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The glacial geology and landscape of Strathmore and adjoining offshore zone, with especial reference to 1:10 000 scale Sheet NO76NW

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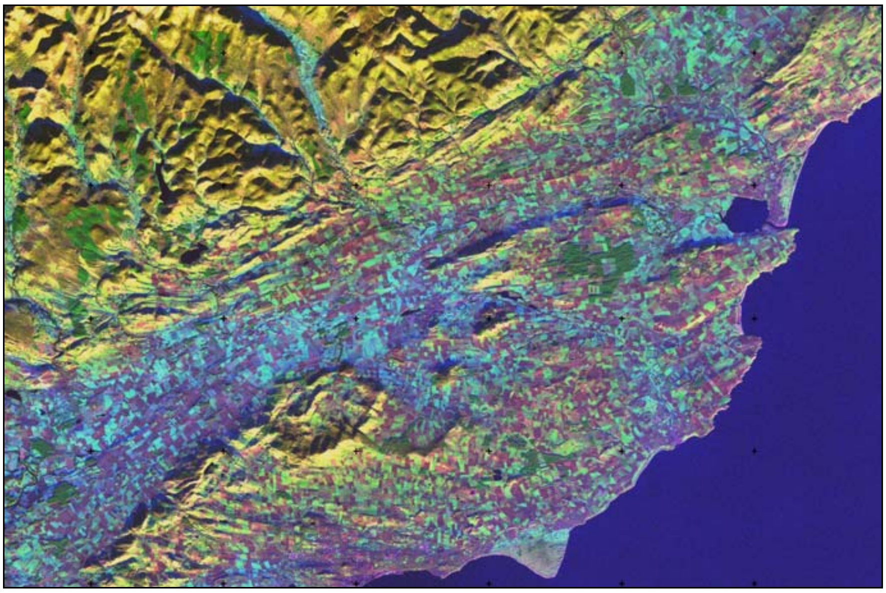

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/04/178

The glacial geology and landscape of Strathmore and adjoining offshore zone, with especial reference to 1:10 000 scale Sheet NO76NW

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Key words

Strathmore; Tay-Forth; Montrose; Quaternary; ice streams; glacial geomorphology.

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Foreword

This report is an output from the Midland Valley Integrated Surveys project, a component of the Science Budget-funded BGS core Programme. The research presented here is part of the geological resurvey of the Montrose district (Scotland Sheet 57E) and follows the System for Integrated Geospatial Mapping (SIGMA).

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Field discussions with Jon Merritt, Mike Browne and Dave Millward helped elucidate the nature of much of the onshore geology and geomorphology. Comments from Jon Merritt, Mike Browne and Maxine Akhust improved earlier drafts of this report. We thank Luke Bateson for processing the Landsat TM image and aerial photos, and for providing NextMap data. Aerial photographs were provided by the Royal Commission on Ancient and Historical Monuments of Scotand (RCAHMS).

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1 Introduction

This report describes the Bedrock and Superficial Geology of 1:10 000 Sheet NO76NW (Craig of Garvock) within the Strathmore area of eastern Scotland. It forms part of the revision of Montrose 1:50 000 Geological Sheet (57E).

Strathmore forms a low vale bounded to the north by the Highland Boundary Fault (HBF), and to the south by the Sidlaw Hills. NO76NW is underlain by a Devonian sedimentary sequence with interdigitating contemporaneous igneous sheets.

The northern edge of the field-mapped area (NO76NW) lies 1-2 km south of Laurencekirk, Kincardineshire, and the southern edge at St. Cyrus, just north of the River North Esk. The ground has greater relief than that either to the north (Strathmore) or to the south (Montrose Basin), and includes much of the elongate Hill of Garvock in the north, and associated minor hills to its south. Maximum elevation in the field area is 277 m O.D. on the Hill of Garvock, and the minimum is c. 60 m O.D. at the coastal village of St. Cyrus. The dominant grain of the landscape is southwest-northeast, reflecting major bedrock structures and the influence of ice-moulding.

1.1 HISTORY OF SURVEY

Early descriptions of the bedrock geology of Strathmore and the surrounding area by Imrie (1812), Lyell (1829), Jameson (1835) and Agassiz (1835) are summarised by Armstrong and Paterson (1970). These early accounts address the regional sedimentary sequence and their relation to the ‘primary rocks’ of the Scottish Highlands. Considerable advances were made in defining regional stratigraphies through the application of early biostratigraphy, based on the local occurences of various Devonian plants and fish. Of particular interest to the area described in this report is the finding of fossil fish at Canterland Den, otherwise known as the Den of Morphie, by Mitchell (1860; 1861). Attempts were made, albeit controversially, to correlate the Devonian strata of Strathmore with those in Caithness (c.f. Murchison 1859; Geikie 1879; Traquair 1902; Hickling 1908).

The igneous rocks of the area were initially described by Lyell (1829), Fleming (1838) and Harkness (1862). Following primary mapping by H M Skae, D R Irvine and G Barrow (Geological Survey of Scotland, 1897), Jack and Etheridge (1877) added more detail to the descriptions of the Ochil Lavas in Perthshire, whilst Geikie (1897) highlighted the occurrence of thick (3000 m) conglomerates along the Kincardineshire coast below the main Montrose volcanic zone. Research to the south-west of Montrose indicated that these volcanic units were intercalated with the sedimentary rocks (Goodchild 1904; Macnair 1908).

Although no recent Geological Survey Memoir exists for Sheet 57, details of the Lower Old Red Sandstone (ORS) strata in the Stirling area can be found in Waterston (1965), Francis *et al*., (1970), and Armstrong and Paterson (1970). Petrological descriptions of many of the key units can be found in Phillips (2004), and an authoritative account of the Devonian (ORS) stratigraphy at national scale is given in Browne *et al*., (2002).

Considerably less is known about the Superficial deposits of the Sheet 57 area. However, detailed descriptions of the major units in Fife and Perth/Dundee are provided in Forsyth and Chisholm (1977) and Armstrong *et al*., (1985) respectively. A generalised account of the Quaternary geology of the whole of the Midland Valley can be found in Cameron and Stephenson (1985), whilst more expansive descriptions of the Quaternary stratigraphy, palaeo-climate and glacier history for the whole of north-east Scotland, including the offshore zone, is given in Merritt *et al*., (2003). In summary, the stratigraphic sequence mainly reflects Late

Devensian glaciation and subsequent Holocene (Flandrian) deposition. Glacial tills are variably overlain with sand and gravel outwash or morainic deposits, and locally with laminated glaciolacustrine sediments. Late-glacial sea level change resulted in significant evolution of the coastline. Raised beaches were formed against abandoned clifflines and in major river mouths subsequently became buried by estuarine sediments. Buried peat layers, the 'sub-carse peat' of Armstrong *et al*., (1985), mark early Holocene marine regressions between c. 9.5-8.5 ka BP.

2 General Account

This report describes the Superficial and Bedrock Geology of 1:10 000 scale map sheet NO76NW, north of Montrose, reviews lithostratigraphical units in adjacent offshore Quaternary deposits and correlations with onshore deposits, and identifies local and regional-scale onshore geomorphological lineaments and streamlined landforms and their relevance to existing models of glaciation in eastern Scotland. Sedimentary and volcanic strata of the Lower Devonian Arbuthnott-Garvock Group underlie most of NO76NW; comprising the interbedded Dundee Flags, Scone Sandstone, Montrose Volcanic and Deep Conglomerate formations. The Cromlix Mudstone Formation of the overlying conformable Strathmore Group is at outcrop in the north-western corner of the sheet. A late Carboniferous quartz-microgabbro dyke is recorded near Craig of Garvock [NO 720 683]. Quaternary deposits of the Mearns Glacigenic Subgroup, products of the Main Late Devensian glaciation, are extensive. The Mill of Forest Till, Ury Silts and Drumlithie Sand and Gravel Formation are mapped within the sheet. It is often difficult to distinguish glacigenic sand and gravel deposits from underlying Devonian strata where the latter are deeply weathered. Holocene peat and alluvium are only locally developed. Quaternary formations recognised in the immediately adjacent shallow offshore area include the Forth, St. Abbs and Wee Bankie formations. Additionally, marine landform indicators, such as tunnel valleys and glacial lineations are described and represent a potential continuity of glacial geomorphological landforms across the boundary of the present-day coastline. The ice-stream models proposed by earlier studies, and currently being developed by onshore workers, provide a basis for future revision, refinement and reinterpretation of the offshore succession.

3 Descriptive Account

3.1 SEDIMENTARY STRATA AND IGNEOUS SHEETS

Sedimentary and igneous strata of the Arbuthnott-Garvock (ATGK) and Strathmore groups (Browne *et al*., 2002) underlie NO76NW (Craig of Garvock). Montrose Volcanic, Dundee Flagstone and Scone Sandstone formations of ATGK show an intercalated relationship within the extent of the map area.

3.1.1 Montrose Volcanic Formation (MVF), Arbuthnott-Garvock Group

Woodstone Hill [NO 745 668] is underlain by basaltic rock of the Montrose Volcanic Formation. Locally this intercalates with sandstone of the Dundee Flagstone Formation (DEF), although the base was not seen. Regionally the base of the formation varies from conformable to diachronous, the latter particularly to the north-east (Browne *et al*., 2002). At [NO 74381 66500] (Woodstone Hill) the dark red porphyritic basaltic rock has minor bedded siltstone inclusions. The laminated siltstone units may be up to 0.26 m thick. The siltstone is massive at its base, but becomes increasingly laminated upwards, with laminae being c. 3 mm thick towards the top. The rock is dark-reddish in colour and overall the unit dips 20° towards 297° – strike therefore being approximately southwest-northeast. The upper surface appeared to be planar.

The formation was first recognised by Armstrong and Paterson (1970) and was recently defined by Browne *et al*. (2002). Armstrong and Paterson (1970) identified the Morphie-Bruxie Hill member within the extent of NO76NW and note that this was previously referred to as the Arbuthnott Lavas (Campbell 1913), although the distinction of members is not made by Browne *et al*. (2002).

