation of the sedimentary rocks prior to surficial alteration such as oxidation.

This report builds on previous studies of the glacigene sedimentary rocks within the Troubridge Basin and adds to them by re-examining the sedimentology (including at microscopic scale) with emphasis on the mineralogy and composition of the Cape Jervis Formation at key sections across the Troubridge Basin. The recognition of subtle sedimentary features and changes to the clast morphology allows a more detailed and specific depositional setting to be constructed. This report also discusses lateral variations in the sedimentological record and depositional environment of individual units. Sedimentological differences across the basin that may have resulted from subtle changes in the glacial environment as it progressed across the basin are discussed.

GEOLOGICAL SETTING

The Troubridge Basin was first defined by Wopfner (1972). The sediments were assigned to the Cape Jervis Formation by Alley and Bourman (1984, after Ludbrook 1967) who nominated the coastal cliffs of Cape Jervis as the type section. The Cape Jervis Formation varies in thickness from <5 to 50 m where it is exposed on shore but is locally in excess of 1000 m where it has been intersected in offshore drill holes (Flöttmann and Cockshell 1996). The Cape Jervis Formation is the only unit within the Troubridge Basin and unconformably overlies a variety of Neoproterozoic to Cambrian rocks and is partially overlain Jurassic to Quaternary-aged sedimentary rocks (Crawford 1965, Johnson 1982a, 1982b, Alley and Bourman 1984, Bourman and Alley 1990, 1999, Zang and Hore 2001, 2003).

The Cape Jervis Formation has an upper age constraint of Sakmarian (295–290 Ma; Table 1) age based on foraminifera observed at Cape Jervis and Waterloo Bay and in drill holes Minlaton 1, Stansbury 1 and Troubridge Shoal 1 (Fig. 1; Ludbrook 1967, 1969, Harris and McGowran 1971, Foster 1974). Age constraints of individual units are summarised in Table 1. As yet no dates have been ascertained for unit one of the Cape Jervis Formation and hence the age of initial deposition remains unconstrained. However, it has been postulated that the glaciation initiated in the late Carboniferous and reached its maximum extent by the early Permian (Sakmarian; Alley and Bourman 1984, Alley et al. 2013).

Table 1. Summary table of characteristics for each of the units within the Cape Jervis Formation and description of lithologies used to correlate sections within the Troubridge Basin.

Unit, unique lithology, age	Characteristic of unique lithologies	Overall unit characteristic	Palaeoenvironmental interpretation
Glaciomarine sediments (unit 5) – clay, Late Asselian-Sakmarian (295–290 Ma)[1, 2, 3, 4]	• Green • Massive • Prismatic fracturing	Dominated by clay, with occasional sandstone beds	Ice-influenced cold water, relatively deep water slope[a, c]
Flow till complex (unit 4) – diamictite	• Unconsolidated or clast-supported • Typically coarsen upwards	Diamictite beds interbedded with sandstone, silt clay and pebble beds	Subglacial or subaqueous deposition with intermittent fluviolacustrine and debris flow depositional processes[a, b, c]
Fluvioglacial beds (unit 3) – clay	• Grey-green clay • Fine to coarse sandstone beds • Finely laminated, thin beds • Variable matrix-supported diamictite – clay to coarse-grained sand • Clasts - up to 40 cm - large proportion subrounded to rounded - lithology variable	Clay beds interbedded with sandstone and diamictite beds with rounded and striated dropstones	Subaqueous or subglacial deposition with sediment heavy flows, channel fill, ice rafted debris flows and minor channel flows[a, b]
Lodgement till (unit 2) – diamictite, Asselian (298–295 Ma) age[5, 6]	• Matrix-supported • Sandstone matrix • Clasts - up to 10 cm - angular to rounded - dominantly locally sourced - faceted and striated • Massive, structureless and well consolidated	Only diamictite seen in the unit	Subglacial deposition with debris flow[a, b, c]
Basal fluviolacustrine and glaciolacustrine sedimentary rocks (unit 1)	Not observed	Fine-grained, cross-bedded sandstone with thin lenses of diamictite and occasional dropstones	Fluvioglacial deposition with scour fill and subglacial fluvial flows[a, b]

Unit characteristics are based on observations by the author, Alley and Bourman (1984) and Bourman and Alley (1990, 1995). Age of the units is constrained by palynological studies by [1, 2]Ludbrook (1967, 1969), [3]Harris and McGowran (1971), [4]Foster (1974), [5]Bourman and Alley (1990) and [6]Alley and Bourman (1995). Palaeoenvironmental interpretation is based on observations made by [a]Eyles et al. (1998), [b]Miall (2000) and [c]Bennett and Glasser (2009).

In addition to Alley and Bourman's (1984) formation defining study, there have been a series of studies focussed on key stratigraphic sections of the Cape Jervis Formation. Studies at Kangaroo Island (Bourman and Alley 1999, Alley et al. 2013), Kings Point (Bourman and Alley 1995) and Hallett Cove (Bourman and Alley 1990) included the identification and stratigraphic logging of the Cape Jervis Formation glacigene sedimentary rocks and refinement of their interpreted depositional setting. Other investigations have concentrated on exposures of the Cape Jervis Formation away from coastal cliffs on the Fleurieu Peninsula (including Mawson 1962, Milnes and Bourman 1972, Bourman et al. 1976, Bourman and Milnes 1976, Milnes et al. 1981) and identified glacial landscape features such as roche moutonnée, erratic fields and glaciated pavements. Crawford (1965) identified and described the sedimentary rocks of the Cape Jervis Formation across the Yorke Peninsula while Foster (1974) investigated the palynology of the sedimentary rocks in the coastal cliffs of Waterloo Bay, southern Yorke Peninsula.

Alley and Bourman (1984) divided the Cape Jervis Formation into five informal units with each reflecting a different depositional setting: 1) basal fluvioglacial and glaciolacustrine sedimentary rocks; 2) lodgement till; 3) fluviolacustrine beds; 4) flow till complex; and; 5) glaciomarine sediments (Alley and Bourman 1984). The characteristics of each unit are summarised in Table 1.

The basal fluviolacustrine and glaciolacustrine sedimentary rocks of unit one (Table 1) are interpreted to have been deposited during the initial stages of glaciation in a basin where glacial lakes formed at the front of an icesheet (Alley and Bourman 1984). Alley and Bourman (1984) note that the sedimentary rocks of unit one were observed in an excavation at the base of the Cape Jervis type section, however, this excavation is now covered in scree. Unit two has been interpreted by Alley and Bourman (1984) as a lodgement till. Numerous frost-shattered, polished, striated and glaciated pavements on the Fleurieu Peninsula and Kangaroo Island (Fig. 1b) are immediately overlain by sedimentary rocks assigned to unit two (Table 1). Alley and Bourman (1984) inferred that unit two was deposited at the base of a wet-based glacier. Local differences in ice movement direction recorded by striations (Fig. 1b) reflect deviation of the icesheet around topographic features (Bourman 1986).

Bourman and Alley (1990, 1995) suggest that the alternating clay, sand and diamictite beds of the fluviolacustrine beds (unit three; Table 1) are the result of variable ice decay rates. They also postulated that the icesheet was stagnant in the Gulf St Vincent, and that materials were deposited around the icesheet via meltwater streams. Small lakes formed, some of which contained icebergs that released dropstones as they melted. Unit four is interpreted as flow till complex by Alley and Bourman (1984) which is in sharp contact with the underlying fluvioglacial sedimentary rocks. Unit four is interpreted to have been deposited as the icesheet retreated, resulting in meltwater streams with increased energy and sediment load. The uppermost unit of the Cape Jervis section (unit five) marks an abrupt change to glaciomarine sediments (Alley and Bourman 1984). These sedimentary rocks were deposited in shallow marine conditions that are influenced by the fluvial input of glaciers and icebergs melting nearby (Alley and Bourman 1984).

The initial migration of the icesheet caused gelifract (fracturing of the bedrock via freezing of the substrate prior to ice presence; Alley and Bourman 1984), scouring of U-shaped valleys and glacial pavements and deposition of diamictite (Bourman and Alley 1988). The evolution from unit one to unit five has been interpreted by successive workers (e.g. Bourman 1973, Alley and Bourman 1984, Bourman 1986, Bourman and Alley 1990, 1995, 1999) to represent a cycle of broadly northward glacial advance beginning in the late Carboniferous (unit one and two), followed by stagnation in the Gulf St Vincent resulting in the deposition of sandstone and clay units, suggesting meltwater streams and glacial lakes formed during this stage (unit three; Bourman and Alley 1990). Southward decay of the icesheet and further retreat deposited diamictite units with sandstone beds (unit four) was then followed by the final stage of deglaciation. The final wasting of the glacier lead to an eustatic rise and deposition of glaciomarine clay and sand units (unit five; Alley and Bourman 1984).

METHODS

SAMPLE COLLECTION

Suitable sites for logging and sampling were selected based on the exposure being extensive enough to allow sampling through the stratigraphic profile. Profiles sampled for this study were from Cape Jervis, Kings Point, Hallett Cove, Kingscote, and Waterloo Bay (Table 1). These sections are in the same or similar locations to the sections investigations by previous researchers as these sites are the most complete, best exposed and accessible sections across the basin. The previous studies provided a guide to the basic lithology of the sedimentary rocks.

Samples were collected at each change in lithology or every metre if no change occurred. Five to ten centimetres of overlying material was removed prior to sample collection to reduce risk of surface contamination. Approximately 0.5 kg of sample was then removed using a geo pick and put into a clean, plastic snap lock bag. Each bag was labelled with a predetermined sample number and location name. For each sample, a GPS location was recorded along with a description of the sediment lithology and any overprinting and weathering that was apparent. Surrounding field relationships were also recorded as well as information such as vegetation growth or proximity to possible contaminants such as roads or the possibility of sea spray. Samples were collected for investigations into the petrography and mineralogy of the sedimentary rocks as well as detailed sedimentological descriptions. Splits of selected samples were used for geochronological and geochemical analysis (results not detailed in this report). The samples were of varied lithologies including sand, clay, silt and diamictite with varying degrees of weathering.

MINERALOGICAL ANALYSIS

The mineralogy of samples was investigated using petrographic and spectroscopic analysis. Petrographic analysis of thin sections determined relationships between grains and matrix as well as alteration. Petrologic analysis was performed on representative samples from each unit within the Cape Jervis section. These samples were selected based on being representative of each of the preserved units, having minimal post-depositional alteration and their consolidated nature.

Petrological thin sections (dimensions: 7.5 x 2.5 cm) of consolidated sediment were prepared by Pontifex and Associates Pty Ltd, Adelaide. Slides are polished and are without a cover-slip. Petrographical analysis was done at Adelaide Microscopy, University of Adelaide using a Nikon Petrographic Microscope.

Spectroscopic analysis was used to determine the bulk mineralogy of samples and was performed on all samples collected. A representative split of each sample was placed into black chip trays and analysed in black chip trays using the HyLogger™3-3 at the Core Storage Facility in Glenside, Adelaide. HyLogger™ Core Scanning and HyChips™ modes were used to detect the visible to shortwave infrared (Vis-SWIR: 380-2500 nm), and the thermal infrared (TIR: 6000-14500 nm, core logging mode only) wavelengths. The minerals identified using infrared wavelengths include white micas, kaolinite, carbonate minerals in the SWIR, and tectosilicates such as pyroxene, silica, feldspars and garnets in the TIR. High resolution images were taken on every sample every 2 mm. HyLogger™ core logging mode analysis was done by scanning across each sample four times, allowing for overlap to maximise the viable spectra. HyChip™ mode analysis was done by scanning three times using only Vis-SWIR wavelengths. Three readings were taken per sample.

Results were processed using The Spectral Geologist (TSG) HotCore software to allow viewing in the free TSG Viewer software provided by AusSpec International Inc. Data processing included removal of data from any non-sample material (e.g. black plastic of the chip trays). Processing did not account for geological context of the samples or removal of any specific mineral species prior to processing. Routine machine calibrations were performed prior and post-analyses.

SEDIMENTOLOGY AND MINERALOGY

In this section, the field observations, spectroscopic mineralogy and petrography of the sedimentary rocks within the Cape Jervis Section have been described in detail as the section is the type section for the Cape Jervis Formation. Other measured sections investigated are discussed in relation to how the sedimentary rock differ from the type section. Stratigraphic logs and field images are provided for each section. Detailed descriptions of measured sections away from Cape Jervis are in Appendix 1.

CAPE JERVIS TYPE SECTION

The most complete section of the Cape Jervis Formation is within two coastal cliffs of Cape Jervis, north of the lighthouse (Fig. 2a). The type section occurs within two, steep erosional gullies. The southern gully (here informally termed section A; Fig. 2a) was originally described by Ludbrook (1967). Alley and Bourman (1984) used Section A and a second gully to the north (here informally termed Section B; Fig. 2a) to define the Cape Jervis Formation and develop a composite type section. The composite section begins approximately 10 m above the shore platform and extends for approximately 50 m to where the Cape Jervis Formation is overlain by limestone and calcareous sandstone of the Quaternary Point Ellen Formation with calcrete at the top of the cliff. The Cape Jervis Formation overlies the very steeply dipping, Cambrian Kanmantoo Group metasedimentary rocks, and the section is in part deposited against the steeply sloping bedrock valley surfaces of the cliffs and U-shaped valleys (Alley and Bourman 1984). All five units of the

Cape Jervis Formation as defined by Alley and Bourman (1984) are preserved within the section, however, unit one is now not exposed and covered by scree.

The base of the section (0–1.5 m) comprises frost-shattered (or gelifract) Cambrian Kanmantoo Group metasedimentary rocks (here called bedrock), or gelifract bedrock and approximately 1 m of bedrock rubble (Fig. 3a). The Cambrian metasedimentary rocks are bedded at decimetre to metre-scale and vary from metagreywacke to metasiltstone (Fig. 3a). They are dark-grey and contain abundant quartz, minor feldspar and lithics and a variable pelitic component characteristic of relatively immature turbiditic sedimentary rocks. Muscovite, goethite, hematite and nontronite have been identified by hyperspectral analysis (Fig. 2b). Amongst the scree deposits, on the shore platform, and near the gelifract at the base of the section are large, rounded, polished and occasionally striated Encounter Bay Granite erratics, some of which are up to 5 m in diameter (Fig. 3b).

Unit two (1.5–7 m) has an unusual depositional geometry, being deposited against the sloping bedrock surface of the valley where it is overlain by other units of the sequence. The unit is dominated by matrix-supported diamictite with angular to rounded, polished and faceted clasts, mostly less than one centimetre diameter but occasionally up to 10 cm, comprising approximately 30% of the rock. Pebbles and cobbles, up to 20 cm diameter, become more common toward the top of the unit. The clasts are dominantly metasedimentary rocks comparable to the underlying Kanmantoo Group with lesser granitic rocks that are texturally and mineralogically comparable to the Encounter Bay Granite which is exposed in the Victor Harbor region (Fig. 1a) about 55 km to the south-southeast. The matrix of the diamictite is buff-coloured, poorly-sorted, medium- to coarse-grained and relatively unconsolidated sand. The sand is dominated by quartz grains that range from 300 to 1200 μm and average about 500 μm (Fig. 3c). Subrounded to rounded grains of feldspar (largely altered to kaolinite; Fig. 3c) and muscovite are also present. These grains are surrounded and supported by a cement of clay, Fe-oxide minerals (identified as hematite and goethite in the hyperspectral data) and lesser siderite (Figs 2b and 3c).

Two lenses of poorly sorted, clast-supported pebble and cobble lenses up to 20 cm thick are preserved within the diamictite at approximately 4 and 7 m. These lenses comprise rounded, faceted clasts, mostly less than 10 cm in diameter with some (<10%) up to 50 cm (Fig. 3d, e). The clast lithologies are consistent with those in the diamictite being dominated by metasedimentary rocks and granite. Large (up to 1 m) clasts of granite occur throughout unit two. Rounded, polished and occasionally striated granite erratics, some of which are up to 5 m in diameter (presumably sourced from unit two) are scattered along the foreshore (Fig. 3b).

Unit three comprises 20 m of heterolithically bedded clay and sand beds with occasional beds of diamictite, pebble and cobble lenses and isolated boulders (Fig. 3f). The lower 7.5 m of unit three (7–14.5 m) is dominated by very thinly bedded (centimetre-scale), fine-to medium-grained, yellow to orange sand and minor clay. At the type section, bedding is tilted toward the east at 15–20° (Fig. 3f), in comparison to the flat-laying underlying unit two and overlying upper unit three. The sedimentary rocks are poorly-sorted, with grain sizes ranging from 20 to 500 μm, and dominated by subangular to subrounded grains of quartz and feldspar (Fig. 3g). Occasional subrounded rock fragments greater than 500 μm are also present (Fig. 3g). The grains are surrounded by a cement of secondary minerals of mixed clay and Fe-oxide minerals (identified as kaolinite, montmorillonite, goethite and hematite in the hyperspectral data; Fig. 2b). Two pebble and cobble lenses are preserved within the tilted beds at 10 and 14.5 m (Fig. 2b). These lenses are approximately 20 cm wide and are dominated by rounded, polished, striated and faceted metasedimentary rocks and minor granites that are 5–10 cm in diameter (Fig. 3f).

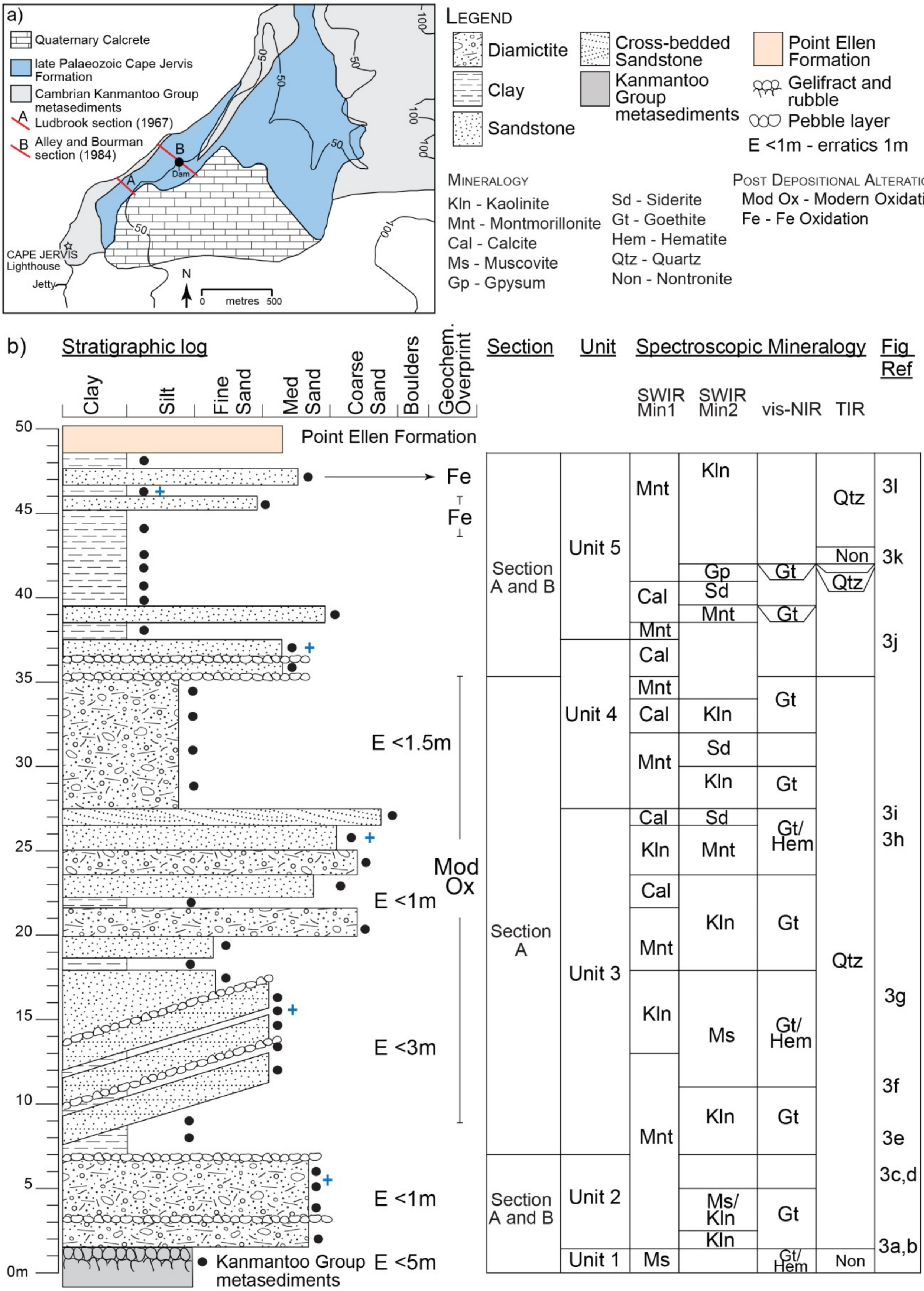

Figure 2. a) Simplified regional geology of the Cape Jervis area adapted from Alley and Bourman (1984) showing section locations; b) Stratigraphic log of the sedimentary rocks including an indication of which section units are within, the unit and the spectroscopic mineralogy. The location of Cape Jervis is shown in Fig. 1. Blue cross: thin section location; black dot: sample location of HyLogger™ analysis. Units as described by Alley and Bourman (1984).

Figure 3. Photos a–h of the Cape Jervis measured section.

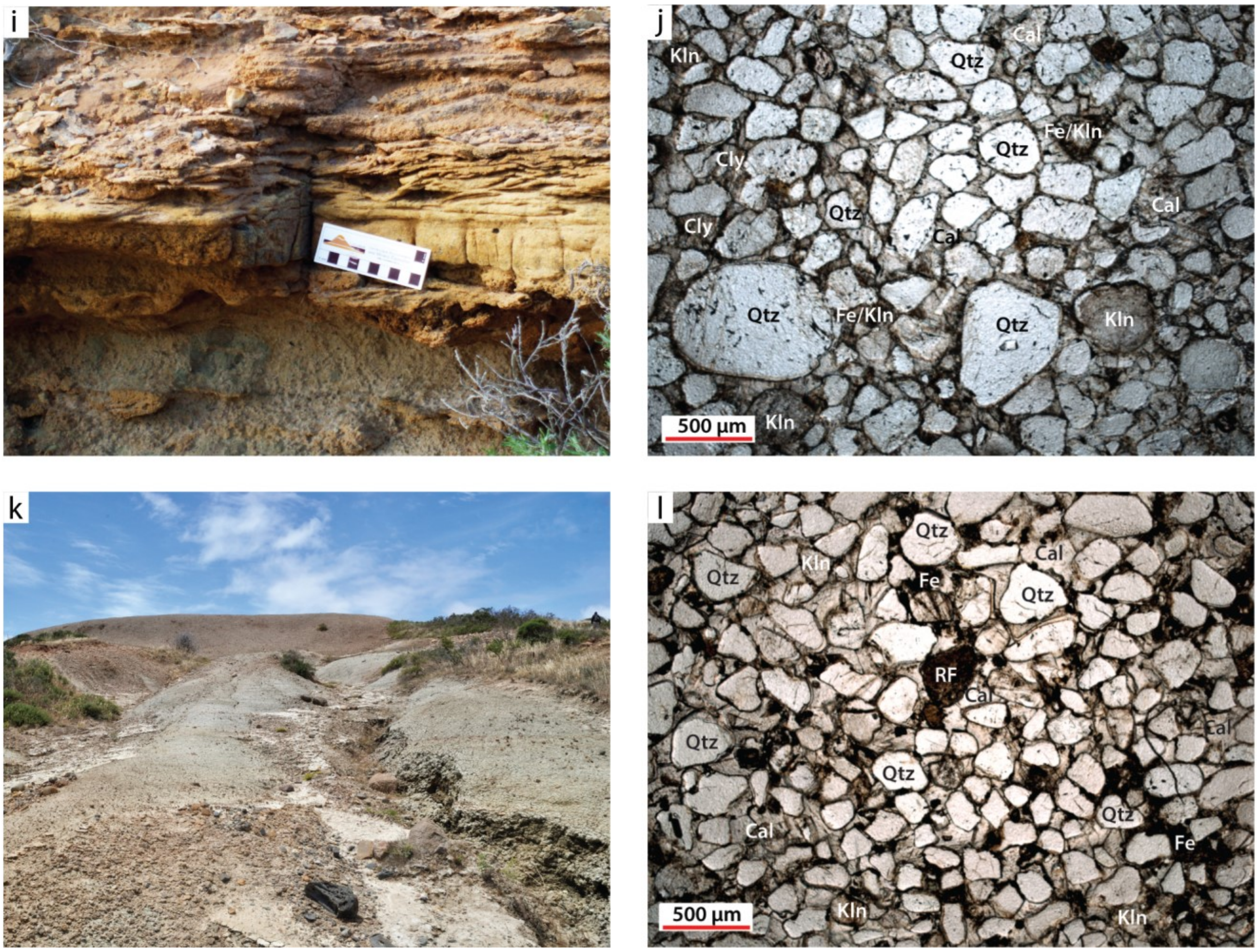

Figure 3. Photos i–l of the Cape Jervis measured section.

a) Fractured (gelifract) Kanmantoo Group metasedimentary rocks at the base of the Cape Jervis Section (at 0–1.5 m), orange lichen commonly grows on the exposed surfaces;
b) Large Encounter Bay Granite erratic at the base of the Cape Jervis Formation type section;
c) Photomicrograph of the matrix-supported diamictite of unit two. The sample was collected from a height of 5 m;
d) Striated and faceted Kanmantoo Group metasediment dropstone within the diamictite of unit two (at 6 m);
e) Pebble and cobble layer within unit two at a height of 7 m, showing the rounded nature and size (up to 10 cm) of the clasts. Matrix-supported diamictite containing smaller (>5 cm) clasts can be seen below the pebble and cobble layer;
f) Tilted beds from 7–14.5 m (as outlined by dotted lines) of the base of the fluviolacustrine beds (unit three). Erratics of Kanmantoo metasedimentary rocks (approximately 1 m) and Encounter Bay Granite (approximately 3 m) can be seen in the foreground;
g) Photomicrograph of clay bed at 15.25 m within the tilted beds of unit three showing very fine-grained to clay sized subrounded to angular quartz grains within a ferruginous cement;
h) Photomicrograph of flat-lying beds within the fluviolacustrine beds (unit three) at 25.25 m comprising of subrounded quartz grains and rock fragments;
i) Laminated sandstone beds of unit three at 26.5 m the top of the unit three, flaggy beds above the scale bar have poorly preserved cross-beds;
j) Photomicrograph of laminated sandstone at 37.2 m near the top of unit four showing angular to rounded quartz grains within a calcareous cement;
k) Massive, green grey clay of unit five at 39.5–45 m. Photo taken looking up section B to the southeast;
l) Photomicrograph of the first sandstone lens at 46.3 m within the of unit five, the quartz grains are <100 µm with clay cement. Qtz: quartz; Kln: kaolinite; Cal: calcite cement; Sd: siderite; Fe: Fe-oxide mineral cement; Fe/Kln: Fe-oxide mineral and kaolinite cement; cly: clay mineral; RF: rock fragment; PS: pore space; approximate location of photos are shown in Fig. 2b.

The upper 12.5 m of unit three (14.5–27.5 m) comprises flat-lying beds of sandstone, diamictite and minor clay interbedded at metre-scale (Fig. 2b). The sand and sandstone dominated horizons are typically yellow to brown, poorly-sorted with angular to subrounded grains of quartz, feldspar, lithic fragments and a mixed clay and Fe-oxide mineral cement. Individual horizons differ on the basis of their finest fraction, which increases up-sequence from fine- to coarse-grained sand. Clasts up to 5 cm in diameter comprise <20% of the rock and are dominated by metasedimentary material comparable to the underlying Kanmantoo Group. The uppermost sandstone bed (27 m) in unit three is distinctive in that it exhibits poorly-preserved, 1–10 cm cross-beds (Figs 2b and 3i). The sandstone beds from 26–27.5 m in unit three (Fig. 3i) do not contain clasts larger than 1 cm diameter. The diamictite beds within the upper parts of unit three (between 20 and 25 m) are up to 20 cm thick in 1.5 m bed sets (Fig. 2b). Clasts within the matrix-supported diamictite are poorly-sorted, subrounded to rounded, up to 4 cm in diameter within a matrix of coarse-grained sand.

Scattered throughout unit three are isolated pebbles and boulders of metasedimentary rock and granite that are typically polished, faceted and striated. The sedimentary rocks immediately underneath some of the metasedimentary boulders are compressed, while the overlying beds are draped over the stone, consistent with the boulders being deposited as dropstones. In contrast, the granite boulders do not appear to contort the underlying sedimentary rocks; rather the sedimentary rocks are often deposited against the granite boulders suggesting they had been in place prior to the deposition of unit three.

Within the upper 5 m of unit three (22.5–27.5 m), calcite commonly forms a crystalline cement that efficiently fills the intergranular spaces of 1 cm diameter (Fig. 3h). This is a significant change compared to the Fe-oxide and clay minerals that occupy the pore spaces in unit two (Fig. 3c) and the lower parts of unit three (Fig. 3g).

The base of unit four (27.5 m) is a buff-coloured, clast-supported diamictite that is 8.5 m thick (Fig. 2b). Smaller clasts (<5 cm) within the diamictite are rounded to angular metasedimentary rocks with comparable composition to the underlying Kanmantoo Group. Larger clasts (up to 20 cm) are subrounded to rounded, mostly polished, faceted and striated and are metasedimentary or granitic in composition. The loosely consolidated matrix of the diamictite is medium- to coarse-grained sand with approximately 40% silt.

Overlying the diamictite, at 35–37.5 m, is 2.5 m of laminated, calcareous, fine-grained sandstone interbedded with lesser medium- to coarse-grained sand lenses and two narrow pebble and cobble lenses (Fig. 2b). The sandstone is buff to yellow and dominantly comprises poorly sorted, angular to subrounded quartz grains up to 500 µm. Minor detrital feldspar, now altered to kaolinite, with the same size and shape as the quartz grains is also present (Fig. 3j). Sand lenses have the same characteristics as the sandstone but are friable and typically unconsolidated. The pebble and cobble lenses are unconsolidated, and comprise rounded pebbles up to 10 cm in diameter within a matrix of fine-grained sand with a minor clay component. The clasts up to 10 cm in diameter are either metasedimentary or granitic. Calcite is an abundant phase throughout unit four, forming an intergranular cement within pore spaces along with minor kaolinite, montmorillonite and Fe-oxide minerals (Fig. 3j).

Unit five is approximately 11 m (37.5–48.5 m) of massive to bedded, green clay beds interlayered with occasional thin sandstone beds (Fig. 2b). The massive clay (37.5–45 m) is up to 7.5 m thick (Figs 2b and 3k). Prismatic fracturing occurs within the clay immediately overlying the sandstone at the top of unit four. Bedding within the clay becomes more defined upwards. The clay comprises montmorillonite and kaolinite with minor siderite (Fig. 2b). The clay is mostly green in colour (Fig. 3k). Several red to orange beds are preserved in the middle of the clay unit and are silty and gritty. The clay is interbedded with medium-grained, buff to yellow sandstone beds, up to 20 cm thick, these occur at 39, 45 and 47 m. The sandstone beds comprise poorly sorted, angular to subrounded quartz and occasional kaolinite grains that range from <50 to 500 µm (Fig. 3l). Calcite and minor goethite cement completely fills the pore spaces. (Figs 2b and 3l). Unit five has a sharp contact with the overlying calcareous, coarse-grained sands, limestone and calcrete of the Quaternary Point Ellen Formation.