There is now considerable doubt, however, as to whether the basaltic rocks of the MVF are lavas, as previously assumed. Exposures in the cliffs near St. Cyrus, to the east of map sheet NO76NW, suggest instead that the sequence is better explained as a 'sill stack' (D.Millward spoken communication 2005). The intercalated relationship of the basaltic rock with the siltstone, its pepperitic texture, and the absence of extrusive igneous lithologies all indicate that sheet intrusions at relatively shallow depths exploited unlithified silt units within an accumulating sediment pile. Chilled margins to the basaltic rocks and evidence of fluidisation of sandier layers imply that water was still present in the host sediment at the time of intrusion. A degree of contemporaneity for both sediment pile and sill stack can thus be inferred for the MVF as a whole, whilst also recognising that individual sills must be younger than the sediments they intrude.

3.1.2 Dundee Flags Formation (DEF)

Siltstone of the Dundee Flagstone Formation was recorded in the Den of Morphie at [NO 72085 65553] forming units 0.7 – 0.8 m thick, conformably interbedded with sandstone, dipping 15° towards 290° and strike to the north-north-east. The siltstone is intensely fractured and fine- to thickly-laminated with lamination generally thickening upwards. Less than 600 m to the south-west at [NO 71649 65203] in the bank of the Den of Morphie a > 1.5 m high section also revealed alternating siltstone and sandstone beds, the siltstone forming several variably fossiliferous beds (from which samples were taken). Much of the siltstone is light grey, sandy, with thick laminae / thin beds up to 2 cm thick dipping 17° towards 321°, and an overall shaley texture. The main fossiliferous horizon, however, is massive, darker grey, and only 0.11 m thick. It forms a distinct unit between two of the lighter grey siltstone units.

In Den of Morphie at [NO 72085 65553] the sandstone that is interbedded with the siltstone forms units 0.3 – 0.8 m thick, and is variably massive, thickly bedded, or finely laminated. As with the siltstone, lamination or bedding often thicken upwards. Ripple lamination was seen in two of the units, always near the base (Figure 1). The beds dip 15º to the north-west.

Figure 1: Ripple-laminated sandstone, NRG 182, [NO72085 65552]. BGS registered photograph P581348.

The DEF is thought to interdigitate with the Catterline Conglomerate Formation and the Ochil Volcanic Formation. The base of the unit is only seen overlying the latter. The top of the unit is diachronous with the Scone Sandstone Formation (Browne *et al*., 2002).

3.1.3 Scone Sandstone Formation (SCN)

Weathered cross-bedded interbedded grey and red sandstone was recorded in the Den of Morphie at [NO 70748 63887], where it is assumed to conformably overlie sandstone of the DEF. The base of the SCN was not, however, seen. Regionally the base of the unit may pass transitionally into the DEF or Ochil Volcanic Formation, whilst the top is transitional with the Cromlix Mudstone Formation or intercalated with the Deep Conglomerate (Browne *et al*., 2002). In the exposure at [NO 70748 63887] the overall dip of the beds was 23º towards north–north-west, whilst the cross-bedding suggested a palaeoflow direction to the south-west. The rock is intensely weathered and disaggregates easily. The medium-grained red sandstone beds are more coherent than the coarse-grained grey sandstone beds.

3.1.4 Deep Conglomerate Formation (DECO)

Sections expose the Deep Conglomerate Formation in the Burn of Balmakelly [NO 70013 68001] and Wideopen Burn [NO 72100 67800], [NO 72600 68000], presumably overlying or interbedded with andesitic / basaltic rock of the ATGK. The sections reveal up to 5 m of this lithology, all weathered to a soft diamicton. No contacts were seen, but are assumed to be conformable. Regionally the DECO is thought to conformably overlie the MVF, and laterally interdigitates with the SCN formation (Browne *et al*., 2002). Where exposed the conglomerate is often clast-supported, or matrix-poor, with constituent clasts ranging from 5 to 30 cm. All clasts are very well rounded, although many are cracked, fractured or completely broken. Some clasts are decomposed and disaggregate easily. Clasts within the conglomerate are highly varied in origin and range from locally derived sandstone and conglomerate to dark red chert, quartzite, semipelite, psammite, granite, gneiss and basalt. Sections in the Wideopen Burn show the conglomerate in different weathering states. At the first, [NO 72100 67800] the rock is decomposed to such an extent that even the constituent clasts can be dug with a trowel. At the second, [NO 72600 68000] the conglomerate has weathered to gravel with a sandy matrix hosting coherent, but fractured, clasts.

DECO conglomerate often incorporates sandstone interbeds, such as at [NO 72085 68220] (Hill of Garvock). Here the sandstone units are less than 0.5 m thick and dip slightly south of west, which is at odds with the regional north-westerly dip. On this basis it is suggested that these particular sandstone beds are channel fills or small ‘ponds’ whose architecture bears little relationship to the dominant bedrock grain. In exposures along the Wideopen Burn and Burn of Balmakelly, sandstone laminae drape over cobbles in underlying (DECO) conglomerate units. Generally the sandstone is coarsely laminated or fine to medium bedded, often with beds 1–3 cm thick. At Burn of Balmakelly, [NO 70013 68001], the beds thicken upwards from a minimum of 1 cm to a maximum of c. 5 cm. Some sub-rounded or rounded centimetre-size clasts occur within the sandstone, forming interbeds of conglomerate where most abundant . The base of the sandstone is defined by a cobble ‘lag’ that rests on siltstone. Cobbles in this unit deform the underlying siltstone laminae.

At Hill of Garvock, [NO 72501 69698], a unit of sandstone 0.3 m thick was recorded, separating weathered (Deep Conglomerate Formation) conglomerate from till. The sandstone and the sparse clasts that it contains are also completely weathered.

3.1.4.1 GARVOCK LAVA MEMBER

Outcrops of Arbuthnott-Garvock Group vesicular igneous rock, presumably basaltic and andesitic, occur above the Wideopen Burn along the spur that runs ENE eventually up to Hill of Garvock. It is assumed to intercalate with conglomerate of the DECO. Indeed, the landscape is one of prominent crestlines and dip slopes that strongly suggest such a relationship between the more resistant basaltic rocks and the softer sandstone and conglomerate units. Rarely does the basaltic rock exceed 0.5 m in thickness where exposed. Often the basaltic rock is partially weathered, appearing dark, randomly fractured and easily disaggregated. A dark to mid-grey fine-grained basaltic rock seems to constitute the upper ridge of the Hill of Garvock, where it protrudes from the ground surface in numerous places and is unweathered.

The Garvock Lava Member was originally assigned to the MVF by Armstrong and Paterson (1970), but is now thought to be younger, and contemporaneous with the DECO (Browne et al., 2002). Given the recent reinterpretation of the MVF described above, it may be reasonable to assume a similarly intrusive origin for the Garvock Lava Member, which consequently would require renaming.

3.1.5 Cromlix Mudstone Formation (CXF), Strathmore Group

The Cromlix Mudstone is not exposed in the area but has been inferred to underlie the north-western corner of NO76NW by the previous survey. Typically the base of the CXF is transitional with the Arbuthnott-Garvock Group. The formation passes laterally and upwards into the Teith Sandstone Formation (Browne *et al*., 2002).

3.2 LATER INTRUSIVE IGNEOUS ROCKS

3.2.1 Late Carboniferous minor intrusions (CSTD)

A minor basaltic intrusion, part of the Late Carboniferous tholeiitic dyke swarm, is mapped on Craig of Garvock at [NO 7265 6841]. The dyke forms a poorly-exposed low ridge of dark grey, highly weathered basaltic rock intruded into sandstone of the DECO group.

3.3 SUPERFICIAL DEPOSITS

3.3.1 Devensian

All glacigenic deposits mapped in NO76NW are assigned to the Mearns Glacigenic Subgroup of the Caledonia Glacigenic Group (McMillan *et al*., 2005). This subgroup, which is equivalent to the Mearns Drift Group of Merritt *et al*., (2003), comprises Mill of Forest Till, Ury Silts, and Drumlithie Sand and Gravel formations. All deposits are the product of the Main Late Devensian glaciation, and were laid down by, or at the margins of, ice that flowed north-eastward into the North Sea from Strathmore. A more comprehensive description of the regional stratigraphy can be found in Merritt *et al*., (2003).

3.3.1.1 TILL, MILL OF FOREST TILL FORMATION (MFT)

All tills observed in the area are red, ranging in colour between dusky red (2.5Y 3/4), yellowish red (5YR 4/6) and strong brown (7.5 YR 4/6) (Figure 2). Although mostly seen in auger holes, some exposures were found for example along the Garvock Burn [NO74295 68810], where it is up to 3.5 or 4 m thick. Generally the till has a sandy matrix with variable silt and clay content. Proximity to bedrock favours a more sandy diamicton, whilst the thicker deposits found on the lower ground are more silt and clay dominated. Augering is very difficult due to the large number of clasts in the till, most of which are probably reworked from the conglomerate bedrock in the area. In some cases till is distinguished from weathered bedrock only by its greater matrix to clast content. Often the till is friable and would probably grade as silty sand and gravel. This is of significance when interpreting borehole logs. Overall, a thin cover of till is likely even on the highest ground, whilst the thickest deposits are found on the low, smooth, rolling topography that characterises much of NO76 NW.

Figure 2: Red till overlying weathered sandstone and conglomerate, NRG 179, [NO 72488 69722], BGS registered photograph P581330.

3.3.1.2 MORAINIC DEPOSITS, (HMGD)

Morainic deposits have been mapped around Mill of Criggie at [NO 728 660] and [NO 727 657]; at [NO 736 652]; and along the hillslope on the northwest side of Den of Morphie [NO 712 654] over a distance of c. 1 km. Together they appear to represent ice limits of a retreating margin that was confined by the higher ground of the Hill of Canterland and the Hill of Morphie. The landforms are distinctive because although low, their orientations are discordant with all the other linear landforms in the area. Augering reveals that the features are composed of sand, gravelly diamicton, or clayey till – or all three. The moraines are also closely associated with meltwater channels that trend obliquely across and down the surrounding hillslopes.

Smaller moraines are also mapped around Spittalmyre at [NO 720 666], associated with intervening glaciofluvial sediments, and on the south slope of Hill of Canterland 1 km to the south-west. Similar low morainic ridges also occur around Greenburn [NO 747 665] and have crestline orientations whose trends are approximately consistent with the trend of ice-marginal meltwater channels in the area.