HALLETT COVE SECTION

The northernmost known occurrence of the Cape Jervis Formation on the Fleurieu Peninsula is in the coastal cliffs of Hallett Cove (Figs 1a and 4a). The area is host to a well-preserved exposure of Cape Jervis Formation and the underlying glaciated pavements. The section investigated begins at the edge of the shore platform and is exposed in a 30 m interval in the incised gullies of Sugarloaf Creek (Fig. 4a). Units two and three are observed at the Hallett Cove section.

The basement rocks within the Hallett Cove area dominantly comprise Neoproterozoic Wilpena Group as opposed to the type section that is underlain by the Kanmantoo Group. The Wilpena Group at Hallett Cove comprises green-grey and purple micaeous siltstone. These sedimentary rocks are well preserved as a glaciated pavement, which is best exposed at the top of Black Cliff, north of Sugarloaf Creek (Fig. 5a). The glaciated pavement has been polished and striated and preserves chatter marks and grooves (Fig. 5a). Bourman and Alley (1990) calculated a northwesterly ice movement direction using measurements of the striae and till fabric studies. There is no exposed glacial bedrock pavement at the base of the measured section, at Sugarloaf Creek, however, diamictites overlie polished pavement at Black Cliff (Fig. 5b). There are no polished pavements at the type section.

Unit two at Hallett Cove is up to 6 m thick, although only 2 m is exposed. The matrix-supported diamictite (0–2 m) differs from the type section in that clasts comprise up to 70% of the whole rock and range from 1–45 cm in size. At the type section there is a lesser percentage of smaller clasts. The clast composition is dominated by the underlying stratigraphy as it is at the type section. The diamictite matrix coarsens upward from grey-green sandy clay to buff coloured coarse-grained sand (Fig. 4b). The top of unit two and bottom of unit three in this area is obscured by approximately 4 m of grasses and aeolian sands (Fig. 4b).

Unit three (5.5–31 m) in the Hallett Cove measured section comprises ~26 m of clay, silt and medium- to coarse-grained sand beds with minor diamictite and cobble and pebble beds (Figs 4b and 5e–g). The lowermost 8 m of unit three (5.5–13.8 m) comprises silty clay (clay with 50–70% silt) beds interbedded with lesser medium to coarse-grained sand beds. The silty clay beds are pale grey with orange and red mottles and up to 2 m thick. Silty clay beds were not observed at the type section (Fig. 2b), instead 8.5 m of tilted, fine- to medium-grained sandstone beds dominate the base of the unit.

The sand, sandstone, clay beds with occasional diamictite beds from 13.8–31 m (Fig. 4b) are similar to those at the top of unit three at the type section (Fig. 2b). From 13.8–22 m, red and purple, medium- to coarse-grained sandstone beds interbedded with occasional diamictite and clay beds (Fig. 5e) dominate. The sand and sandstone beds vary from consolidated to friable. The sandstone comprises coarse-grained, angular quartz sand with clay mineral cement. The diamictite beds are 0.5–2 m thick. The characteristics of these sand and sandstone beds are similar to those at the type section however the colour of the Hallett Cove sand is different.

In the pebble and cobble layer at 15.2 m, 50% of the layer is pebbles and cobbles, which are up to 35 cm size and comprise dominantly of Wilpena Group rocks. The matrix-dominated diamictite at 16.5 m, has clasts that comprise 40% of the whole rock, are angular, up to 5 cm and consists mostly of Wilpena Group sedimentary rocks. The matrix of the diamictite is coarse- to very coarse-grained sand. A pebble lens is preserved within one of the lower sandstone beds (Fig. 4b).

Similar to the top of unit three at Cape Jervis, a coarse-grained, buff to yellow sandstone and a thick (~50 cm) matrix-supported diamictite lens occurs from 22–25.7 m (Fig. 4b). In both sections, the sandstone and diamictite are coarse- to very coarse-grained. In the Hallett Cove section, several <1 m size dropstones occur within the sandstone. The majority of the dropstones are between the diamictite lenses and are rounded, polished and occasionally striated. Some of the dropstones have disturbed the sedimentary rocks directly below them (Fig. 5f, g).

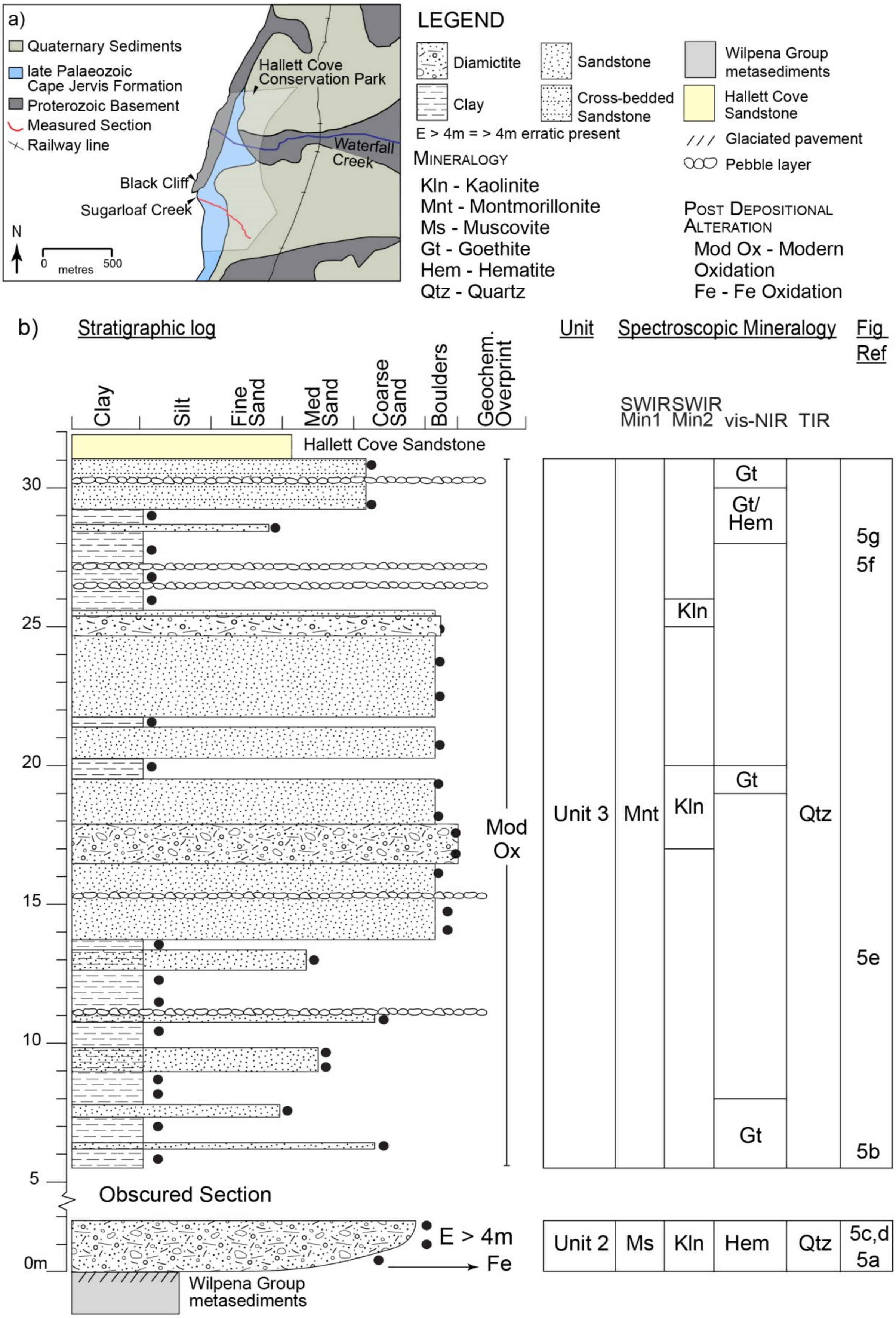

Figure 4. a) Simplified regional geology of the Hallett Cove area adapted from Bourman and Alley (1990) showing section locations; b) Stratigraphic log, spectroscopic mineralogy and unit for Sugarloaf Creek in Hallett Cove area. The location of Hallett Cove is shown in Fig. 1. Black dots: sample location for HyLogger™ analysis. Units as described by Bourman and Alley (1990).

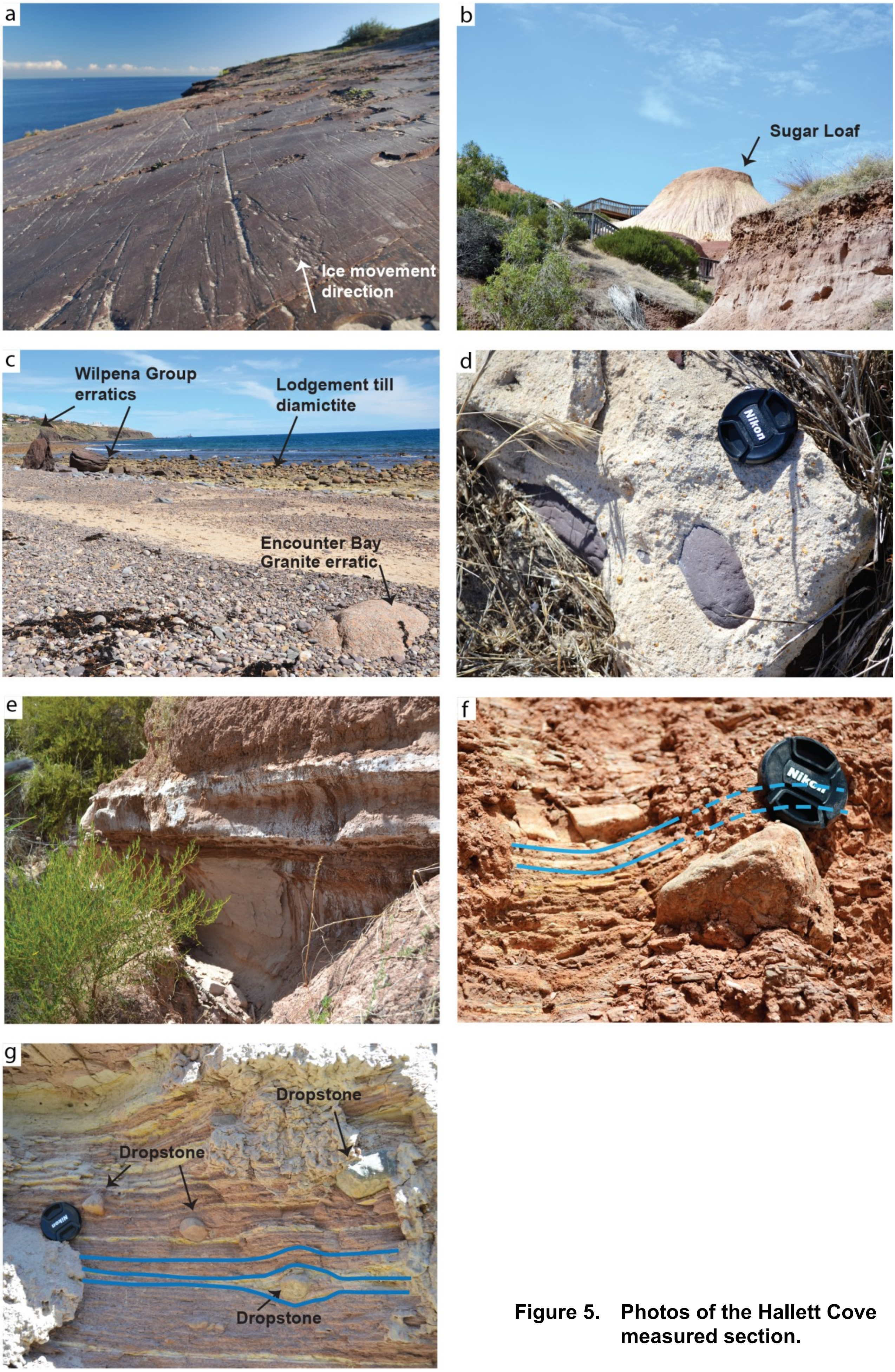

Figure 5. Photos of the Hallett Cove measured section.

Figure 5 captions

a) Striated glacial pavement of Wilpena Group basement at the top of Black Cliff, Hallett Cove;
b) Looking southeast upstream of Sugarloaf Creek (from 5 m of the section) towards the Sugar Loaf. Silty clay beds of unit three make up the banks of Sugarloaf Creek;
c) Shore platform of Hallett Cove (at 0.5 m) exposed at low tide showing sandy clay diamictite and scattered clasts and erratics. Encounter Bay Granite erratic in foreground is approximately 1 m diameter and the Wilpena Group erratic is approximately 5 m in diameter;
d) Wilpena Group metasediment clast within coarse-grained matrix diamictite at the outlet of Sugarloaf Creek, at 1.8 m. Polished, rounded and striated clasts greater than 50 cm are accumulated at the mouth of Sugarloaf Creek;
e) Purple medium-grained sandstone beds (5.5**–**12.5 m) overlying buff, coarse-grained sandstone beds (12.5**–**16 m);
f) Red, fine-grained laminated sandstone preserving a dropstone at 27.2 m. The beds have draped over the drop stone, (blue solid line). The dotted blue line shows the probable continuation of the laminations under the weathered surface;
g) Bedded clay and fine sands at the top of unit three of the Hallett Cove section at 28.3 m. Dropstones have disturbed the bedding below and above them (blue lines). Approximate locations of photos are shown in Fig. 4b.

At the top of the exposed unit three (25.7–31 m), which includes much of the Sugar Loaf, is up to 3 m silty clay beds and up to 2 m of partially consolidated, medium- to coarse-grained, yellow, bedded sandstone. Several metres of loosely consolidated Pliocene Hallett Cove Sandstone overlie the top of the exposed Cape Jervis Formation in this area.

KINGS POINT SECTION

The coastal cliffs of Kings Point preserve 14 m of Cape Jervis Formation exposed in two erosional gullies (Fig. 6a). Both sections unconformably overlie the Cambrian Petrel Cove Formation of the Kanmantoo Group (Bourman and Alley 1995). It is not clear whether the late Palaeozoic sedimentary rocks of the southwestern gully directly overlie the late Palaeozoic sedimentary rocks of the eastern gully or if some late Palaeozoic sedimentary rocks have been eroded creating a disconformity between the sections. Units three and four are observed at the Kings Point section.

The base of the section (0–5.2 m) is exposed in the eastern erosional gully and includes rocks of the lower part of unit three (Fig. 6b). The sediments in unit three are not tilted, however, the sedimentological characteristics of the silty clay, clay and fine-grained sandstone beds are similar to the type section. The clay beds include rounded and polished 40 cm clasts derived from the local metasedimentary rocks (Fig. 7a) and smaller (up to 20 cm) granitic clasts also occur throughout the clay beds.

Unit four of the Cape Jervis Formation is exposed in the southwestern gully (5.6–14.2 m; Fig. 6a). Unit four of the Kings Point section differs from that of the type section as there is a greater occurrence of sandstone beds throughout the unit as well as the differing diamictite characteristics. The matrix- to clast-supported diamictite beds from 5.6–9.8 m (Fig. 6b) have clasts which comprise of 25–75% of the whole rock, are mostly 20 cm, can be up 40 cm, and are rounded to angular in shape. The diamictite matrix coarsens upward from clay to coarse-grained sand, diamictite and becomes increasingly clast-supported up section (Figs 6b and 7b).

The upper 4 m (9.8–25.2 m) consists of diamictite and coarse-grained sandstone beds. These sandstone beds are different to those at the top of unit three in the type section as they are poorly sorted with rock fragments. Diamictite beds are not observed in this part of the type section. The gully at Kings Point is littered with Encounter Bay Granite erratics that are up to 2.5 m, rounded and polished (Fig. 7c), and were not observed at the type section. The Cape Jervis Formation is overlain by up to 10 m of undifferentiated Cenozoic sands.

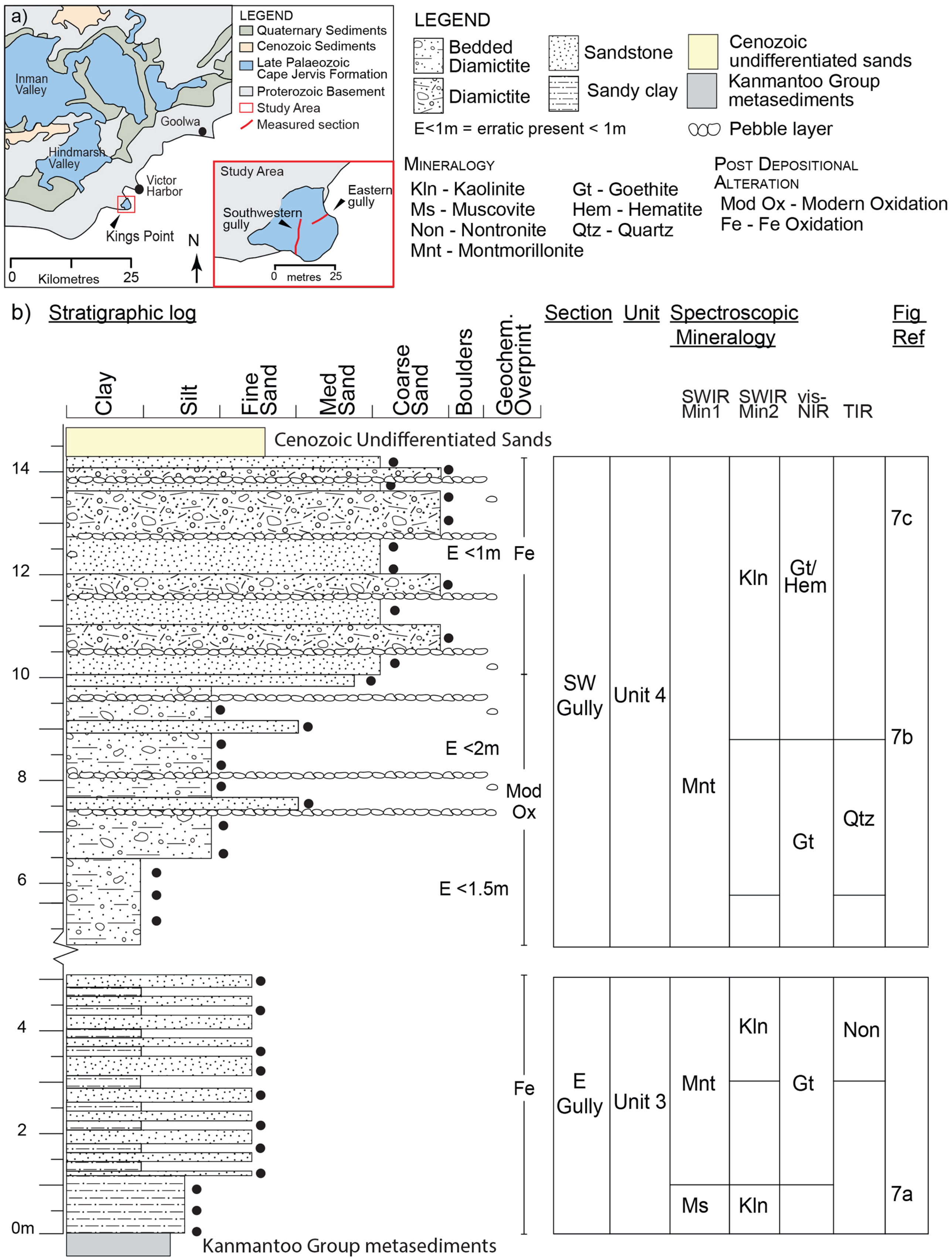

Figure 6. a) Simplified regional geology of the Kings Point area adapted from Bourman and Alley (1995) showing section locations; b) Stratigraphic log and spectroscopic mineralogy for the gullies investigated in the Kings Point area. The location of Kings Point is shown in Fig. 1. Black dots: sample location for HyLogger™ analysis. Units as described by Bourman and Alley (1995).

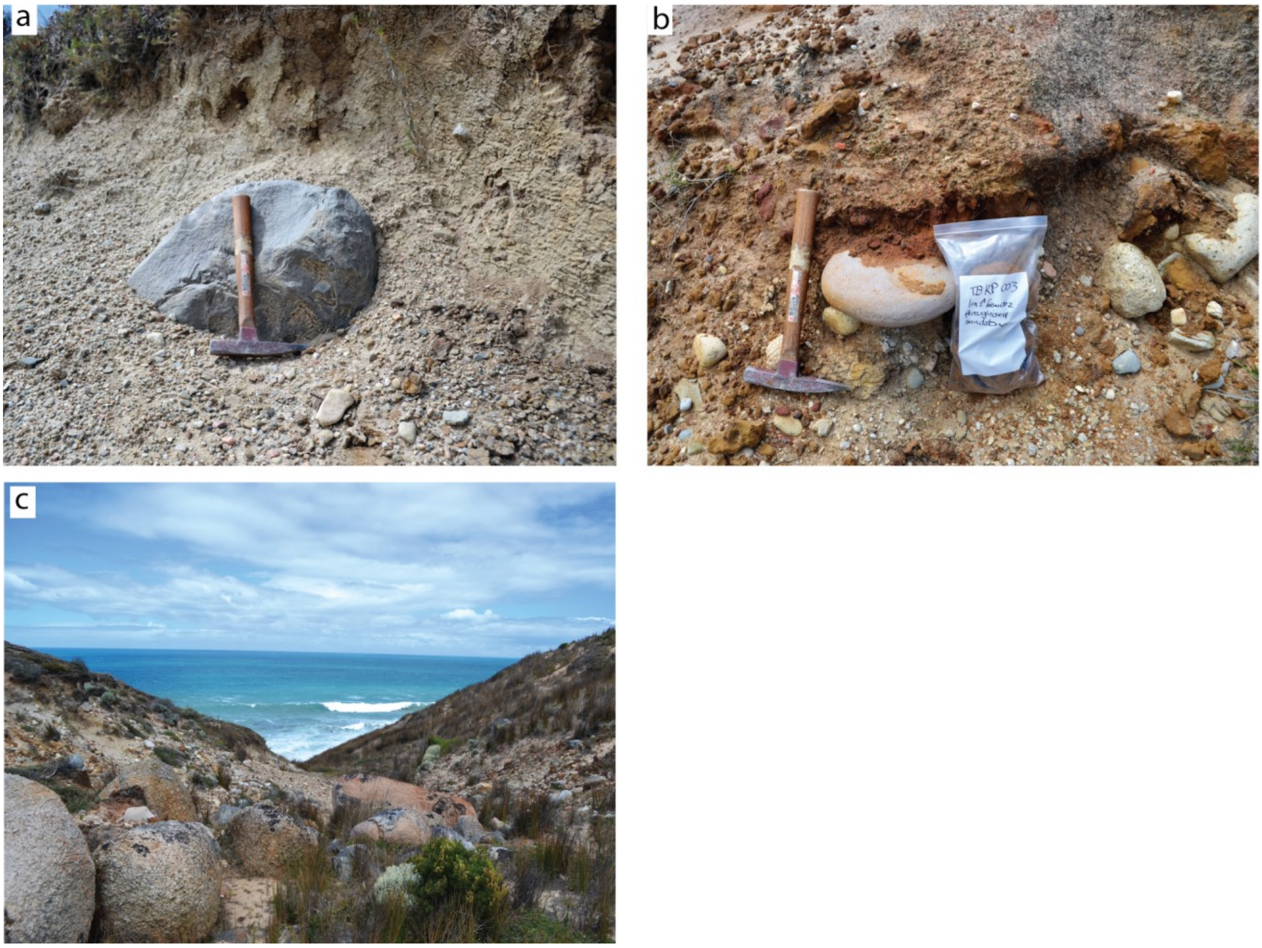

Figure 7. Kings Point Section. a) Clasts of Kanmantoo Group metasediment within the clay at 1.2 m in the eastern gully (unit three); **b)** Pebble lens within the matrix-supported diamictite beds at 8.2 m in the southwestern gully (unit four); **c)** Encounter Bay Granite erratics scatter the landscape in the southwestern gully, photo taken at 13 m looking down section. Geology hammer is approximately 30 cm long; approximate locations of photos are shown in Fig. 6.

WATERLOO BAY SECTION

The Waterloo Bay section preserves approximately 3 m of Cape Jervis Formation that are unconformably overlain by about 4 m of Quaternary sedimentary rocks (Figs 8 and 9a). The unconformity is well preserved and is an undulating surface. Units four and five are present in this section.

The Cape Jervis Formation in the Waterloo Bay section consists of bedded clay and diamictite of unit four (0–2 m) overlain by massive clay of unit five (2–3.2 m; Fig. 8b). Unit four at Waterloo Bay is distinctive from that of the type section as matrix-supported diamictite (Fig. 9b) has clay to silty clay and is interbedded with clay rather than the sandstone seen at the type section. Unit four at Waterloo Bay is also green to grey whereas at other sections, the sedimentary rocks are buff to yellow. The hard, red and orange mottles of hematite and goethite preserved on the surface of the silty clay beds (Fig. 9b) are also not observed at the type section.

Unit five at Waterloo Bay is similar to the massive to bedded clay with lesser sandstone at the type section. At Waterloo Bay, red and orange mottles (Fig. 9c) are preserved and a fine-grained, sandstone bed (<20 cm) at 2.6 m. The section is overlain by a palaeosol containing alunite and limestone and calcrete of the Quaternary Bridgewater Formation.

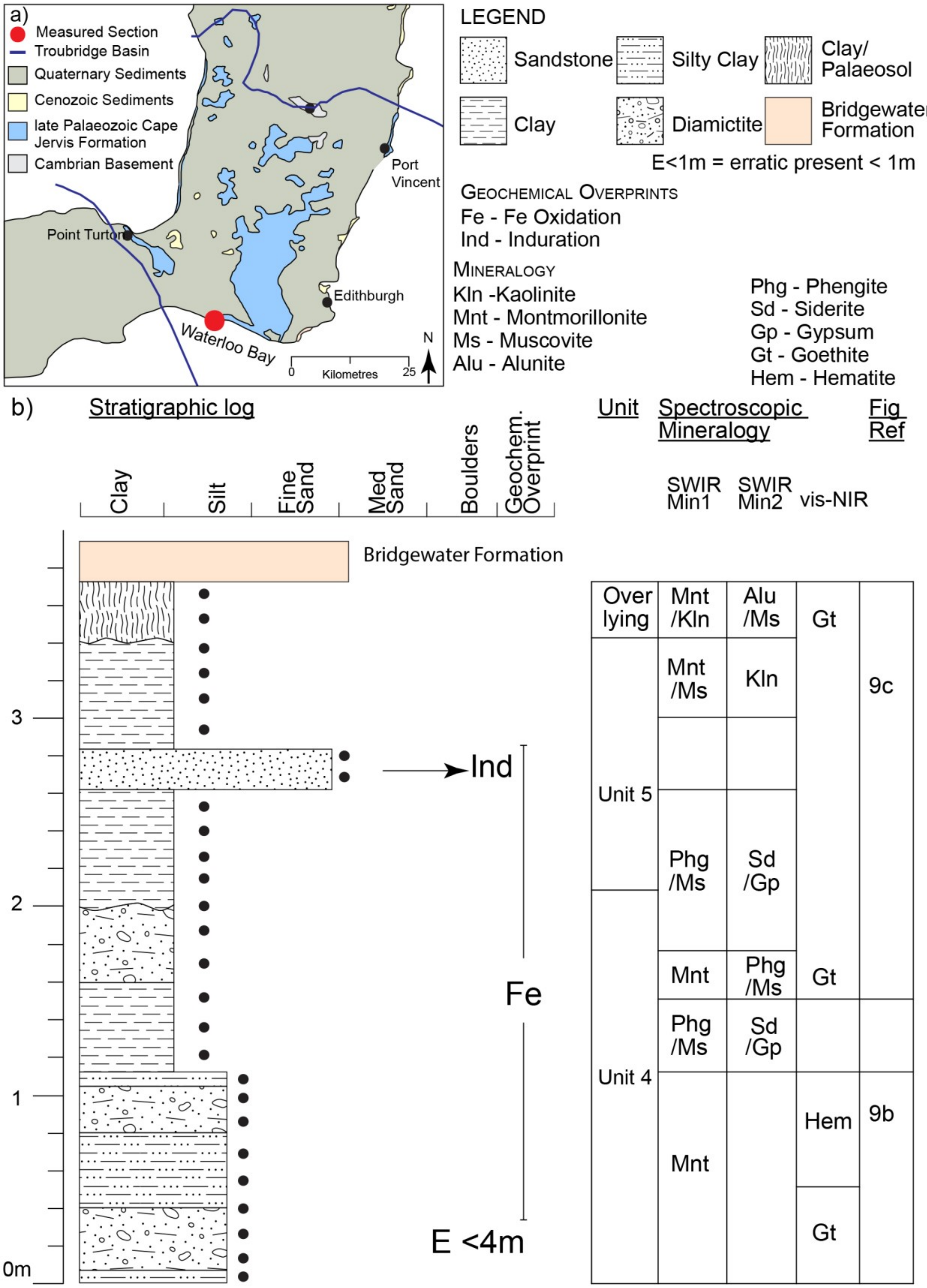

Figure 8. a) Simplified regional geology of the southern Yorke Peninsula showing the location of the Waterloo Bay profile adapted from Alley and Bourman (1995); b) Stratigraphic log and spectroscopic mineralogy for Waterloo Bay. The location of Yorke Peninsula is shown in Fig. 1. Units were originally described by Foster (1974) as all glaciomarine sediments however using the unit descriptions of Alley and Bourman (1984) the units have been reclassified as shown. Black dots: sample location for HyLogger™ analysis.