3.3.1.3 GLACIOLACUSTRINE DEPOSITS, URY SILTS FORMATION (USI)

On the south side of Hill of Garvock [NO 734 695] 1 m of silt and clay was augered beneath c. 1 m peat and is interpreted to be of glaciolacustrine origin based on its context. The hollow in which it lies would likely have held a small glacial lake during retreat of the last (Late

Devensian) ice mass. No surface exposure of the material could be found, and augering did not prove the base of the deposit.

Silty grey clay augered around [NO 746 658] in the south-eastern part of NO76NW is interpreted as a glaciolacustrine deposit associated with nearby glaciofluvial meltwater channel deposits.

The largest area of glaciolacustrine sediments mapped within the sheet are around Spittalmyre [NO 715 666], close to the glaciofluvial deposits at Hill of Canterland described above. Eight auger holes in this area proved waterlain sediments ranging from coarse-grained sand to very soft plastic red/grey clay. The generally flat area has low ridges aligned west-east which seem to be composed of gravelly sand and may have been point bars relating to fluvial infilling of the former lake. In total area the lake may have covered c. 0.12 km^2. Confined by the topography except in the southwest, it is likely that the lake was dammed on that side by the retreating ice margin.

3.3.1.4 Glaciofluvial deposits, Drumlithie Sand and Gravel Formation (DSG)

Sand and gravel deposits of glaciofluvial origin on NO76NW are often difficult to distinguish from deeply weathered sandstone and conglomerate bedrock. The distinction is therefore largely based on a combination of the greater degree of grain-size sorting in bedrock units, the geomorphological context of the sediments, and deposit morphology. At Burn of Balmakelly [NO 700 680], the burn cuts through flat ground identified by Primary Survey as undifferentiated glaciofluvial deposits, and indeed appears to be a small area of glaciofluvial outwash, possibly a fan deposit sourced from the northwestward-aligned channel now occupied by the Wideopen Burn [NO 710 677]. Only one small scraping revealed cobble gravel, but the sloping terrace landform that it forms suggests that the gravel is most likely glaciofluvial in origin, rather than weathered conglomerate bedrock.

Ice-marginal glaciofluvial deposits consisting mainly of sand were augered on Hill of Canterland around [NO 713 656]. These sediments occupy a very flat area upslope from ridges interpreted to be moraines. The sediments are less than 1 m thick and overlie a red sandy and gravelly diamicton that may be an ice-marginal debris-flow deposit. Approximately 1 km to the north-east glaciofluvial deposits are mapped in abandoned meltwater channels [NO 718 663] that extend for c. 1 km. These sediments range from well-sorted, red, silty sand to poorly sorted, non-cohesive, gravelly sand, often greater than 1 m thick. Their presence is proved by augering but the sediments were not seen in section. They are associated with morainic ridges in the area around [NO 720 665], suggesting ice-marginal deposition. Similarly, around Greenburn at [NO 747 655] glaciofluvial sand was augered in the bottom of ice-marginal meltwater channels, and the abundant rounded cobbles on low terraces flanking the channels were assumed to be part of the same deposit.

North-east of Woodstone Hill [NO 750 675] greater than 1 m thickness of silty sand was augered in a low, flat hollow. The hollow forms a basin within a meltwater channel descending the northern flank of the drumlinoid Woodstone Hill.

3.3.2 Holocene

3.3.2.1 Peat, Tay Catchment Subgroup (PEAT)

Peat is largely absent from the field area, most probably as a result of fairly extensive land improvement for arable farming. Basin peat was seen at [NO 73400 69500] and exceeded 1 m depth, but as it contained a significant proportion of silt and sand it is in essence a waterlogged organic-rich soil. The true thickness of this accumulation could not be proved due to waterlogging. Peat was also mapped north of Brandshill Wood [NO 732 679]), where it is waterlogged and is at least 0.5 m thick Overall, none of the peat seen in the field area was fibrous, but rather just organic mud. Stratigraphically the peat is assigned to the Tay Catchment Subgroup of the Britannia Catchments Group.

3.3.2.2 ALLUVIUM, TAY CATCHMENT SUBGROUP (ALV)

Very few fluvial deposits were mapped in the area. Generally, alluvial sedimentation is limited in extent and is often the result of small burns incising and reworking till or weathered bedrock, but rarely forming significant new deposits or terraces. Some small terraces c. 1 m above modern watercourses were mapped, such as Wideopen Burn [NO71173 67713], and were seen to be composed of bedded sand and gravel (Figure 3). South of the mapped area, however, larger rivers such as the North Esk have formed floodplains up to 200 m wide. These are thought to be composed mainly of sand, based on auger hole and borehole evidence. They are stratigraphically assigned to the Tay Catchment Subgroup of the Britannia Catchments Group.

Figure 3: Sediments forming alluvial terrace, Wideopen Burn, [NO 71173 67713], BGS registered photograph P581308.

3.3.3 Artificial ground

3.3.3.1 WORKED GROUND

Areas of worked ground are restricted to small pits generally less than a few hundred square metres in size. Pits are present at:

Hill of Garvock [NO 728 698];

Stoneydale [NO 714 684];

Kirkton Hill [NO 702 688] and [NO 705 671];

Woodstone Hill [NO 747 672], [NO 748 670] and [NO 744 665];

Hill of Canterland [NO 706 653];

Hill of Morphie [NO 726 651].

3.3.3.2 Infilled ground

Infilled or made ground is restricted to very small occurrences where either embankments or dams have been created, rubbish has been dumped, pipelines have been dug, or where reservoirs have been buried.

Hill of Garvock [NO 749 694] (covered reservoir);

Brandshill Wood [NO 726 673] (agricultural refuse) and [NO 731 678], [NO 734 679] water retention banks;

Canterland [NO 706 659] (dam);

Den of Morphie [NO 721 658] and [NO 722 658] (pipeline spoil heaps);

St. Cyrus [NO 749 651] (dismantled railway embankment).

3.3.3.3 Disturbed ground

Small areas of disturbed ground are present in many places but, where landscaped, are often not easily identified. Pipeline routes across the area are often backfilled quickly and well-landscaped, leaving minimal trace. Obvious areas of disturbed ground were seen at:

West Bradieston [NO 732 684];

Taylorspark [NO 733 660] (fishing pond development);

Den of Morphie [NO 722 658] (pipeline disturbance).

3.4 OFFSHORE STRATIGRAPHIC SCHEME

The area offshore Montrose, between about 56º 30’–57º 00’ N and 1º 30’–2º 30’ W, was investigated with a view to integrating the offshore geology with that onshore. Particular focus was directed toward:

- A review of offshore geomorphological landforms and Quaternary deposits from bathymetric, sea-bed sediment and Quaternary geology maps and reports, including the seismic character of the sediments and their mode of deposition.
- Discussion of the above in the light of onshore regional scale geomorphological interpretation (from remotely sensed data) and detailed scale interpretation (field mapping) for the Montrose sheet.

Following initial discussions concerning ideas related to onshore indicators of ice-sheet flow directions in the Tay–Forth region, the geographic area of the study was expanded much further offshore, as indicated on Figure 5. The rationale behind this modification was to incorporate some of the better defined indicators of subglacial activity that are known to exist offshore, but occurring beyond the strict eastern limit of sheet 57E. These include possible glacial lineations, as well as tunnel valleys.

Thus, in order to satisfy all of the objectives detailed above, description of the offshore data is structured as follows:

1. Physiography
2. Quaternary stratigraphy, including onshore–offshore correlation, environmental conditions and geological development
3. Marine landform indicators of subglacial activity

The data utilised in this study include the published 1:250,000 series offshore Quaternary maps (Tay–Forth and Marr Bank, British Geological Survey 1985, 1986a, 1986b, 1987), BGS reports, published scientific papers (see References), the legacy geophysical dataset (high-resolution seismic profiles and sidescan-sonar images) and DigBath 250k for UK waters.

The physiography of the offshore area can be broadly divided into three zones:

1. An inner (coastal–nearshore) zone, ranging from 5–20 km wide and including the mouth of the Tay estuary. The bathymetric contours are generally smooth and reflect a seaward dipping seabed of variable, albeit gentle, gradient down to a water depth of about 50 m.
2. A middle zone of highly irregular bathymetry, which reflects a channelised sea bed with locally rapid variation in water depth between 60 and 120 m. The trend of the channels is very variable (Figure 5). These features are described further in section 5.2.1.
3. An outer zone where the bathymetric contours become much smoother, reflecting a generally more flat-lying to gently mounded sea bed with water depths in the range of 60 to 80 m.

Physiographic zones 1 and 2 cover the bulk of the study area. Their character is primarily controlled by bedrock type and glacial history. The highly irregular middle zone (2) is underlain by Permian and Triassic rocks; the Permian strata include Upper Permian Zechstein sedimentary rocks that locally crop out in the study area. Solution and halokinesis have greatly affected the Upper Permian evaporites and have led to the collapse of the overlying Triassic red beds in this area, as evidenced by the highly irregular 'Top Anhydrite reflector' which marks the Permian–Triassic boundary (BGS 1986b Tay–Forth Solid Geology sheet) (Figures 4 and 7). It is not inconceivable that the process of solution has been accentuated by the meltwater flux associated with Quaternary ice streaming in the Tay–Forth region.

The inner zone (1) is underlain by a different bedrock foundation consisting of Devonian and Carboniferous sedimentary and volcanic rocks (BGS 1986b Tay–Forth Solid Geology sheet). These appear to be more resistant lithologies as expressed by the preservation of the upstanding inner shelf topography (Figure 4).

Our current understanding of the offshore Quaternary succession in the Tay–Forth area (cf. Stoker *et al*. 1985; BGS 1987 Tay–Forth Quaternary Geology sheet) is essentially represented by the following subdivision, listed in descending stratigraphic order:

Sea-bed sediment layer (Holocene)

Forth Formation (Late Devensian– Early Holocene)

St. Andrew's Bay Member

Largo Bay Member

St. Abbs Formation (Late Devensian)

Wee Bankie Formation (Late Devensian)

This succession is interpreted to preserve a record of the activity of the last British Ice Sheet (Late Devensian) in this region. It is essentially a seismostratigraphic scheme (Stoker *et al*., 1985). The lithostratigraphic hierarchy utilised in this scheme retains an informal status. The essential characteristics of these units are summarised below (in descending order), and their stratigraphic relations are illustrated in Figure 4.