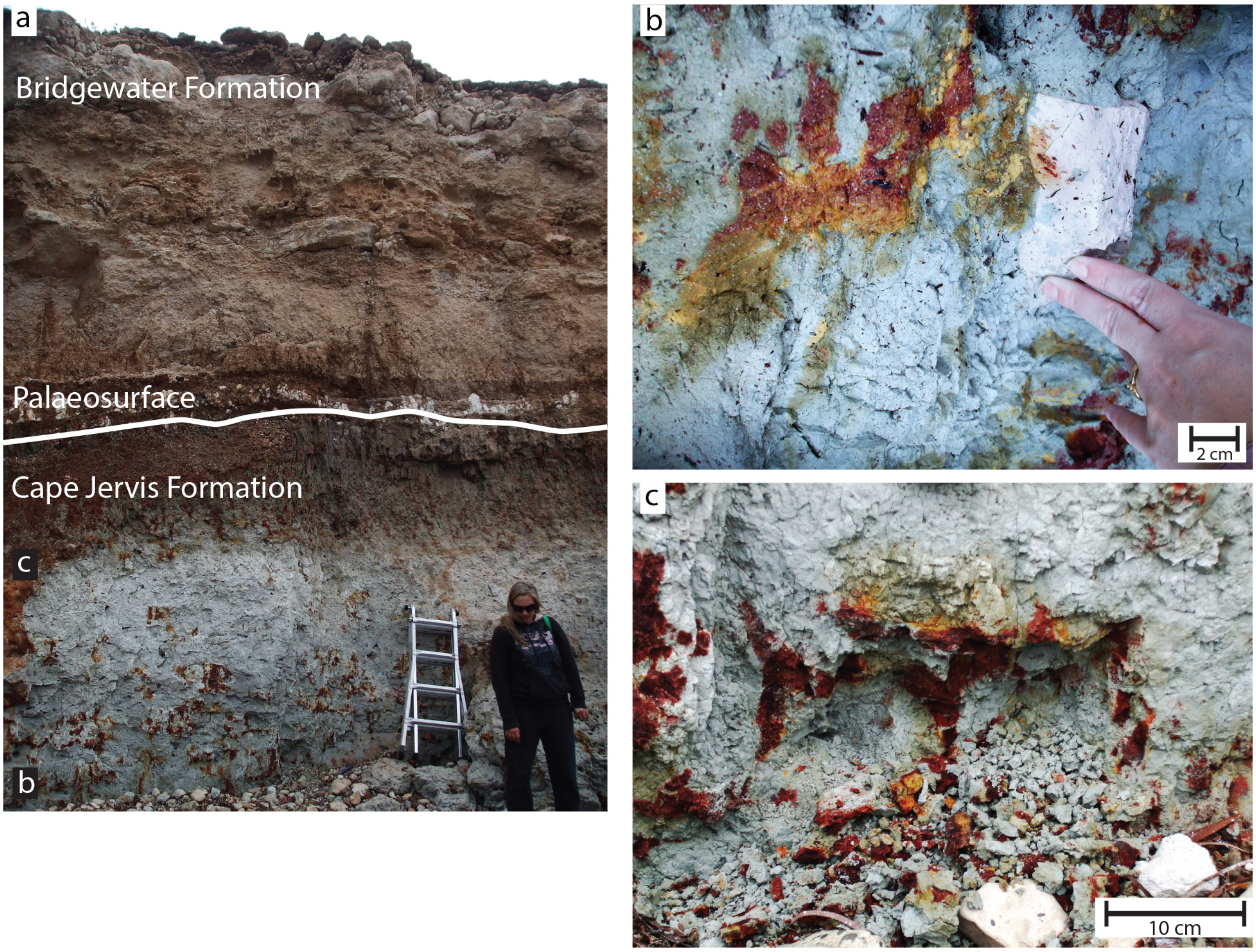

Figure 9. **Waterloo Bay Section. a)** Cliff showing the Waterloo Bay section. Sedimentary rocks of the Cape Jervis Formation are overlain by Quaternary Bridgewater Formation, between the white lines is the palaeosol at 3.4–3.7 m; ladder is 1.5 m high; **b)** Clasts of Encounter Bay Granite within the lowermost diamictite in the Waterloo Bay section at 1 m. Red and orange mottles can also be seen; **c)** Mottles of hematite and goethite within the massive clay at 3.2 m near the top of the exposed Cape Jervis Formation. Approximate locations of photos are shown in Fig. 8. Location of photos b) and c) are shown by black boxes in a).

KINGSCOTE COMPOSITE SECTION

The unit underlying the Cape Jervis Formation in the Bluff Quarry and Kingscote foreshore sections (Fig. 10a) is unknown although it is interpreted that the sedimentary rocks are underlain by Cambrian Kanmantoo Group as seen at other locations on the Kangaroo Island (Bourman and Alley 1999). The sedimentary rocks of the Bluff Quarry section (0–4.5 m; Fig. 10b) comprise interbedded silty clay, diamictite and sandstone (Fig. 11a). The Cape Jervis Formation exposed in the coastal cliffs near the Kingscote Wharf (5–10.7 m; Fig. 10b) are a sequence of clay to sandstone beds (Fig. 11e). The Cape Jervis Formation at both measured sections is unit three.

Unit three of the Kingscote Composite section (0–4.5 m) is similar to the upper portion of unit three at the type section. The sandstone beds (Fig. 11b, c) are fine- to coarse-grained with minimal rock fragments and clasts. The cross-bedded sandstone at 2.2 m (Fig. 11d) in the Kingscote composite section is not at the top of the section, rather, it is overlain by another 8 m of sandstone and clay beds. The clay beds from 5–7.5 m of the Kingscote composite section (Figs 10b and 11f) are similar in characteristics but thicker than the clay beds of the type section. The fine-grained sand that make up the top 2 m of the section (9–10.7 m) has yellow with purple and orange mottles (Fig. 11g) and is unconsolidated except in places where the beds are contorted. These contortions were not observed at the type section. The section is overlain by Jurassic Wisanger Basalt (Fig. 11a).

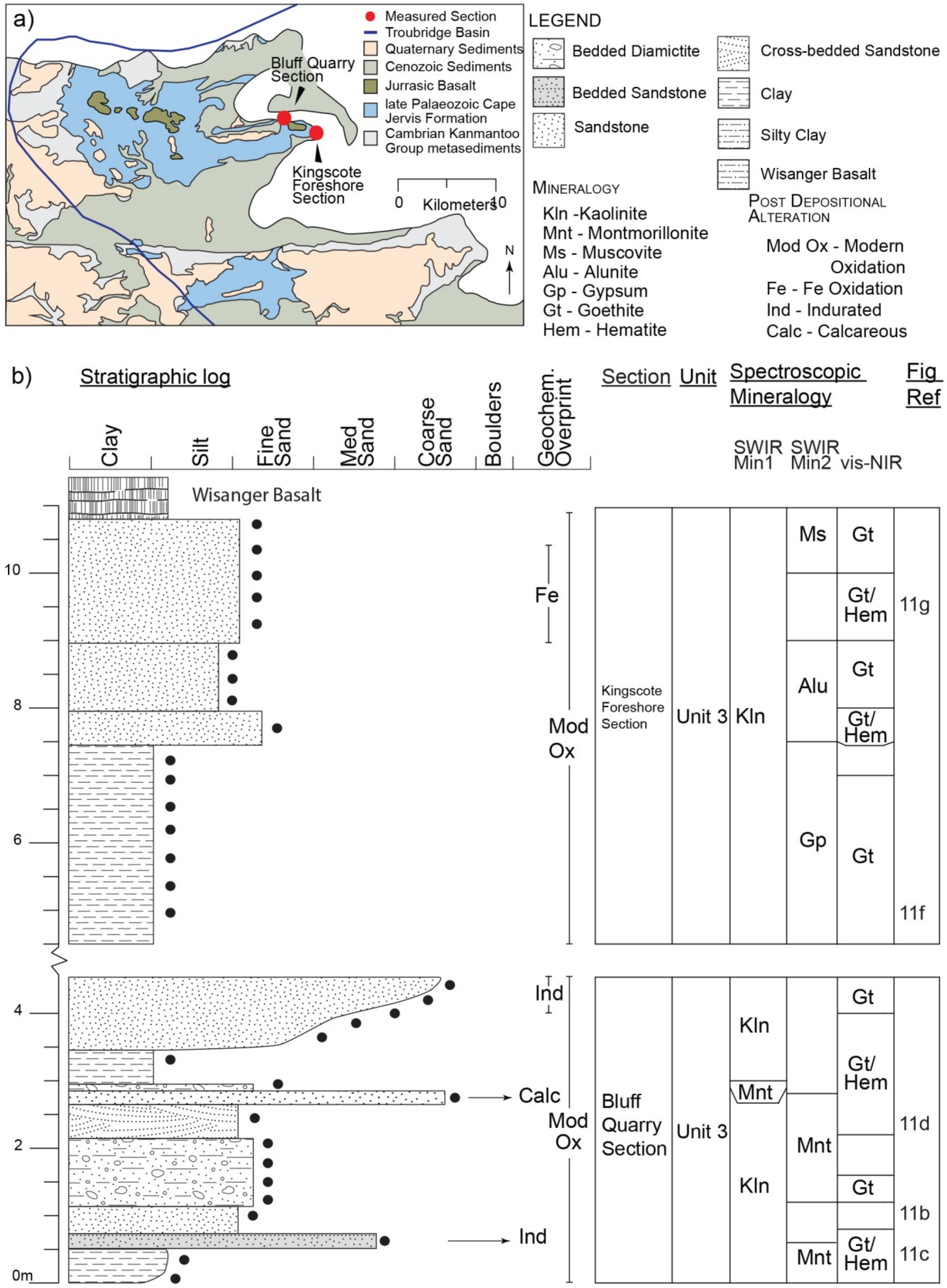

Figure 10. a) Simplified regional geology of northeastern Kangaroo Island adapted from Alley and Bourman (1995); b) Stratigraphic log and spectroscopic mineralogy of the Kingscote composite section. The location of Kingscote composite section is shown in Fig. 1. Black dots: sample location for HyLogger™ analysis. Units as described by Alley et al. (2013).

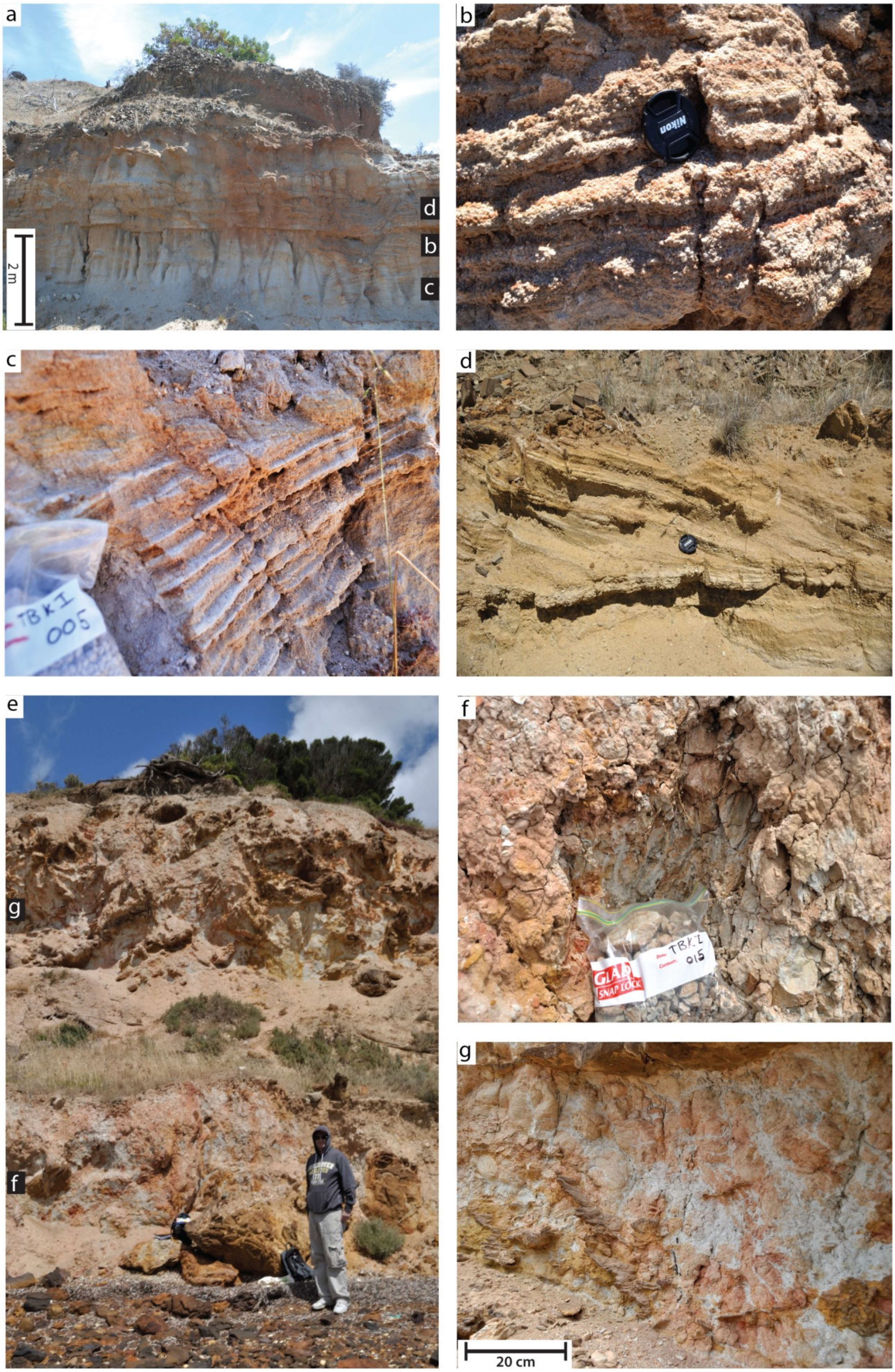

Figure 11. Photos of the Kingscote composite measured section.

Figure 11 captions

a) Bluff Quarry section (0–4.5 m), Cape Jervis Formations are overlain by Jurassic Wisanger Basalt;
b) Pebbly sandstone beds at 1 m, with angular, coarse-grained quartz grains bedding in preserved where the silty clay matrix remains;
c) Hard, indurated, medium- to coarse-grained sandstone at 0.5 m, that preserves bedding at the base of the Bluff Quarry section;
d) Poorly-preserved, planar cross-bedding within medium- to coarse-sandstone at 2.5 m of the Bluff Quarry section;
e) Kingscote Foreshore section (5–10.7 m), the Cape Jervis Formation make up the entire cliff;
f) Clay at the base (at 5.5 m of the composite section) of the Kingscote Foreshore section with prismatic fracturing and orange mottles;
g) Sandstone of the upper part of the Kingscote section (9.5 m) with light orange mottles.
Approximate locations of photos are shown in Fig. 10. Location of photos b), c) and d) are shown by black boxes in a), and location of photos f) and g) are shown by black boxes in e).

DISCUSSION

STRATIGRAPHIC CORRELATIONS

Previous researchers (e.g. Alley and Bourman 1984, Bourman and Alley 1990, 1995, 1999) were able to recognise the units described by Alley and Bourman (1984) within sections away from the Cape Jervis type section. However, correlations between sections are yet to be made. With the exception of the Waterloo Bay section, all sections logged in this study were also investigated by Alley and Bourman (1984) and Bourman and Alley (1990, 1995, 2013). Here, the sedimentary rocks observed in the Waterloo Bay section are suggested to represent units four and five of Alley and Bourman (1984; Fig. 11b) based on similarity in the lithologies preserved and stratigraphic relationships of the lithologies. Where the units were described in relation to the sedimentary rocks at the other sections, specific unit boundaries have been established at each section (see stratigraphic logs above). The unit boundaries were positioned using the depositional setting described by Alley and Bourman (1984) and Bourman and Alley (1990, 1995, 2013), however, the units were not visually represented in the previous studies.

The correlation of units across the Troubridge Basin will allow spatial distribution to be assessed and for any lateral differences to be recognised, leading to better understanding of basin-wide variations in depositional setting. The stratigraphic correlations made here (Table 1; Fig. 12) are based on the unit descriptions of Alley and Bourman (1984) together with interpretations based on the facies analysis approach of glacigene settings described by Eyles et al. (1983) and Miall (2000). The approach in facies analysis of glacigene rocks and the interpretation of the depositional processes is based on the identification of key sedimentary characteristics, in particular sedimentary structures and the relationship of these characteristics with depositional processes. Given the weathered nature and lack of well-preserved sedimentary structures in the measured sections it is not possible to use these facies definitions as intended by Eyles et al. (1983) and Miall (2000), however, where possible the relationships between the glacigene sedimentary rocks and depositional processes have been assessed.

Table 1 has a summary of the characteristics of each unit, the unique lithologies of the unit as well as the overall unit characteristics based on observations described in Section 2.3. The correlations between the measured sections are demonstrated in Fig. 12, where the unique characteristics for each unit have been used to correlate the sections.

Depositional setting of the late Palaeozoic sedimentary rocks

Previous researchers (e.g. Crowell and Frakes 1971b, Alley and Bourman 1984, Crowell and Frakes 1971a, Alley et al. 1995, Bourman and Alley 1988, Bourman and Alley 1999) have proposed that during the Permo-Carboniferous glaciation Gondwana was at high latitudes and close to the South Pole. During this time a continental-scale, wet-based ice mass moved from Antarctica through southern Australia and advanced north and east to cover most of South

Australia and extended into surrounding states. The ice mass then retreated in a south to southeasterly direction. This was followed by a marine transgression and subsequent regression. The Troubridge Basin was initially covered by the ice mass and was later covered by the transgressing sea.

The Cape Jervis Formation represents changing glacial environments as the ice mass advanced then retreated. The glacial conditions varied depending on the underlying substrate and surrounding landscape. These conditions are reflected not only in the differences between sections but also within the same unit.

GLACIATED BEDROCK SURFACES

Two types of glaciated basement surfaces are exposed; polished glacial pavements; and, frost-scattered bedrock (Figs 1b, 3a and 5a). Striated, polished pavements are present in close proximity to the Hallett Cove, Kings Point and Kingscote composite sections (Fig. 1; Milnes and Bourman 1972, Bourman and Alley 1988, 1990, 1995, 1999). These surfaces have been eroded by the abrasive action of rock particles transported at the base of the ice mass to create a polished, striated and rock-scoured pavement (Fig. 13a; Glasser and Bennett 2004, Bennett and Glasser 2009). Striations and other rock-scoured features such as chatter marks and concentric grooves provide an indication to the direction of ice movement (Bennett and Glasser 2009). These properties were all observed at Hallett Cove (Figs 6 and 7a). A northwesterly ice movement direction was interpreted by Bourman et al. (1976), Bourman and Alley (1988) and Bourman and Alley (1990) from ice movement indicators across the Troubridge Basin.

Although the general ice movement direction is northwesterly there is some variation in the striae direction measured across the basin. Milnes and Bourman (1972), Bourman and Milnes (1976) and Bourman et al. (1976) observed an east to west ice movement near Mount Compass, at Port Elliot and in the Inman Valley (Fig. 1b). While Milnes and Bourman (1972), Bourman and Alley (1990 and 1999) and Alley et al. (2013) observed northeast to north-northeast ice movement directions at Hallett Cove and across Kangaroo Island. The difference in ice movement direction have been attributed to the presence of ice tongues that preceded the icesheet (Bourman and Miles 1976, Bourman and Alley 1999, Alley et al. 2013).

The basal melting of ice tongues typically causes the over-deepening of existing valleys (Alley et al. 1995) forming U-shaped valleys such as the Inman Valley and the valley at Hallett Cove. The polished pavements document the abrasion and quarrying of the underlying strata while the striations document the direction the ice flows (Benn et al. 2003).

Gelifract is not the product of direct contact with the ice mass, however, is an example of a glaciated bedrock surface (e.g. Alley and Bourman 1984). Gelifract was observed underlying the glacigene sedimentary rocks of the Cape Jervis section (Figs 2b and 2.3a). The fracturing of basement rocks has been attributed to frost shattering that occurred due to periglacial conditions prior to the beginning of the glaciation of the area (Alley and Bourman 1984, Matsuoka 1990). Though these glaciated bedrock surfaces are not part of the Cape Jervis Formation, it is important to recognise their presence as it indicates that the overlying sedimentary rocks are glacial in nature.

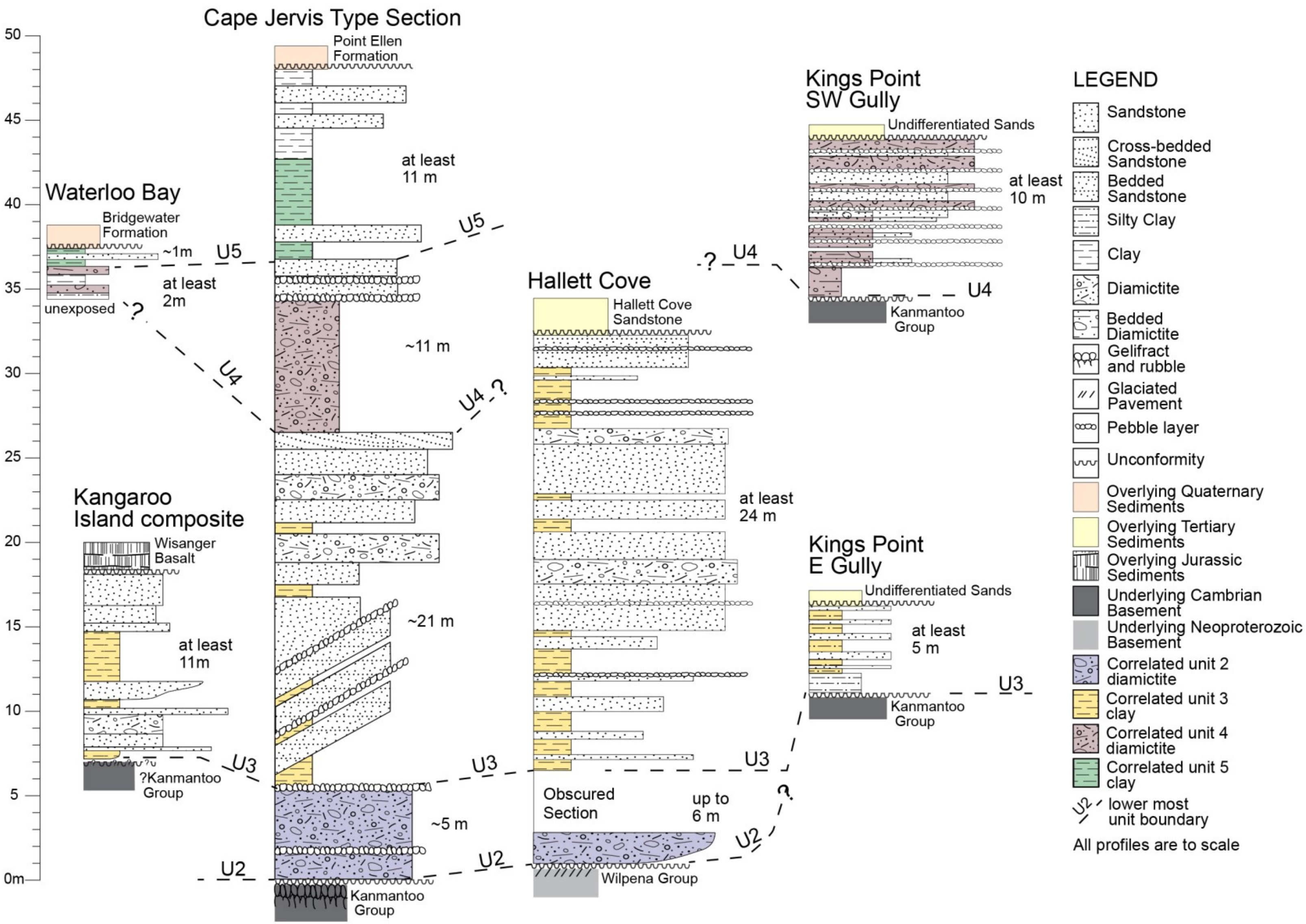

Figure 12. Correlation of measured sections from east to west across the basin. The approximate thickness of each unit is recorded within the unit boundaries. The unique lithology for each unit is highlighted. These lithologies were the basis for correlations detailed in the text and Table 1. Section locations are in Fig. 1. Detailed stratigraphic logs of each section are in Appendix 1. Overlying and underlying stratigraphy from (left to right) Zang et al. (2006), Bourman and Alley (1990), Alley and Bourman (1984), and Bourman and Alley (1999, 1995).

DEPOSITIONAL SETTING OF LODGEMENT TILL (UNIT 2)

Diamictite of unit two are exposed at Cape Jervis and Hallett Cove. At both locations the lodgement till directly overlies bedrock. Although the Cape Jervis Formation overlies the bedrock at Kings Point, lodgement till is not exposed (Fig. 7b). This may be an example of where the lodgement till was removed by the advancing ice mass or that no lodgement till was deposited in the area. This differs from Hallett Cove (Fig. 4b) and Cape Jervis (Fig. 2b) where the glaciated basement is directly overlain by lodgement till.

Lodgement till (unit two) represents deposition of debris that is transported subglacially (e.g. within or by a glacier) in crudely stratified basal layer with an intense abrasive action (Eyles and Miall 1984, Bennett and Glasser 2009; Fig. 13a). Deposition occurs when the friction between the ice mass and the debris (sediment and rock fragments) is such that the debris stops moving or the debris is released by melting (Bennett and Glasser 2009; Fig. 13a). The debris deposited is typically a dense, matrix-supported diamictite with a high concentration of locally-derived clasts (Eyles et al. 1983). A proportion of the clasts have glacially-faceted shapes which are characteristic and diagnostic (Eyles and Miall 1984). The debris is then deposited at the front and preserved underneath the advancing glacier. The typical geometry of lodgement till across sedimentary basins is 'sheet-like'; lying above local and regional unconformities (Eyles and Miall 1984, Hambrey and Glasser 2012). Hambrey and Glasser (2012) concluded that debris deposited in a subglacial, basal setting of a temperate glacier would have a rare abundance, when compared diamictites deposited in other glacial settings, be clast-rich (5–30%) with very angular to subrounded clasts where twice as many clasts were faceted then striated, poorly-sorted within a silt to sand matrix. The characteristics of unit two (Table 1) are consistent with the criteria for basal subglacial deposition within a temperate glacial setting of Eyles et al. (1983), Eyles and Miall (1984) and Hambrey and Glasser (2012).

Unit two of the Cape Jervis Formation was deposited at the front and base of the glacier (Fig. 13a). Up to 6 m of the diamictite of the lodgement till was been preserved across the basin; specifically as valley fill at the Cape Jervis and Hallett Cove sections (Fig. 12). Bourman and Alley (1990) reported that they had not seen any greater thickness of lodgement till or pre-till glacigene sedimentary rocks in the Troubridge Basin and after extensive investigation no greater thickness was seen during this study. It is unlikely that a greater thickness would be found as the continual erosion of the till underneath the advancing ice mass would have minimised accumulation. Erosion of the unit may also have occurred during the retreat of the ice mass resulting in some reworking and resedimentation of the debris (Eyles and Miall 1984, Ashley et al. 1985, Hambrey and Glasser 2012).

As unit one was not observed, there is no evidence as to the change in depositional setting between units one and two. The contact between the underlying basement and the lodgement till is unconformable, which is caused by the erosion of sedimentary rocks by the glacier as it moved across the landscape. This fulfils the requirement of Eyles and Miall (1984) and Hambrey and Glasser (2012) for subglacial basal deposition. The overlying contact with sedimentary rocks of the fluviolacustrine beds is an abrupt contact between the diamictite of the lodgement till and fluviolacustrine clay beds (Fig. 12). Where the contact was observed, there is no evidence of a pause in sedimentation by means of an erosional contact or palaeoweathering surface (Figs 2b and 4b).

The lack of other lithologies (e.g. sandstone and clay units) within unit two (Figs 2b and 4b) suggests that there was a limited supply of meltwater to deposit beds of smaller grain size at this time. Elyes and Miall (1984) suggested that a wide range of lithologies are commonly associated with subglacial basal deposition within cold based glacial settings where channel fill is a result of subglacial stream drainage. This expands on the depositional setting described by Alley and Bourman (1984) and (Bourman and Alley 1990, 1999, Alley et al. 2013) that the lodgement till was deposited by the advancing ice mass.

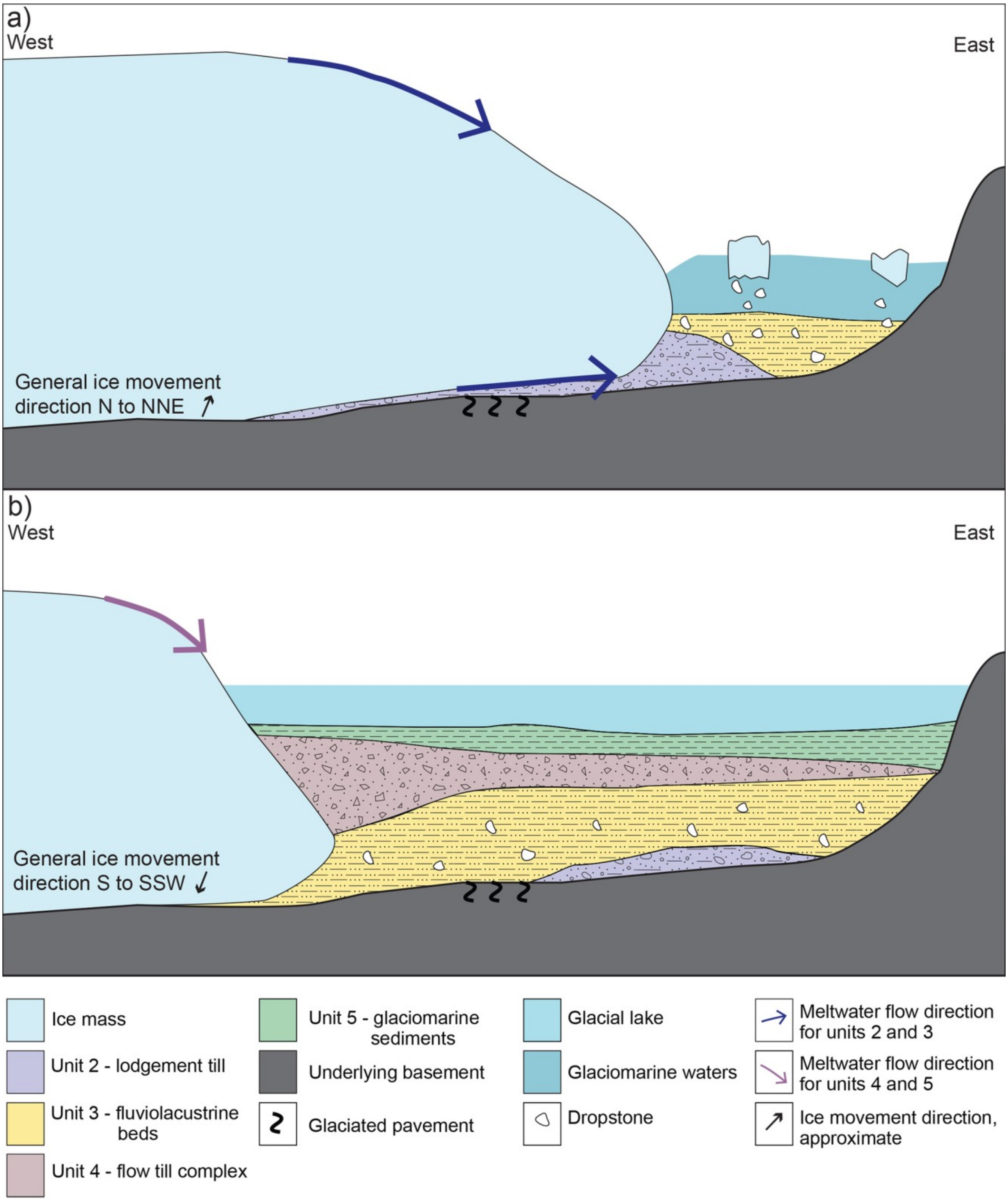

Figure 13. a) Stylised depositional setting during the migration and stagnation of the ice mass and the deposition of units two and three; b) Stylised depositional setting during the retreat of the ice mass and related marine transgression and the deposition of units four and five. These diagrams are a representation of a perfect exposure and are based on what is seen typically along the coastal exposures of the basin such as the type section at Cape Jervis.