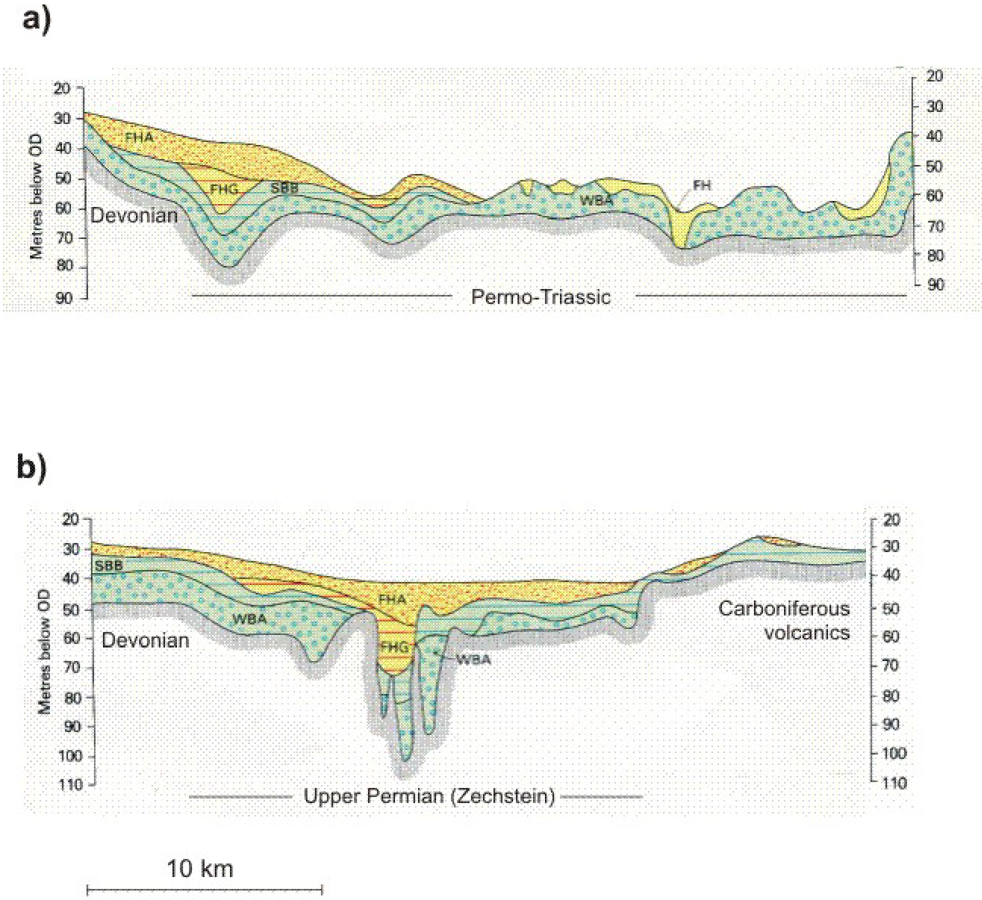

Figure 4: Sections showing the general relations of the Quaternary formations as well as the relation between bedrock physiography and the underlying geology. Abbreviations: FHA, St. Andrew's Bay Member (Forth Fm); FHG, Largo Bay Member (Forth Fm); SBB, St. Abbs Formation; WBA, Wee Bankie Formation. Sections taken from BGS Tay-Forth Quaternary Geology sheet (British Geological Survey, 1987).

3.4.1 Sea-bed sediment layer (Holocene)

The sea-bed sediment layer represents the superficial layer of unconsolidated material occurring at the sea bed. For the most part, this layer probably represents reworked Late Devensian–Early Holocene sediments, which generally form a veneer, <0.5 m thick, over the pre-existing sediments. The sea-bed layer is predominantly sandy, though locally gravelly and muddy, and occasionally shaped into linear to sinuous sand waves and / or megaripples (Tay–Forth Sea-Bed Sediment sheet, BGS 1986a). A northeasterly directed, coast parallel, sand transport direction currently operates in this area (Stride, 1973). The tide and current data indicate that the flow has sufficient strength to transport and possible erode medium-grained sand-grade material (Tay–Forth Sea-Bed Sediment sheet, BGS 1986a).

3.4.2 Forth Formation (Late Devensian to Holocene)

In the study area, the Forth Formation mainly occurs west of 2º W, though it is commonly preserved in the deep troughs to the east (Figure 5). It varies in thickness from <5 to 40 m. On the basis of seismic stratigraphy, lithology and environment of deposition, the formation has been divided into two members, the St. Andrews Bay and Largo Bay members.

3.4.2.1 St. Andrews Bay Member (Early Holocene?)

The St. Andrews Bay Member rests unconformably on all pre-existing units. The distribution of this unit is indicated on Figure 5, where it shows a clear linkage to the coastal and nearshore zone. On high-resolution seismic profiles it commonly displays a progradational reflection pattern (Figure 8a). In the study area, the sediments predominantly consist of sands and silts, deposited in a fluviomarine environment. It should be noted that in the Firth of Forth, the base of this unit is highly erosional. The top of the unit is also marked by a planar erosion surface in places.

3.4.2.2 LARGO BAY MEMBER (LATE DEVENSIAN)

The Largo Bay Member is mostly preserved in bathymetric hollows, commonly those associated with the channelised bathymetry, and overlies the St. Abbs Formation or rests directly on bedrock (Figure 4). On high-resolution seismic profiles, this unit displays internal reflections that are indicative of onlap fill. Internal discontinuity surfaces occur locally. The sediments consist predominantly of interbedded estuarine / marine muds, silty muds and silts with rare small pebbles.

3.4.3 St. Abbs Formation (Late Devensian)

The St. Abbs Formation is generally <10 m thick, and lies unconformably on the Wee Bankie Formation or directly on bedrock (Figures 4 and 7a). This formation characteristically displays a structureless to opaque acoustic signal on seismic profiles (Figure 7a), with occasional faint, discontinuous, subparallel, internal reflectors. Lithologically, pebbly glacimarine muds dominate the unit.

3.4.4 Wee Bankie Formation

The Wee Bankie Formation ranges from <5 to 40 m thick. Its offshore limit is shown in Figure 5. It commonly occurs as a veneer on the irregular bedrock surface, though locally it is hummocky and forms discrete, often linear, mounds and ridges (Figure 8). Localised accumulations also occur in the overdeepened channels. On high-resolution boomer profiles (e.g. Figure 8), this unit is rarely penetrated by acoustic signals. On sparker profiles (e.g. Figure 7), occasional point source hyperbolic reflectors are present, suggestive of a bouldery character. It is not always easy to distinguish between rockhead and the Wee Bankie Formation. Lithologically, the unit is dominated by sandy and gravelly diamicton (most probably a subglacial till) with interbedded fluvial sand and pebbly sand. Coarse sand and gravel have also been proved in the channelised areas.

3.5 ONSHORE–OFFSHORE CORRELATION

A general correlation between the offshore and onshore sequences is shown in Table 1. This correlation has not been updated since the publication of the BGS Tay–Forth Quaternary Geology sheet in 1987, thus it may require some revision. The stratigraphic sequences from two onshore areas are listed; from Grangemouth (after Browne *et al*., 1984) and from Tay–Earn (after Paterson *et al*., 1981).

GRANGEMOUTH	TAY–EARN	TAY–FORTH
Grangemouth Beds	Post-Carse Estuarine Deposits	Sea-bed sediments
Claret Beds	Carse Clay	St. Andrew’s Bay Member (Forth Formation)
Bothkennar Gravel	Port Allen Gravel	(major erosion?)
Abbotsgrange Beds	Culfargie Beds / Powgavie Clay	Largo Bay Member (Forth Formation)
Kinneil Kerse Beds	Fluvioglacial sand and gravel	St. Abbs Formation
Loanhead Beds	Till	Wee Bankie Formation

Table 1. General correlation of onshore and offshore Quaternary sequences (from BGS Tay–Forth Quaternary

Geology sheet BGS, 1987).

3.6 SUMMARY OF ENVIRONMENTAL CONDITIONS

The following summary of environmental conditions is taken from the BGS Tay–Forth Quaternary Geology sheet (BGS, 1987), and is based on the palaeontological work of Gregory *et al*. (1978).

- **St. Andrews Bay Member** (Forth Fm): Temperate, shallow-water, estuarine to fluviomarine environment. Climatic conditions similar to present day.
- **Largo Bay Member** (Forth Fm): Climatic amelioration in the lower part of the unit (late glacial interstadial) gives way to a gradual deterioration in climate towards the top of the unit (Loch Lomond stadial. Cold offshore marine environment, shallowing towards top of sequence.
- **St. Abbs Formation**: Arctic marine environment similar to areas off Arctic Canada, Greenland and Spitsbergen at the present day.
- **Wee Bankie Formation**: Arctic environment.

4 Geomorphology

The use of Geographical Information Systems (GIS) to collate and analyse data at a variety of scales has been described most notably by Clark (1997), who also proposed a 'strategy' for using such tools in palaeoglaciological reconstructions. The method adopted here closely follows that outlined by Clark (1997), involving initial collation of topographic and geological datasets, orthophoto mosaics and satellite imagery, and the subsequent capture of glacial lineaments in a digital (GIS) environment. Full details of the types, scales and resolutions of all the datasets considered here are presented in Table 2.

Type of data	Dataset	Data type	Copyright	Scale and / or resolution	Scale of application
Topographic	Land surface contours	Vector (line)	OS	1:10 000 / 5m (v)	Regional and Local
	NextMap DTM	3D grid raster	BGS	5m (h), 1.2m (v)	Local
	BGS Profile DTM	3D grid raster	BGS	10m (h), 5m (v)	Regional and Local
	Topographic base maps	Monochrome raster	OS	1:10 000	Local
Imagery	Stereo aerial photographs	Monochrome raster	RCAHMS	1:24 000	Regional and Local
	Orthophoto mosaic	Monochrome raster	BGS	1:24 000	Regional and Local
	Landsat TM	3 band colour raster	BGS	30m (h)	Regional
	Side scan sonar	2D sonograph	BGS	400 m range, 0.5 m (v)	Regional and Local
Onshore geology	Geological field survey data	Raster	BGS	1:10 000	Local
	DigMap GB	Vector (line & polygon)	BGS	1:250 000	Regional and Local
Offshore geology	Boomer (seismic profile)	2D, Analogue	BGS	0.25 - 1.0 m (v)	Regional and Local
	Sparker (seismic profile)	2D, Analogue	BGS	5 - 10 m (v)	Regional and Local

Table 2: Data sources used in this study

ESRI ArcGIS 8.3 was used for easy visualisation and rapid comparison of disparate datasets, their interrogation, and the efficient capture of new data. Crestlines of streamlined landforms identified on the Thematic Mapper satellite imagery and the monochrome orthophotographs were digitised on-screen and checked against Ordnance Survey (OS) Profile topographic data for positional accuracy. End point co-ordinates for each lineament were generated automatically in the GIS and used to generate rose diagrams of feature orientation following the application devised by Baas (2000).