DEPOSITIONAL SETTING OF THE FLUVIOLACUSTRINE BEDS (UNIT 3)

The fluviolacustrine beds (unit three) were observed at all sections except for Waterloo Bay (Fig. 12), the thickness of the unit varies from 5 m at Kings Point up to at least 24 m at Hallett Cove (Fig. 12) The varying lithologies (i.e. clay, sandstone and diamictite) within unit three suggest that the depositional processes for vary implying a dynamic, evolving depositional setting. Bourman and Alley (1990) and Bourman and Alley (1995) propose that the alternating clay, sand and diamictite beds of the fluviolacustrine beds (unit three; Table 1) are the result of variable ice decay rates. Investigating the depositional process of each lithology can provide a better understanding of the depositional setting of unit three.

The massive to finely laminated clay and silt beds were likely deposited in a low energy environment. Miall (2000) suggests that the fine laminations in the clay beds were deposited in an abandoned channel or waning flood plain setting; while, Hambrey and Glasser (2012) proposed that very fine-grained laminate with no clasts suggest deposition in an ice-proximal glaciolacustrine setting. Given that the ice mass was likely still proximal to the Troubridge Basin and the similarity of the clay beds in unit three to Hambrey and Glasser's (2012) description an ice-proximal glaciolacustrine is the most likely depositional setting.

Glacial lakes can develop in a number of environments, such as at the front of a stagnant glacier, or between moraines and the ice mass, or by the draining of glacial waters into pre-existing basins (Bennett and Glasser 2009). It is likely that the glacial lakes of the Troubridge Basin formed from glacial water draining into low-lying areas (Fig. 13a) when the ice stagnated in the Gulf St Vincent. This depositional setting was also surmised by Bourman and Alley (1999) and Alley et al. (2013).

The fine- to medium-grained sandstone beds of unit three, are typically interbedded with the clay beds (Fig. 13). The sandstone beds increase in frequency up section suggesting a gradual change in glacial conditions. Bennett and Glasser (2009) listed resedimentation by gravity flows, current reworking or shoreline sedimentation as mechanisms for sandstone deposition within a glaciofluvial environment. Eyles et al. (1983) and Miall (2000) both correlated horizontally bedded sandstone beds with sediment-heavy flows and laminated clays deposited into subglacial ponds. Hambrey and Glasser (2012) linked a high abundance of well sorted sand or silt beds with a very low (<5%) striated and faceted clast occurrence with fluvioglacial streams.

The sandstone beds of unit three are typically massive to thinly bedded with minor occurrences of poor-preserved planar and trough cross-beds in the Cape Jervis and Kingscote sections. Due to the poor-preservation of the cross-beds information such as palaeocurrent directions could not be established. Of the depositional processes listed by Bennett and Glasser (2009), gravity flows, current reworking and shoreline sedimentation can be ruled out due to the lack of sedimentary structures. The processes of Eyles et al. (1983), Miall (2000) and Hambrey and Glasser (2012) are similar in that they describe meltwater streams transporting sediment away from the ice mass. Meltwater streams (or channels) associated with the flow of water away from the ice mass can form subglacially (beneath the ice), laterally (along the ice margin; Fig. 13a) and in proglacial locations (in front of the ice; Bennett and Glasser 2009). The cross-bedded sandstone beds are likely scour fill or minor channel fill deposits (Miall 2000). Given the discontinuous exposure of the sand and sandstone beds across the basin it is not possible to determine where the meltwater streams originated. It is likely that all three types of meltwater streams introduced sedimentary rocks into the glacial lake(s).

Dropstones occur sporadically throughout both the clay and sandstone beds of unit three, particularly at the Cape Jervis and Hallett Cove sections (Figs 3b and 5f, g). The presence of dropstones is indicative of glacial 'rain-out' or ice-rafted debris flows (Eyles et al. 1983, Miall 2000, Bennett and Glasser 2009, Hambrey and Glasser 2012). When icebergs and the resultant 'rain-out' are in low concentrations, isolated dropstones are deposited on the finer materials that have accumulated at the bottom of the lake (Bennett and Glasser 2009). The presence of dropstones in unit three suggests that there were ice bergs on the surface of the glacial lakes (Fig. 13). The dropstones at Cape Jervis and Hallett Cove and contortion of the underlying beds and draping of overlying beds (Figs 5f, g and 13a) suggests they were deposited via gravity (underlying contortion) and remained undisturbed (overlying draped beds). Bourman and Alley (1990) also suggested that icebergs were the source of the dropstones and contorted beds associated with them in unit three at Hallett Cove.

Eyles et al. (1983) suggested that ice-rafted debris flows may also be the depositional process responsible for diamictite deposits. In unit three, diamictite beds are interbedded with the sandstone and clay beds in the upper unit three (Fig. 13). The irregular shape and lithological nature of the diamictite lenses and beds (e.g. sorting, clast shape) suggests deposition in an environment where there was the degree of disaggregation of grainsize and current activity was minimal, which occurs where the depth of the lake is at a minimum (Bennett and Glasser 2009). Eyles et al. (1983) attributed these characteristics with bank erosion and collapse into melt stream channels. Hambrey and Glasser (2012) extended the characteristics of the diamictite to boulder to gravel sized, very angular to rounded clasts within a sand to silt matrix that is well sorted. These clasts are deposited by supraglacial channels and deposited where water ponds.

The sandstone and diamictite of unit three (Fig. 12) represent a transient influx of higher energy into the glacial lake system. This may have been triggered via several mechanisms, including deposition from meltwater flows, direct deposition from the front of the ice mass, 'rain-out' from icebergs, resedimentation by gravity flows, current reworking and shoreline sedimentation (Bennett and Glasser 2009).

Unit three of the Cape Jervis Formation was likely deposited in a subaqueous or subglacial fluviolacustrine setting where sediment-heavy channel flows and ice rafted debris flows with minor channel flows were supplying sediment and debris into glacial lakes. Bourman and Alley (1990) and Alley and Bourman (1984) postulated that the ice was likely stagnant in the Gulf St Vincent to enable the development of glacial lakes. The presence of the silt and clay beds in unit three are evidence of the glacial lakes that formed between the ice mass and palaeoshore. It is not known if the lakes were continuous along the coastline or if a series of discrete lakes formed. This is also reflected in the depositional setting postulated by Alley and Bourman (1984).

The lower section of the unit is dominated by clay and silt beds suggesting that the glacial lake was likely a very low energy environment and there was minor input from meltwater streams depositing the sandstone beds. The increased presence of sandstone beds and diamictite lenses and beds towards the top of the unit (Fig. 12) suggests that at some point the conditions changed, perhaps initiated by a change in climate and retreat of the glacier. Additionally, the cross-bedded sandstone in the Cape Jervis and Kingscote sections (Fig. 2b) suggests deposition within shallow water environment, such as channel flow following downwasting of the ice mass. It is therefore possible that the glacial lake became increasingly shallow due to the deposition of sediment and the decrease of water input via meltwater before the ice conditions changed to enable the deposition of the flow till complex (unit four). These changing depositional processes have caused the variations in thickness of unit three.

The tilting of the lower fluviolacustrine beds at Cape Jervis is likely due to sub-aqueous collapse of the saturated sedimentary rocks prior to consolidation. Similar tilting of unit three was not observed at any other section or above and below the tilted unit three sedimentary rocks at Cape Jervis.

The depositional setting change represented by the clay dominance of the lower part of the section and the sand dominance in the upper part of the section is important as it indicates a change from dominantly lacustrine to fluvial settings. The damming of meltwater to create glacial lakes occurred during the stagnation of the ice mass causing thick beds of clay and silt to deposit between the deposition of thin sandstone and diamictite beds. The change to dominant sandstone and diamictite beds and thin clay and silt beds was triggered by the initiation of the melting of the ice mass. This change in depositional setting was also recognised by Alley and Bourman (1984) who suggested the formation of a series of kame terraces where interfingering alluvial and lacustrine sediments were intermittently deposited.

DEPOSITIONAL SETTING OF THE FLOW TILL COMPLEX (UNIT 4)

Unit four is approximately 11 m thick at the type section; at Kings Point the unit is at least 10 m thick while at Waterloo Bay it is at least 2.5 m thick (Fig. 12). At the type section, the unit consists of unstratified and unconsolidated diamictite (Fig. 2b) whereas at the other sections it consists of thin (<1 m) beds and lenses of diamictite interbedded with either clay or sand beds (Figs 6b and 8b). Sedimentary rocks similar to those at Kings Point were also observed at Hallett Cove and Kangaroo Island by Bourman and Alley (1999) and Alley et al. (2013). The different lithologies of the flow till complex across the Troubridge Basin reflects variable depositional conditions during the decay and retreat of the glacier.

Alley and Bourman (1984) and Bennett and Glasser (2009) suggest that the deposition of flow till complex is the result of highly unstable supraglacial debris flowing downslope. The debris is released due to constant ablation occurring on the surface of the melting ice mass. The unstable material accumulates on the constantly changing ice surface until enough debris has accumulated to be released down the melting ice slope where it is deposited (Fig. 13b). The properties of the resulting diamictite is dependent on water content, debris character, (e.g. size of clasts, proportion of rock flour), the surface gradient and the composition of the depositional surface (Bennett and Glasser 2009). Broadly, the greater the water content the more debris is deposited. Sand and silt beds within the flow till complex are associated with the reworking of the debris by meltwater that originates from the base and top of the ice mass (Bennett and Glasser 2009). Miall (2000) suggested that unconsolidated to clast-supported diamictites are deposited as debris flows from valley glaciers. If the diamictites also have inverse grading. Miall (2000) proposed depositional processes such as low-strength and pseudoplastic debris flows.

The unconsolidated or clast-supported nature of the diamictite beds suggests reworked glaciofluvial materials according to Hambrey and Glasser (2012). Other properties associated with reworked glaciofluvial deposits include, deposits with 80 to 100% clasts that have a very low (<10%) occurrence of striated and faceted clasts within a sand to silt sized matrix that is moderately well sorted. Eyles et al. (1983) associate a diamictite that is mostly unconsolidated, with dominantly rounded clasts that have no orientation interbedded with fluvial lithologies and other resedimented diamictites with depositional processes within a valley glaciers. The resedimented diamictites extend into channel fills where they may become increasingly sandy with reduced clasts. Eyles et al. (1983) also suggest that coarsening-up of deposits, such as that seen in the diamictite matrix at the Kings Point section (Fig. 6b), may be evidence of resedimentation in an environment with debris-rich and debris-poor glacial ice that is melting. While Bennett and Glasser (2009) attribute it to the preferential washing out of the clay and silt sized particles before coarser sedimentary rocks where deposited.

The interbedded clay and sand beds of unit four may have been deposited via meltwater, as suggested by Eyles et al. (1983), that either reworked the finer sedimentary rocks in the debris, or via the same mechanisms as the sand beds of the fluviolacustrine material in the underlying unit three (i.e. pooling glacial water such as glacial lakes and sediment laden meltwater streams). The variation in the degree of interaction with meltwater between the flow till complex sedimentary rocks deposited at the Cape Jervis versus Kings Point and Waterloo Bay sections may reflect the position of the ice mass in relation where the till was deposited. The mixing of meltwater flow and debris flow deposits at Kings Point and Hallett Cove is indicative that the ice mass was stagnant or slowly moving, which would permit the formation of meltwater streams (Bennett and Glasser 2009). The mass flow of the debris at Cape Jervis was likely at the front of the retreating ice mass.

The varied lithofacies within the flow till complex are due to the diversity of glacial environment and instability of the ice mass as it retreats and decays. Deposition occurred both subglacially and subaqueously with debris flows and intermittent fluviolacustrine depositional processes. The clay and silt beds were deposited via glacial lakes that remained or were formed by trapping water between the ice and the built up debris. The sand and sandstone beds were deposited via meltwater streams flowing out from the ice mass. The diamictite beds were deposited when the top of the ice mass released debris trapped in the upper ice mass. These varied depositional settings are the cause of the differing thicknesses of the individual beds and the total thickness of the flow till complex at each measured section.

These observations are consistent with Alley and Bourman (1984) and Bourman and Alley (1999) where it was surmised that the flow till complex was deposited during the downwasting and slow retreat of a large ice mass. Additionally the occurrence of temporal glacial lakes and the associated glaciolacustine sedimentary rocks was suggested by Bourman and Alley (1990) and Alley et al. (2013).

Compared to the diamictite of the lodgement till (unit two), the diamictite of the flow till complex (unit four) has larger clasts which are mostly angular and are both locally- and distally-derived. The clasts increase in size up-profile. The matrix of the diamictite also reflects the dynamic depositional conditions. The matrix consists of unconsolidated sand grains which increase in size up-profile. It is likely that the diamictite was deposited by an icesheet rather than an ice tongue. The ice tongues likely melted before the ice mass retreated to the Troubridge Basin, likely decaying first as the ice would have been not as thick as the icesheet. The angular clasts and mixed source are indicative of an icesheet deposition.

At Waterloo Bay the contact between the flow till complex and overlying glaciomarine clay is transitional (Figs 8a and 9b), which is suggested to be indicative of a glacial environment where debris deposition continued during the influx of marine waters. The debris deposition occurred periodically allowing the silty clay beds to be deposited between deposition of debris beds. At Cape Jervis the contact between unit four and the clay of unit five is a sharp contact (Fig. 2b).

DEPOSITIONAL SETTING OF THE GLACIOMARINE SEDIMENTS (UNIT 5)

The glaciomarine sediments preserved at Cape Jervis and Waterloo Bay vary in thickness up to at least 11 m (Fig. 12). Unit five was deposited in a quiet, marine environment where it is likely that the marine waters were locally influenced by the downwasting and presence of glaciers or icesheets.

Previous studies (e.g. Ludbrook 1969, Foster 1974, Alley and Bourman 1984) recognised the sedimentary rocks are glaciomarine and surmised that deposition occurred in marine waters influenced by the presence of glaciers or icesheets where meltwater continually introduced sedimentary rocks to the environment. Ludbrook (1969) and Foster (1974) both recognised the effects of the glacial meltwater on the salinity and density of the marine waters which in turn affected the species of foraminifera. Foster (1974) added that the influence of the meltwater was likely to be isolated to the proximity of the meltwater inlet. Palynological studies conducted by Ludbrook (1969) and Foster (1974) suggest that the marine waters were cold with low salinity during the deposition of the glaciomarine sediments. The cool temperatures of the water are likely a function of the climate and proximity of the ice and meltwater flow input.

The mechanisms of deposition of unit five are similar those that occur in glacial lakes however the presence of marine foraminifera suggests a low energy marine depositional setting. Bennett and Glasser (2009) listed these to be direct deposition from the ice mass front; ‘rain-out’ from icebergs; deposition from meltwater flows; settling of sedimentary rocks in suspension; current reworking; and shoreline sedimentation. Rhythmically laminated clay and silts in glacial successions are typically described as varves however similar deposits such as turbidites can form due to low-viscosity density flows. Turbidite deposits without ripples and slumping suggest proglacial or ice-distal deposition where tidal and seasonal-stimulated changes in meltwater discharge control the amount of finer grained materials transported from the ice and deposited via suspended sediment plumes. Ice-distal deposition of turbidites are typically associated continental ice margin settings (Eyles 1993, Miall 2000). Hambrey and Glasser (2012) observed that glaciomarine deposition of massive or laminated clay with minimal clasts (<5%) and some sandstone beds are typically deposited via a combination of settling from suspension (clay) and iceberg rafting (sandstone).

Given the fine-grained, clay and silty clay nature of the glaciomarine sediments, it is likely that the mechanism of deposition is largely due to settling of sedimentary rocks that are in suspension in a low energy environment as suggested by Eyles et al. (1983), Miall (2000), Bennett and Glasser (2009) and Hambrey and Glasser (2012). The increase of distinct bedding in the clay sedimentary rocks at Cape Jervis (Fig. 2b) indicates that deposition occurred in a marine environment which was potentially deepening due to the increase melting of the ice mass, where sedimentary rocks were continually introduced to the environment via meltwater flows from the retreating glacier (Fig. 13b; Alley and Bourman 1984).