Field survey checked interpretations made from remotely-sensed data sources, as well as gathering new geological and geomorphological data. A 'feature-mapping' approach was adopted for mapping glacial landforms, and natural sections were examined to provide 3D insights into landform-sediment assemblages. Establishing the lithology and structure of the underlying bedrock was particularly important in understanding their influence on the landscape as a whole.

Existing linework recorded by Primary Survey geologists and held as georeferenced raster images in the project GIS was consulted during the mapping, and regional perspectives on the overall stratigraphy and geomorphology of the area were gained from published memoirs, books and journal articles. Remotely-sensed imagery (7-band Thematic Mapper) was incorporated into the project GIS for identification of large-scale features.

4.1 REGIONAL-SCALE LINEATIONS

The terrestrial lineaments shown in Figure 5 are widely but unevenly distributed across the study area, and are by no means ubiquitous. Indeed, many areas show a complete absence of lineations. The features mapped in the northwest of the area show a pronounced but transitional change in orientation from southeast to northeast where glens of the Grampian Highlands meet the larger vale of Strathmore. Within Strathmore the trend of bedforms is predominantly northeast, although some minor variations can also be seen. At the eastern end of Strathmore many of the crestlines display an increasingly north or northeastward alignment (Figure 5). South of the Sidlaw Hills, however, the pattern is markedly different. Here the majority of features trend south of east, increasingly so across the hills of Fife in the south of the study area (Figure 5). Some northeast trending landforms are seen on the low ground bordering the Firth of Tay, but these are limited in number and are sparsely distributed. Whilst few of the landforms south of the Sidlaw Hills exhibit high elongation (length : width) ratios (ER), many of the bedforms in Strathmore are kilometres long but only 100 - 200 m wide.

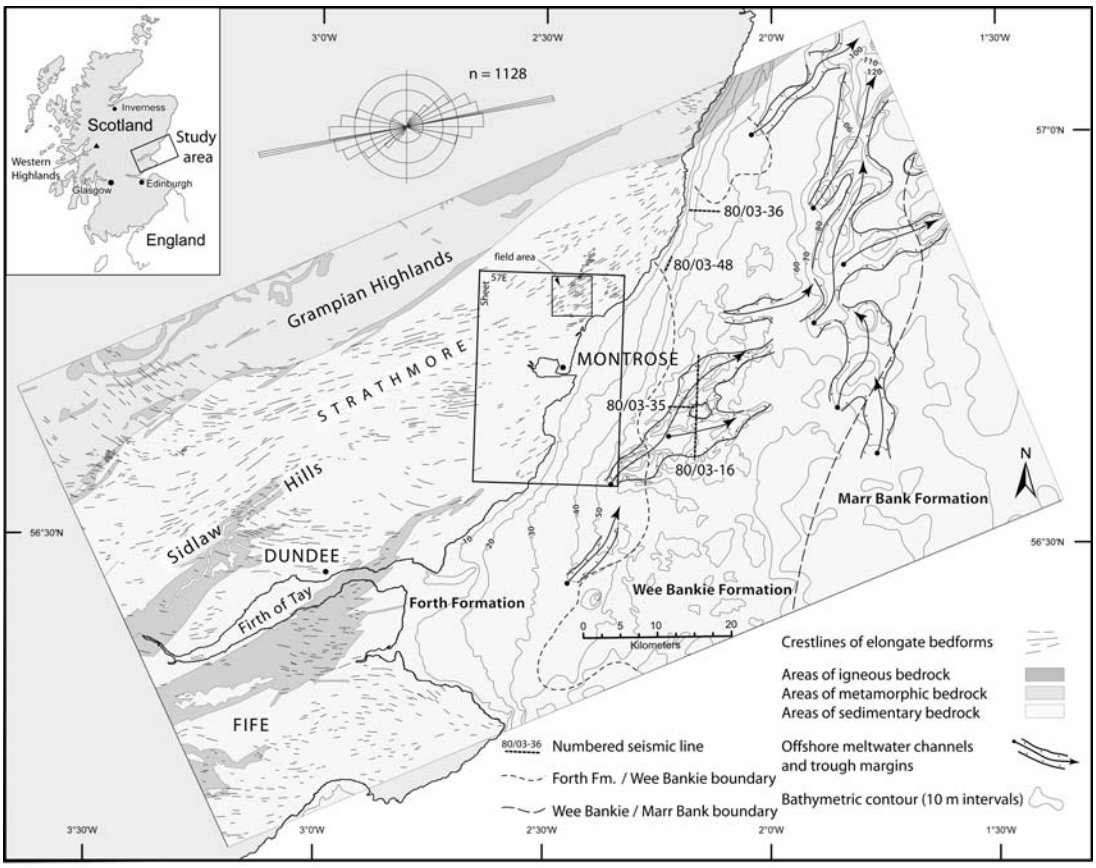

Figure 5: Regional overview showing onshore glacial lineations and major offshore features.

4.2 LOCAL-SCALE FEATURES

4.2.1 Sub-glacially streamlined landforms

The bedforms on NO76NW are extremely tightly concentrated (Figure 6) and show almost exclusively northeastward orientations, with only a small number of the total deviating from the general trend. In the north of the area suites of sub-parallel bedrock lineations commonly less than 100 m apart can be seen. In this area the lineaments appear to be upstanding ridges produced by erosion of surrounding material, rather than constructional (depositional) forms. Many of these features measure several hundred metres in length, but only a few tens of metres in width and a maximum relief of 5 - 10 m. Their alignment is close to, but not entirely concordant with, the strike direction of the bedrock. Significantly, less closely spaced elongate ridges of similar trend were mapped on the hillside below these features, where bedrock was hidden below up to 2 m cover of Superficial deposits (mainly till).

Other hills in the field area also displayed streamlined linear landforms, though none with a spacing density comparable to those described above. In the central part of the area the underlying conglomerate bedrock is intensely weathered and disaggregates easily, giving the appearance of poorly-consolidated sand and gravel. Its true nature is proved, however, by surviving blocks of its lithified sandy matrix, which although lacking cohesion confirms that the material is not a Superficial deposit of recent origin. Such material, however, commonly forms ridges 5 - 10 m high and several hundred metres long. In the south of the field area topographic relief is at its lowest, and yet streamlined landforms with a consistent northeast trend are as abundant as they are elsewhere in the area. The alignment of these features is commonly discordant with local bedrock strike, and although poorly exposed, the landforms appear to be composed of moulded weathered bedrock overlain by 1 - 2 m till. Where seen, contacts between bedrock and subglacial units were gradational rather than erosional, and many of the cobbles in the till have clearly been derived directly from the bedrock.

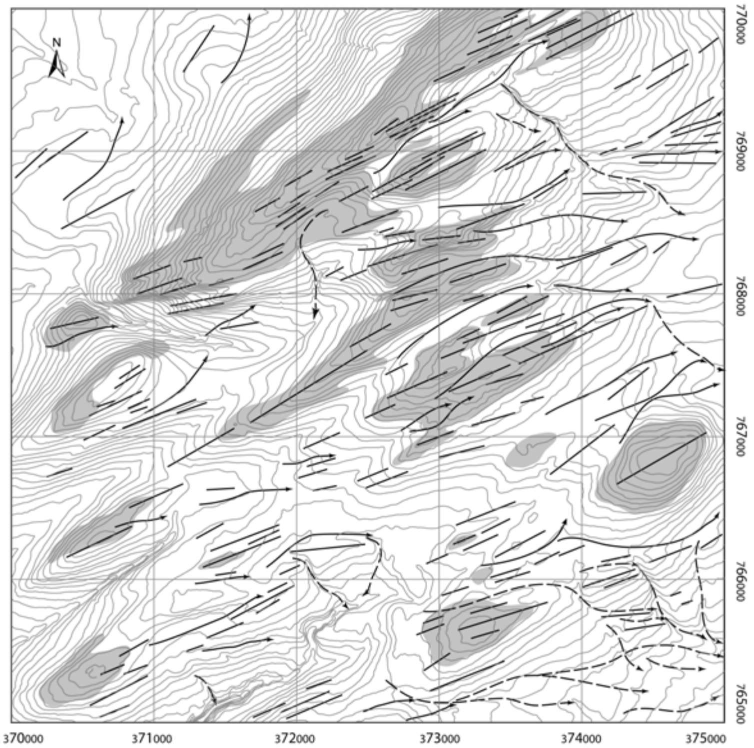

Figure 6: Lineations (straight lines) and meltwater channels (arrows) in the NO 76 NW field area. Solid arrows are subglacial, dashed arrows indicate subaerial (deglacial) drainage. Shading shows areas of bedrock at or near surface.

4.2.2 Meltwater channels

An assemblage of channels can be seen between many of the low hills in the field area (Figure 6), often imparting on the latter a drumlinised or fluted appearance. On the up-ice, or stoss, side of many of the hills, elongate scours form broad troughs that can be followed uninterrupted over contemporary watersheds. Continuing on the lee side of these hills channels are initiated and can be traced over hundreds, and sometimes thousands, of metres. Both Wideopen Burn and Garvock Burn originate in deeply (10-15 m) incised gullies interpreted to be glacial meltwater channels. Numerous smaller channels also exist, with variable but generally easterly or northeasterly trends. The deeply incised channels are cut through bedrock (in the case of the Wideopen and Garvock burns this is weathered conglomerate), and apart from minor meanders are relatively straight.

In addition to the above there are also channels that trend downhill, or obliquely across hillsides. One such intriguing example is a channel c. 30 m wide at its base that trends southeastward down the hillside south of Hill of Garvock. The channel is initiated at the crest of a spur and has no modern drainage to account for its form. Glaciolacustrine sediments in the hollow to the north suggest that the hollow may have hosted a deglacial ice-marginal lake, and so the channel may perhaps have been an overflow channel formed by sub-glacial drainage of the lake during Late Devensian ice sheet recession.

Ice-marginal and pro-glacial channels are best displayed in the south of the field area. Along the flanks of the Den of Morphie are numerous channels that trend at a shallow angle across the hillside before cutting much more steeply downhill towards the aforementioned burn. These channels are initially shallow but become deeper and more steep-sided along their length. Many are flat-bottomed and host ‘misfit’ streams. East of these and beyond the moraine limit around Mill of Criggie, one major proglacial channel drains eastward from NO728 652 towards St. Cyrus, ultimately turning southeastward around NO740 652. The channel exceeds 1.4 km in total length.

5 Synthesis with previous work

5.1 ONSHORE

The landscape of eastern Scotland has been the subject of extensive research (Jamieson, 1906; Linton 1959, 1962; Sissons 1963; Merritt *et al*. 2003). The four stage model of glaciation proposed by Jamieson (1906), based on stratigraphic sequences observed in the region, postulated initially south-eastward flow of ice from the Moray Firth, deflected that way by Scandinavian ice in the North Sea, followed by a subsequent expansion of Highland ice. This was in turn succeeded by a renewed dominance of the Moray Firth and Strathmore ‘ice streams’, the latter flowing north-east on land and deflected north and north-westward by Scandinavian ice in the North Sea. The final stage was the Aberdeen Readvance during which an eastward-flowing glacier reached the North Sea through Glen Dee. Bremner (1943) argued for three stages of glaciation, the first flowing south-east, the second flowing north-east and north, and the final stage being a restricted expansion of ice that included the Aberdeen and the later Dinnet Readvances.

Over a decade later Synge (1956) suggested that the earliest glaciation was characterised in Strathmore by south-east–flowing ice, deflected by Scandinavian ice in the North Sea. In the second glaciation ice flow had assumed a north-east flow on land and a more northerly trend immediately offshore. Synge advocated the existence of large areas of ice free ground in north-east Scotland and along the north-west margin of Strathmore. Synthesising earlier work in the context of new field evidence Armstrong *et al*., (1985) presented a regional perspective on the glacial history of the area around Perth and Dundee. They noted the importance of 'more than one glaciation' in the shaping of the 'ice-moulded features of the landscape', and suggested that changes in flow direction across the area could be explained by an increase in topographic control that occurred due to downwasting of the ice sheet. They postulate that this change in direction of ice flow occurred prior to the Late Devensian (> 28 ka BP). Most recently Merritt *et al*. (2003) concluded that during a pre-Late Devensian glacial period ice streams existed in the Moray Firth and Strathmore, the latter flowing north-east toward the North Sea. A climatic hiatus from 22-18 ka BP gave rise to a cold, dry interstadial with less vigorous ice stream activity in the Moray Firth. The Strathmore ice stream subsequently advanced into the North Sea where it was deflected northward by the presence of Scandinavian ice.

The regional-scale landforms interpreted from Landsat imagery and aerial photographs (Figure 5) certainly lend considerable weight to the patterns of iceflow postulated previously. These landforms can be attributed to glacial processes, and not simply to the structure of underlying bedrock, on the following basis:

- The lineaments cross-cut lithological and structural bedrock boundaries (Figure 5).
- Streamlined landforms are variably present on all rock types, whether igneous (generally resistant), metasedimentary (intermediate strength), or sedimentary (generally weak). There is equally little relationship between the underlying rock type and areas where streamlining is absent (Figure 5).
- Many of these linear features are composed of weathered bedrock that has little coherence, but rather has been moulded into ridges often incorporating glacigenic sediment.
- Ice-moulding of soft or weathered bedrock has been identified elsewhere in Scotland, and structural control on lineament orientations has also been dismissed (Linton 1959, 1962; Sissons 1963; Hall and Sugden 1987).

Thus the crestlines mapped in the study area are interpreted as streamlined subglacial bedforms, which are generally accepted to show long-axis alignments that reflect the direction of former iceflow (Boulton 1976; Morris and Morland 1976; Clark 1994; Mitchell 1994). In addition, their morphometry may be used as a proxy for the relative velocity of the ice under which they formed (Hart 1999; Stokes and Clark 1999, 2002). Since the direction of icesheet flow is essentially governed by ice surface slope (Glasser, 1997), establishing palaeoflow direction is useful in testing and refining ice sheet surface models such as those of Boulton *et al*., (1977, 1985, 1991) and Denton and Hughes (1981). The crestlines in the region show a range of alignments from south-east to north-east, which together form a coherent 'flowset' (*sensu* Clark 1997). Flowsets are characterized by lineaments that are sub-parallel, and an overall topology and extent that is 'glaciologically plausible'. The landsystem in our study area represents a single, generally northeast-directed, flowset within which a number of landforms cross-cut the dominant trend. Some of these cross-cutting landforms are the most highly-attenuated bedforms in the study area, with ER's that greatly exceed the 10:1 ratio suggested by Stokes and Clark (1999) as characteristic of high velocity flow. Flow sets that display cross-cutting alignments or superimposed forms may represent ice-divide migration, lobe retreat, or subglacial streamlining during different glaciations (Rose and Letzer 1977; Clark 1997; Salt and Evans 2004). Given the occurrence of cross-cutting features only in the lowest areas, it seems most likely that these variations in former iceflow reflect the increasing influence of topographic control on a single ice stream as it thinned during deglaciation. This late-stage, north-east-flowing ice partially eroded or remoulded the majority of southeast-aligned bedforms on the very lowest ground, but not elsewhere.

5.2 OFFSHORE

The diamicton of the Wee Bankie Formation is interpreted as a basal till. Evidence for a subglacial origin includes the high cohesive strength of the sediments, the elongate ridge form of the deposit, and clast analysis showing that pebble shape plotted in Boulton's (1978) basal debris field. Morphological evidence for subglacial activity, such as the channelised physiography and possible linear bedform/striae, is described in 5.2.1 and 5.2.2

The offshore limit of the Wee Bankie Formation (Figure 5) is commonly referred to as the Wee Bankie morainal limit, and has been regarded as marking a possible maximum extent to the last British Ice Sheet (e.g. Thomson and Eden, 1977; Cameron *et al*., 1987). Whilst there is no doubt that this morainic limit marks a major standpoint of the last British Ice Sheet, there is increasing evidence to suggest that its maximum limit extended much further offshore (e.g. Sejrup *et al*., 2000; Boulton *et al*., 2002; Clark *et al*., 2004). The Marr Bank Formation, which lies to the east of the Wee Bankie Formation, and generally regarded as a laterally equivalent glacimarine deposit (Stoker *et al*., 1985; BGS 1985 Marr Bank Quaternary Geology sheet), displays a mounded surface morphology that may be indicative of glacial over-riding by Late Devensian ice. Whilst this requires further investigation, it may suggest that the Wee Bankie morainal limit represents a major stabilisation of the ice sheet following collapse and rapid disintegration of the ice mass, when confluence with the Scandinavian Ice Sheet was broken (Boulton *et al*., 2002). This fits well with evidence for possible Late Devensian megascale glacial lineations imaged on 3D seismic east of this limit, and the probability that major incisions cutting the Marr Bank Formation represent tunnel valleys (see below).

As the ice pulled back landward from the morainal limit, the area may have been flooded resulting in a glacimarine setting and the deposition of the St. Abbs Formation pebbly muds. The climate signal preserved in the overlying Largo Bay Member indicates an interval of relative warming followed by deterioration, the latter consistent with the Loch Lomond Stadial. As the ice sheet continued to decay, the major drainage routes of the Forth and Tay valleys probably transported and deposited vast amounts of material into the deglaciated areas, including the nearshore and coastal zone. The St. Andrew's Bay Member preserves a record of fluvial and / or shallow-marine deltaic / outwash fan-type of sedimentation. Evidence of erosion of the top of the St. Andrew's Bay Member may essentially mark the end of any significant sedimentation in this area, and was probably associated with the main Holocene transgression, at about 7000 years BP (cf. Gatliff *et al*., 1994). Since that time, most of the sea bed has probably been starved of terrigenous sediment input, with most offshore activity linked to current and tidal reworking of the Quaternary succession forming the sea-bed sediment layer.

Onshore ice-flow indicators in this region are well expressed, and in order to ascertain whether these features extend beyond the present coastline, the offshore geophysical dataset was examined. Particular emphasis was placed on the identification of possible indicators of ice-stream activity offshore, with a focus on the area to the east and northeast of Montrose. Inspection of sparker, boomer and sidescan-sonar data revealed two possible geomorphological indicators of offshore ice-stream activity: i) tunnel valleys; and, ii) glacial lineations. Whilst the evidence for the tunnel valleys is strong, the status of the lineations remains ambiguous.

5.2.1 Tunnel Valleys

The existence of extensive networks of tunnel valleys in the North Sea has been documented and discussed for over 30 years (Praeg, 2003 and references therein), including those features in the Tay–Forth region (Thomson and Eden, 1977). However, it has not been until the advent of 3D seismic imaging techniques together with the application of a geomorphological approach to investigating the marine landscape that the true geometry and connectivity of these systems is beginning to get established. Consequently, these new approaches to interpreting the offshore

Quaternary succession are giving added value to the BGS legacy dataset.

The channelised physiography illustrated in Figure 5 has long been inferred to be a tunnel valley system cut by subglacial meltwater. However, the variable trend of the features was not easily reconciled with the ‘blanket’ ice-sheet reconstruction. It is now becoming increasingly apparent that certain parts of the British Ice Sheet were more active than others, due to focused ice streams. Moreover, the offshore extension of these ice streams was not necessarily orthogonal to the coastline. This is clearly apparent when viewed against the onshore data for glacial flow directions, which reveal a divergent pattern with flow paths to the northeast and the southeast (Figure 5). By invoking a northeastward moving ice stream in the area offshore Montrose, such a model may help explain the trend of the valleys in that area, and also may have implications for the nature of the Wee Bankie morainal limit, i.e. a shear moraine limit rather than an end-moraine-type limit.