Sandstone beds within the unit (Fig. 12) are proposed to have been deposited via meltwater flows and iceberg ‘rain-out’ (Fig. 13b). Deposition of the sandstone beds via current reworking or shoreline sedimentation would result in cross-bedded sandstone (Bennett and Glasser 2009), which was not observed. The lack of a significant population of dropstones indicates that deposition via ‘rain-out’ from icebergs is not a preferred mechanism for deposition of the sandstone beds.

SUMMARY OF GLACIAL SEDIMENTOLOGY OF THE CAPE JERVIS FORMATION

The deposition of the sedimentary rocks of the Cape Jervis Formation can be summarised as five depositional settings each signifying a change in the glacial environment (Fig. 13).

1. Development of glaciated bedrock surfaces either due to pre-glacial freeze-thaw of the substrata to form gelifract as observed at Cape Jervis or due to the movement of the ice mass over the substrate forming glaciated pavements that were observed across the Troubridge Basin. This movement polished the underlying rock and caused the development of glacial movement indicators such as striations and chatter marks. Large erratics were deposited.
2. Deposition of lodgement till as the advancing of the ice mass moved generally from south to north. The diamictite is made up of dominantly locally-derived sedimentary rocks that were deposited in front of and under the ice mass.
3. The stagnation and subsequent melting and retreat of the ice mass in the Gulf St Vincent led to a series of glacial lakes forming between the ice and coastal cliffs. During this time clay and silt beds were deposited due to the settling of suspended fine material within the lakes. Sandstone beds of unit three were deposited due to the settling of suspended coarser-grained material and via the action of meltwater streams. Dropstones originated from the melting of icebergs within glacial lakes. Indications of a change in depositional settings are marked by an increase in the frequency and thickness sandstone and diamictite beds at the top of unit three, which was caused by an increase in melting of the ice mass.
4. Further down-wasting and the commencement of the southerly retreat of the glacier is signified by deposition of the flow till complex. The diamictite of unit four was deposited as saturated debris released by constant surface ablation and then deposited down slope. Sandstone beds and lenses between the diamictite beds were deposited via meltwater flows from the base of the ice mass.
5. A rise in sea-level, possibly initiated by the melting of the ice mass, led to a marine incursion where glaciomarine clay sedimentary rocks where deposited over the flow till complex. The presence of stagnant and retreating ice continued to supply meltwater and coarser (sand) sedimentary rocks to the marine water, ultimately lowering the salinity. The increasing bedding of the clay indicates a rapidly deepening environment.

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APPENDIX

DETAILED DESCRIPTIONS OF THE MEASURED SECTIONS IN THE TROUBRIDGE BASIN

Hallett Cove section

The northernmost known occurrence of the Cape Jervis Formation on the Fleurieu Peninsula is in the coastal cliffs of Hallett Cove (Figs 1 and 4a). The area is host to a well-preserved exposure of Cape Jervis Formation and the underlying glaciated pavements. The section investigated is begins at the edge of the shore platform and is exposed in a 30 m interval in the incised gullies of Sugarloaf Creek (Fig. 4a).

The basement rocks within the Hallett Cove area dominantly comprise Neoproterozoic Wilpena Group sedimentary rocks. These sedimentary rocks are well preserved as a glaciated pavement, which is best exposed at the top of Black Cliff, north of Sugarloaf Creek (Fig. 5a). The glaciated pavement has been polished and striated and preserves chatter marks and grooves (Fig. 5a). Bourman and Alley (1990) calculated a northwesterly ice movement direction using measurements of the striae and till fabric studies. There is no exposed glacial bedrock pavement at the base of the measured section, at Sugarloaf Creek, however, diamictites overlie polished pavement at Black Cliff (Fig. 5b).

The lowermost 2 m of the Sugarloaf Creek section consists of diamictite that is exposed on the shore platform and in the mouth of the creek. The diamictite has been assigned to unit two of the Cape Jervis Formation (Bourman and Alley 1990). Clasts comprise up to 70% of the whole rock, range from 1 to 45 cm in size and are rounded to angular, though angular clasts are more common. Many of the rounded to subrounded clasts are polished, striated and faceted. The majority of clasts are locally-derived Wilpena Group sedimentary rocks with lesser (~5%) Encounter Bay Granite clasts. The diamictite matrix coarsens upward from grey-green sandy clay to buff coloured coarse-grained sand (Fig. 4b). The shore platform is also littered boulders and pebbles that have been eroded from the sedimentary rocks above and with erratics (Fig. 5c). Larger erratics (up to 5 m), comprise locally-derived shale of the Neoproterozoic basement. Smaller erratics (up to 1 m) also comprise largest Encounter Bay Granite.

At the mouth of the Sugarloaf Creek there is an accumulation of polished, rounded and striated rocks that are on average greater than 50 cm in diameter (Fig. 5d). These boulders are derived from diamictite units higher in the section. The top of unit two and bottom of unit three in this area is obscured by approximately 4 m of grasses and aeolian sands (Fig. 4b).

Unit three in the Hallett Cove area comprises ~28 m of clay, silt and medium to coarse-grained sand beds with minor diamictite and pebble beds (Figs 4b and 5e to g). The lowermost 10 m of unit three comprises silty clay (clay with 50–70% silt) beds interbedded with lesser medium to coarse-grained sand beds. The silty clay beds are pale grey with orange and red mottles and up to 2 m thick. The sand beds are buff coloured, up to 8 m thick and dominantly comprise coarse-grained quartz dominated, unconsolidated sand with clay mineral cement. A pebble layer (~10 cm thick) is preserved within this part of the section (Fig. 4b). Pebbles make up 50% of the layer, are up to 35 cm size and comprise dominantly of Wilpena Group sedimentary rocks. Dropstones are also occasionally preserved. The dropstones are up to 50 cm size and also comprise Wilpena Group sedimentary rocks. The dropstones deform the sediment underneath them and are draped by sediment on top (Fig. 5f, g).

The silty clay beds are overlain by about 7 m of red and purple medium- to coarse-grained sandstone beds interbedded with occasional diamictite and clay beds (Fig. 5e). The sandstone beds vary from consolidated to friable. The sandstone comprises coarse-grained, angular quartz sand with clay mineral cement. The diamictite beds are 0.5 to 2 m thick. The clasts comprise 40% of the whole rock, are angular, up to 5 cm and consists mostly of Wilpena Group sedimentary rocks. The matrix of the diamictite is coarse- to very coarse-grained sand. A pebble lens is

preserved within one of the lower sandstone beds (Fig. 4b). The pebble lens is up to 50 cm thick and is dominated by subangular Neoproterozoic Wilpena Group sedimentary rocks.
The red and purple sandstone dominated beds are overlain by about 5 m of coarse-grained, buff to yellow sandstone and a thick (~50 cm) diamictite lens. The sandstone contains occasional layers of fine- to medium-grained, red, unconsolidated sand up to 20 cm thick. These red sand beds also preserve red and orange Fe-oxide mottles (goethite; Fig. 4b) and thin red laminations (Fig. 5e). The diamictite at the top of the sandstone comprises clasts up to 50 cm in diameter and comprise of Wilpena Group sediment and lesser Encounter Bay Granites. The matrix of the diamictite is a very coarse-grained sand. Several <1 m size dropstones occur within the sandstone. The majority of the dropstones are between the diamictite lenses and are rounded, polished and some are striated. Some of the dropstones have disturbed the sedimentary rocks directly below them (Fig. 5f).

At the top of the exposed unit three and directly behind and including much of the Sugarloaf is 2–3 m of partially consolidated, medium- to coarse-grained, yellow, bedded sandstone. The sandstone comprises of subrounded to rounded, coarse-grained quartz grains with clay mineral (kaolinite and montmorillonite) cement (Fig. 4b). A thin (20 cm) pebble lens is preserved in the middle of the sandstone (Fig. 4b). The pebbles are rounded and are all locally-derived, Wilpena Group sedimentary rocks and between 5 and 10 cm in diameter. Several metres of loosely consolidated Pliocene Hallett Cove Sandstone overlie the top of the exposed Cape Jervis Formation in this area.

Kings Point section

The coastal cliffs of Kings Point preserve 14 m of Cape Jervis Formation exposed in two erosional gullies (Fig. 6a). Both sections unconformably overlie the Cambrian Petrel Cove Formation of the Kanmantoo Group (Bourman and Alley 1995). It is not clear whether the late Palaeozoic sedimentary rocks of the southwestern gully directly overlie the late Palaeozoic sedimentary rocks of the eastern gully or if some late Palaeozoic sedimentary rocks have been eroded creating a disconformity between the sections.

The base of the section is exposed in the eastern erosional gully and are part of unit three (Fig. 6b). Approximately 1 m of dark red, massive, silty clay beds contain occasional rounded and polished, 5 cm clasts typical of the underlying strata. Overlying the silty clay beds is 4.5 m of alternating fine-grained sand and silty clay beds. The fine-grained sand beds are grey-green with orange mottles of goethite (Fig. 6b). The sand comprises of coarse-grained quartz with clay mineral (montmorillonite and kaolinite) cement. The 0.2–1 m thick clay beds comprise montmorillonite, kaolinite and nontronite (Fig. 6b) and include rounded and polished 40 cm clasts derived from the local metasedimentary rocks (Fig. 7a). Smaller (up to 20 cm) granitic clasts also occur throughout the clay beds. These are typical of the Encounter Bay Granite exposed a kilometre to the east. Rounded, polished and occasionally faceted erratics (up to five metres) typical of the Encounter Bay Granite and Kanmantoo Group metasedimentary rocks within the gully have Cape Jervis Formation deposited against them.

The unit four of the Cape Jervis Formation is exposed in the southwestern gully (Fig. 6a).The unit comprises ~8.5 m of diamictite interbedded with sandstone. The lowermost diamictite beds are up to 2 m thick (Fig. 6b). Clasts comprise of 25 to 75% of the whole rock, are mostly 20 cm, can be up 40 cm, and are rounded to angular in shape. Rounded clasts are often polished and striated. The clasts are typical of Kanmantoo Group metasedimentary rocks and Encounter Bay Granite. The diamictite matrix coarsens upward from clay to coarse-grained sand (Fig. 6b). The lowermost 1.5 m of diamictite is faintly laminated with a grey clay matrix consisting of montmorillonite and kaolinite (Fig. 6b). Higher in the sequence the diamictite comprises of fine-grained, friable sand. The buff coloured, medium-grained sandstone interbeds are up to 2 m thick. Lenses of pebbles throughout the diamictite consist of the same lithology as the diamictite clasts. The pebbles are up to 50 cm and are typically rounded and polished (Fig. 7b).

The upper 4 m of sediment exposed in the southwestern gully exposes diamictite and coarse-grained sandstone beds. The diamictite beds are up to 1 m thick, and are massive with either coarse-grained sandstone matrix or clast-supported with minimal coarse-grained sandstone matrix. Clasts typical of Kanmantoo Group metasedimentary rocks and Encounter Bay Granite are rounded to subangular and up to 50 cm. The base of each diamictite bed is defined by a pebble bed consisting of clasts with the same features as the diamictite clasts. The diamictite matrix comprises montmorillonite, kaolinite, quartz as well as goethite and hematite (Fig. 6b). Medium-grained sandstone beds and lenses are throughout the unit. The sandstone is yellow with angular to rounded, poorly sorted quartz with lesser rock fragments that are of the same composition as the clasts within the diamictite. The gully is littered with Encounter Bay Granite erratics that are up to 2.5 m, rounded and polished (Fig. 7c). The Cape Jervis Formation is overlain by up to 10 m of Tertiary sands.

Waterloo Bay section

The Waterloo Bay section preserves approximately 3 m of Cape Jervis Formation that are unconformably overlain by about 4 m of Quaternary sedimentary rocks (Figs 8a and 2.9a). The Quaternary sedimentary rocks unconformity is well preserved and is an undulating surface.

The Cape Jervis Formation in the Waterloo Bay section consists of bedded clay and diamictite of unit four overlain by massive clay of unit five. The lowermost metre of the exposed sedimentary rocks comprises alternating 30–50 cm thick silty clay and diamictite beds (Fig. 8b). The beds are green in colour and dominantly comprise montmorillonite, phengite and muscovite (Fig. 8b). Hard, red and orange mottles of hematite and goethite are also preserved on the surface of the silty clay beds (Fig. 9b). Clasts within the diamictite are subrounded and range from <1–15 cm. The clast lithology is variable. Larger clasts (<10 cm) are typical of Encounter Bay Granite (Fig. 9b) and smaller clasts are typical of locally-derived granite, sandstone and metamorphic basement and Kanmantoo Group metasedimentary rocks. The matrix of the diamictite beds is the same material as the silty clay beds and preserves the same colour and mottling and mineralogy.

Approximately 2 m of unit five overlies the interbedded clay and diamictite beds consisting of clay with lesser sandstone (Fig. 8b). Clay beds are up to 50 cm thick, massive, prismatic fractured, and green in colour with red and orange mottles of hematite and goethite (Fig. 9c). The fine-grained, sandstone bed (<20 cm) is red with some patches of white, the sandstone is extremely hard. Mottles in the clay decrease towards the top of the section. Larger erratics of the same lithologies as the clasts in the diamictites are scattered along the shore line near the section and along Waterloo Bay. The section is overlain by a palaeosol containing alunite and Quaternary limestone and calcrete.

Kingscote composite section

The unit underlying the Cape Jervis Formation sedimentary rocks in the Bluff Quarry and Kingscote foreshore sections is unknown although it is interpreted that the sedimentary rocks are underlain by Cambrian Kanmantoo Group metasedimentary rocks as seen at other locations on the Kangaroo Island (Bourman and Alley 1999). The sedimentary rocks of the Bluff Quarry section comprise interbedded silty clay, diamictite and sandstone (Fig. 10b). The silty clay beds are 0.5–3 m thick (Fig. 10b), and comprise grey-green, bedded, clay (kaolinite) with some thin (<0.1 cm) beds of goethite (Fig. 11a). Diamictite beds are up to 1 m thick (Fig. 10b). Clasts within the diamictite are less than 0.5 cm size, rounded to angular, and comprise metasedimentary rocks typical of the Kanmantoo Group. The matrix of the diamictite is fine-grained silty sand and preserves bedding. Sandstone beds have variable bed thickness and grain size. The lowermost sandstone has bedding preserved by hard, pink, medium- to coarse-grained sandstone beds (Fig. 11c). More commonly, the sandstone is fine- to coarse-grained, with subrounded to rounded quartz (Fig. 11b) with clay mineral (kaolinite and montmorillonite) cement. Planar and trough cross-bedding occurs sporadically throughout the section (Fig. 11d) although it is typically poorly-preserved (Fig. 10b). The uppermost sandstone in the Bluff Quarry section is a fine- to coarse-grained, upward coarsening buff coloured sandstone that is ~40 cm thickness. The section is overlain by Jurassic Wisanger Basalt (Fig. 11a).

The Cape Jervis Formation sedimentary rocks exposed in the coastal cliffs near the Kingscote Wharf (Fig. 10a) are a sequence of clay to sandstone beds (Fig. 11e). The lowermost 3 m are dominated by silty to fine-grained sandstone beds (Fig. 10b) with kaolinite and gypsum cement (Fig. 10b). Approximately 3 m of buff coloured, massive clay overlie the indurated sandstone (Fig. 11f). The base of this clay has prismatic fractures and orange mottles (Fig. 11g) are throughout the clay unit. The uppermost 3 m of the section consists of fine-grained sandstone. The sandstone is yellow with purple and orange (hematite and goethite) mottles. This unit is unconsolidated except in places where the beds are contorted.