Two seismic profiles are shown in Figure 7 to illustrate a tunnel valley system east of Montrose. Profile 80/03-35 (Figure 7a) is an east–west profile, and the sparker and boomer records across parts of this system are shown (the boomer profile is higher frequency, thus higher resolution than the sparker, but cannot penetrate as deep into the section). Profile 80/03-16 is a north–south sparker profile that shows two apparently ‘separate’ valleys separated by an inter-valley high (Figure 7b). The key features to note from Figure 5 and these data are:

- The anastomosing pattern of the valley systems.
- The variable base level within the tunnel valley system. Thus, the longitudinal profile of these valleys is often scalloped in character.
- The occurrence of ‘shallower’ and ‘deeper’ troughs within the same system. 3D seismic imaging and modelling indicates that this is akin to hanging valleys feeding deeper valleys, and as such indicates connectivity within the system. The shallow troughs on the profiles in Figure 7 connect to the deeper troughs.

Collectively, their anastomosing pattern, scalloped base level and connectivity are strong indicators that the valleys were formed by water under high pressure, such as is associated with ice sheets. Pressurised-flow models — as analogues for ice cover — have successfully modelled the creation of such networks (Catania and Paola, 2001).

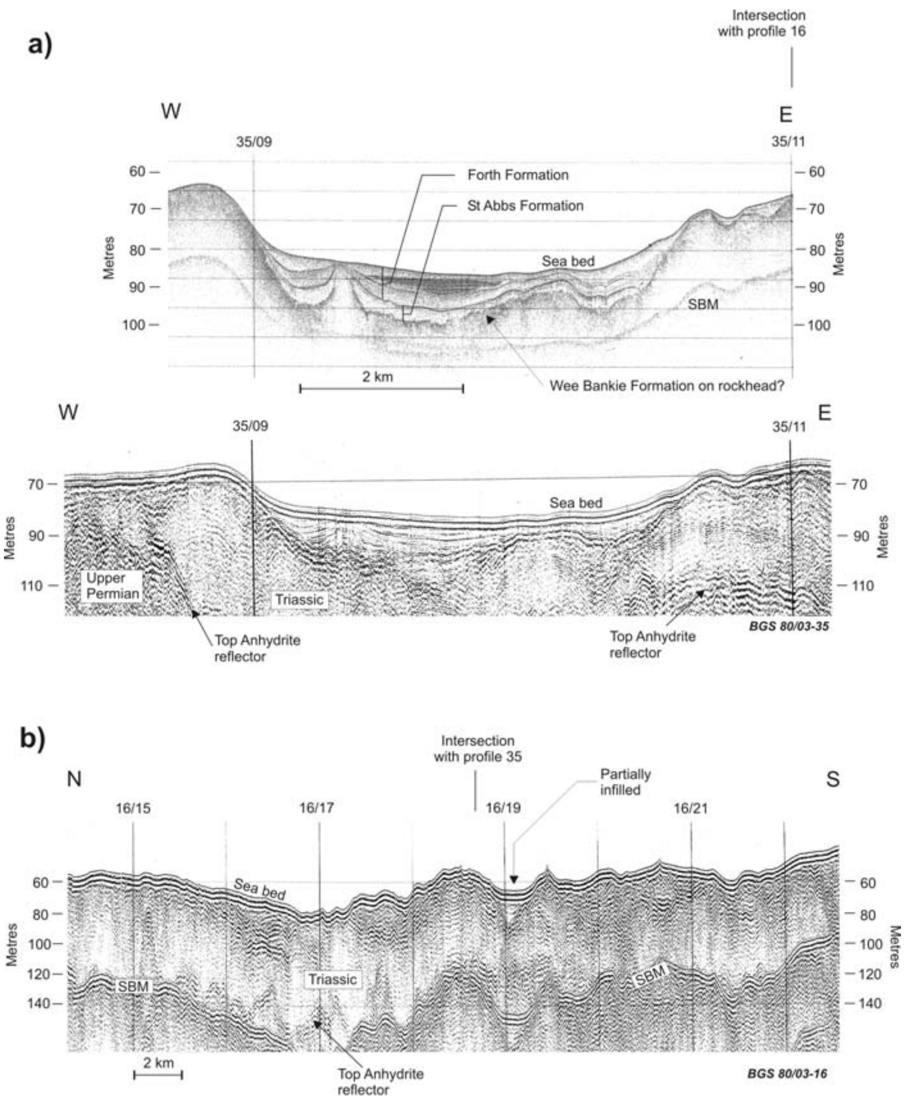

Figure 7: BGS Profiles across offshore tunnel valley system. a) Boomer (upper) and sparker profiles 80/03-35 showing partial infill of valley floor; b) sparker profile 80/03-16 showing more rugged valley floor and less sediment cover. Both sets of profiles show relation of valley system to underlying geology and variable base level of valley floor. The shallower troughs connect the deeper troughs. Abbreviation: SBM, sea-bed multiple reflection. Depths below sea bed based on 1.5 m/s two-way travel time. Profiles located in Figure 5.

5.2.2 Glacial lineations?

Evidence for glacial lineations has recently been presented from 3D data in the North Sea (Clark *et al*., 2004), and from sidescan-sonar data in The Minch (Stoker and Bradwell, 2005). Thus, sidescan-sonar records and boomer profiles were examined offshore to the northeast of Montrose (Figure 8), adjacent to where strong ice flow has been recognised onshore (Figure 5).

Profile 80/03-48 shows the exposed, highly irregular, surface of the Wee Bankie Formation (or rockhead) that becomes buried to the southwest beneath the distal edge of the prograding sediment wedge of the St. Andrew's Bay Member (Figure 8a). The tonal contrast in the backscatter – which is a reflection of surface roughness and sediment texture – of this transition is well imaged; the more compact, highly reflective surface of the till / rockhead is marked by the dark tone. The sidescan-sonar record also shows a hint of lineation associated with the exposed surface of the Wee Bankie Formation (or rockhead), which together with the irregular sea bed may be indicative of some subglacial moulding of till or grooving / fluting of the bedrock.

Profile 80/03-36 shows a series of platforms, interpreted by Stoker and Graham (1985) as a series of submerged rock platforms, overlain by a veneer of Wee Bankie Formation till. The top of the till is undulatory. On the corresponding sidescan-sonar record, there is a distinct linear pattern marked by parallel dark / pale backscatter tones. This pattern may be due to the ridged surface of the seabed, with the pale areas indicating sand between the darker ridges. This bears some similarity with streamlined subglacial bedforms identified on sidescan-sonar profiles in The Minch (Stoker and Bradwell, 2005).

The trend of the lineations is northnortheasterly, which is consistent with the onshore flow direction (Figure 5). The possibility that glacial lineations are preserved in this area has not been previously reported. Although sand waves / ripples have also been reported from this area (BGS Tay – Forth Sea-bed Sediment sheet), there is no doubt that these lineations are intimately related with the irregular surface of the Wee Bankie Formation till and / or rockhead. Bearing in mind the evolving model of ice stream activity onshore, there is clearly a need for further work in the offshore region to better link the Quaternary history across the present-day coastline.

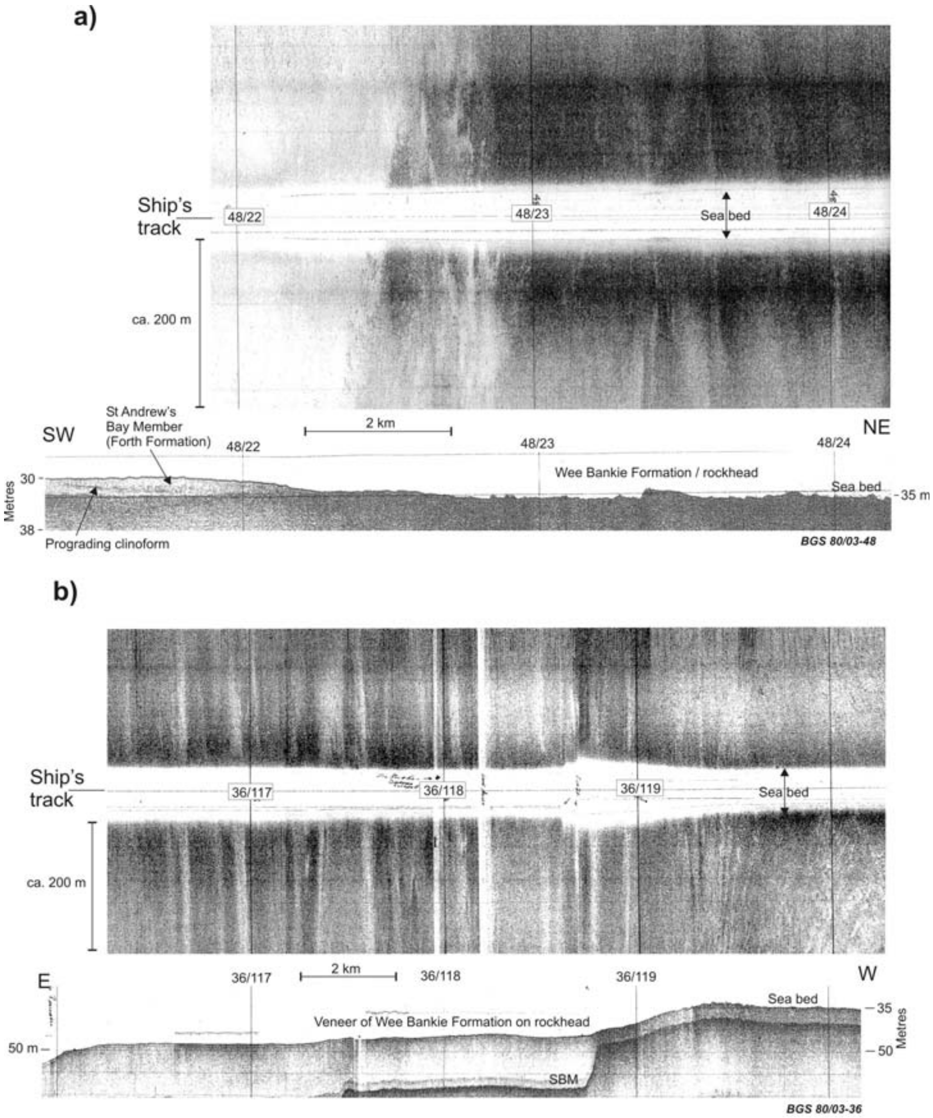

Figure 8: BGS boomer profiles and sidescan-sonar records showing linear features on sea bed. a) Profile 80/03-48 showing irregular top of Wee Bankie Formation (or rockhead) at sea bed and possible associated lineations, which become buried beneath distal edge of prograding sediment sequence of the St. Andrew's Bay Member; b) Profile 80/03-36 showing undulatory veneer of Wee Bankie Formation resting on submerged rock platforms, and a marked lineation pattern possibly related to the irregular top of the till. Abbreviation: SBM, sea-bed multiple reflection. Depths below sea bed based on 1.5 m/s two way travel time. Profiles located on Figure 5.

5.3 RECONSTRUCTION OF EVENTS

The relative timing of ice movements in this part of eastern Scotland can be approximated from a combination of earlier work and the new field evidence. Southward-flowing ice from the Grampian Highlands converged with eastward-flowing ice (sourced in the main ice sheet accumulation centre of the Western Highlands) and consequently engendered a fast-flowing ice stream that flowed south-east across the Sidlaw Hills and towards Fife. This phase may have occurred at or around the Last Glacial Maximum (LGM). Subsequent thinning of the ice sheet, perhaps as a result of partial precipitation-starvation in the Grampian Highlands, led to increasing topographic control and greater dominance of the western ice source. The slight change in flow direction reflected in the alignment of highly-attenuated landforms indicates that the ice stream remained active during deglaciation, even after it had become confined by the 350 - 450 m high Sidlaw Hills. It has been alluded to elsewhere that ice streams may have in fact been instrumental in propagating deglaciation of northern hemisphere ice sheets through the effects of enhanced drawdown (Stokes and Clark, 2003). Whatever the reality, the ice sheet recession that followed must have vacated the coastal area prior to the formation of shorelines at > 20 m O.D. on the cliffs south of Montrose. These shoreline fragments, described by Cullingford and Smith (1980), are assigned to the Main Perth Shoreline by Armstrong *et al*. (1985) who also suggest that the coast may have been ice-free as early as 16 ka BP.

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APPENDIX

PHOTOGRAPHS

The following photographs were taken and are now held in Imagebase:

Registered number	Subject	NGR
P581300	View from Hospitalshields farm, near Laurencekirk, Strathmore	NO72355 67580
P581301	Meltwater channel, Hill of Garvock, near Laurencekirk, Strathmore	NO72183 67810
P581302	Section NRG 178, conglomerate and sandstone overlain by till, Burn of Balmakelly near Laurencekirk, Strathmore	NO70019 67990
P581303	Section NRG 178, conglomerate and sandstone overlain by till, Burn of Balmakelly near Laurencekirk, Strathmore	NO70019 67990
P581304	Section NRG 178, conglomerate and sandstone overlain by till, Burn of Balmakelly near Laurencekirk, Strathmore	NO70019 67990
P581305	Section NRG 178, conglomerate and sandstone overlain by till, Burn of Balmakelly near Laurencekirk, Strathmore	NO70019 67990
P581306	Section NRG 178, conglomerate and sandstone overlain by till, Burn of Balmakelly near Laurencekirk, Strathmore	NO70019 67990
P581307	Escarpment of NW dipping sandstones and interbedded lava, Hill of Garvock near Laurencekirk, Strathmore	NO70434 67915
P581308	Section in alluvial terrace, Burn of Balmakelly near Laurencekirk, Strathmore	NO71173 67713
P581309	Section in alluvial terrace, Burn of Balmakelly near Laurencekirk, Strathmore	NO71173 67714
P581310	> 3 m clast-supported cobble gravel - probably weathered conglomerate, Burn of Balmakelly near Laurencekirk, Strathmore	NO71173 67715
P581311	Rotted conglomerate, Wideopen Burn near Laurencekirk, Strathmore	NO72061 67718
P581312	Interbedded conglomerate and med-grained sandstone, Wideopen Burn near Laurencekirk, Strathmore	NO72089 68230
P581313	Linear ridge - possibly an esker, Hill of Garvock near Laurencekirk, Strathmore	NO72475 68505
P581314	3 m clast-supported cobble gravel, probably weathered conglomerate. Lithologies include quartzite, intermediate & basic igneous rocks, lava, meta-sandstone, and many more. Hill of Garvock near Laurencekirk, Strathmore	NO72645 67997
P581315	3 m clast-supported cobble gravel, probably weathered conglomerate. Lithologies include quartzite, intermediate & basic igneous rocks, lava, meta-sandstone, and many more. Hill of Garvock near Laurencekirk, Strathmore	NO72645 67997
P581316	Meltwater channel, Hill of Garvock near Laurencekirk, Strathmore.	NO72303 67887
P581317	Meltwater channel, bedrock ridge, and pipeline-disturbed fields, Hill of Garvock near Laurencekirk, Strathmore	NO73111 68333
P581318	Bedded sand, probable weathered bedrock, Hill of Garvock near Laurencekirk, Strathmore	NO73194 68335
P581319	Bedded sand, probable weathered bedrock, Hill of Garvock near Laurencekirk, Strathmore	NO73194 68335
P581320	Bedded sand, probable weathered bedrock, Hill of Garvock near Laurencekirk, Strathmore	NO73194 68335
P581321	Meltwater channel cut through conglomerate, Hill of Garvock near Laurencekirk, Strathmore.	NO73470 69461
P581322	Rotting conglomerate and resultant cobble gravel, Hill of Garvock near Laurencekirk, Strathmore	NO73487 69465
P581323	Meltwater channel, Hill of Garvock near Laurencekirk, Strathmore	NO73500 69463
P581325	Red till exposed in small failure scar, Garvock Burn, East Bradieston, near Laurencekirk, Strathmore	NO73832 69188
P581326	Rainbow over farmland near St. Cyrus, Strathmore	NO74398 68468
P581327	Rainbow over farmland near St. Cyrus, Strathmore	NO74398 68468
P581328	View over farmland from West Bradieston, near Laurencekirk, Strathmore	NO74398 68468
P581329	Section NRG 179, soil on thin head on till on weathered sandstone and conglomerate, Hill of Garvock near Laurencekirk, Strathmore	NO72488 69722
P581330	Section NRG 179, soil on thin head on till on weathered sandstone and conglomerate, Hill of Garvock near Laurencekirk, Strathmore	NO72488 69722
P581331	Section NRG 179, thin soil on thin till on bedrock, Hill of Garvock near Laurencekirk, Strathmore	NO72892 69726
P581332	Rib of andesite (?) protruding above surrounding ground surface, Hill of Garvock near Laurencekirk, Strathmore	NO72314 68940
P581333	Siltstone overlying lava, Woodstone Hill, near Laurencekirk, Strathmore	NO74378 66518
P581334	Section NRG 180, lava and sandstone, Kirkton Hill near Laurencekirk, Strathmore	NO70462 67069
P581335	Section NRG 180, lava and sandstone, Kirkton Hill near Laurencekirk, Strathmore	NO70462 67069
P581336	Section NRG 180, lava and sandstone, Kirkton Hill near Laurencekirk, Strathmore	NO70462 67069
P581337	Section NRG 180, lava and sandstone, Kirkton Hill near Laurencekirk, Strathmore	NO70462 67069
P581338	Section NRG 181, interbedded sandstone and conglomerate, Grangehall Farm near Laurencekirk, Strathmore.	NO70932 66146
P581339	Section NRG181, Grangehall Farm. Imbricated clasts in conglomerate. Near Laurencekirk, Strathmore	NO70932 66146
P581340	Section NRG181, Grangehall Farm. Fracture or micro-fault in conglomerate. Near Laurencekirk, Strathmore	NO70932 66146
P581341	Section NRG181, Grangehall Farm. Fracture or micro-fault in conglomerate. Near Laurencekirk, Strathmore	NO70932 66146
P581342	Section NRG181, Grangehall Farm. Fracture or micro-fault in conglomerate. Near Laurencekirk, Strathmore	NO70932 66146
P581343	2 - 3 m sandy red till with sand lenses overlying 1 m grey conglomerate, North Esk near Marykirk, Strathmore	NO70255 63904
P581344	Interbedded grey and red sandstone, Den of Morphie, near Marykirk, Strathmore	NO70638 64061
P581345	Interbedded grey and red sandstone showing cross-bedding, Den of Morphie near Marykirk, Strathmore	NO70638 64061
P581346	Section NRG 182, interbedded siltstone and sandstone, Den of Morphie near St. Cyrus, Strathmore	NO72085 65552

SAMPLES

The following samples were collected:

Samples

	Sample identifier	NGR	Location	Geological description
Biostratigraphy	NKG018 (unregistered)	NO71649 65203	Den of Morphie	Sandstone
	NKG019 (unregistered)	NO71649 65203	Den of Morphie	Sandstone
	NKG020 (unregistered)	NO71649 65203	Den of Morphie	Siltstone with plants
	NKG021 (unregistered)	NO70013 68001	Burn of Balmakelly	Siltstone (reddened)
	NKG022 (unregistered)	NO72085 65553	Den of Morphie	Siltstone
	NKG023 (unregistered)	NO74378 66520	Woodstone Hill	Siltstone (reddened)
Mineralogy and Petrology	N5330	NO71649 65203	Den of Morphie	Sandstone
	N5331	NO71649 65203	Den of Morphie	Sandstone
	N5332	NO74381 66500	Woodstone Hill	Lava
	N5333	NO74296 63841	St. Cyrus	Lava
	N5334	NO72730 66845	Brandshill	Lava
	N5335	NO70698 67946	Craig of Garvock	Lava
	N5336	NO72090 68231	Craig of Garvock	Sandstone
	N5337	NO72085 65553	Den of Morphie	Sandstone
	N5338	NO73316 65764	North Snadon	Lava
	N5339	NO72897 69715	Hill of Garvock	Lava
	N5340	NO72926 65473	South Snadon	Lava
	N5341	NO70937 66136	Grangehall Farm	Sandstone
	N5342	NO74381 66500	Woodstone Hill	Siltstone
	N5343	NO70248 63887	Den of Morphie	Sandstone
	N5344	NO72750 66832	Brandshill	Sandstone
	N5345	NO72926 65473	South Snadon	Lava & siltstone