Ardersier Peninsula and the Ardersier Silts Formation

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The Ardersier Peninsula is formed mainly of rhythmically bedded silts and sands of probable glaciomarine origin (*Ardersier Silts Fm*), locally capped by till, and trimmed on the north and west sides by Late Devensian (late-glacial) and Holocene (postglacial or Flandrian) raised shorelines. The peninsula rises to an altitude of about 40 m OD, but the highest marine features are shingle ridges at 28-31 m OD, below which lie late-glacial shoreline fragments at altitudes of 28.5 m, 26.6 m, 21-21.6 m and 18.5 m OD (Firth, 1984, 1989b) (Fig. 30). The prominent 'Main Postglacial Cliffline' borders raised shingle beach ridges at about 11 m OD (see cover photo). This prominent abandoned cliff line was generally thought to have been created by marine erosion during the Holocene, but it is now considered to have been formed mainly in the cold climate of the Loch Lomond Stadial (Younger Dryas) and that the feature was only trimmed during the mid- Holocene (Sissons, 1981a). The peninsula includes important evidence for a significant glacial readvance within the Inverness Firth, termed the *Ardersier Readvance* by J.S. Smith (1968, 1977) or the *Ardersier Oscillation* by Merritt et al. (1995).

The deposits at Ardersier were first described by Jamieson (1874), who recorded, near Kirkton, a small exposure [NH 793 561] of grey clay containing shells of Arctic molluscs, which was either overlain by, or incorporated within a deposit of gravel and silt. Wallace (1883) reported that specimens examined by Jamieson included *Nuculana pernula*, *Macoma calcarea* and *Tridonta elliptica*. Robertson (in Wallace, 1883) identified *Astarte sulcata* and several species of ostracod and foraminiferid. Although the shells were largely fragmented, Robertson noted that many of the pieces were in a natural position. The original fossil collection has been re-examined using modern terminology by I.P. Wilkinson and D.K. Graham (Merritt et al., 1995). The fauna is of cold water aspect, not necessarily high-Arctic, and not characteristic of ice-proximal conditions. Nevertheless, it can be attributed to a cold interstadial period (J.D. Peacock, personal communication).

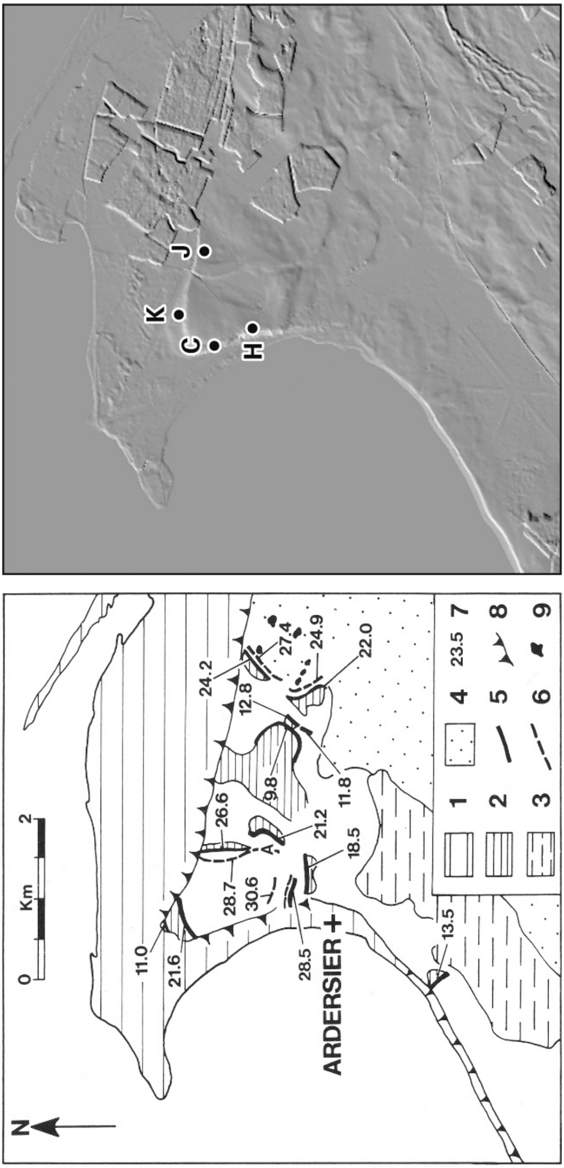

Figure 30. A) Geomorphological map of the Ardersier Peninsula (from Firth, 1990). (1) Holocene coastal flats and dunes, (2) Late-Devensian raised-beach, (3) ice decay hollow, (4) ice-contact topography, (5) shoreline fragment, (6) shingle ridge, (7) altitude of shoreline fragment (m OD), (8) degraded cliff line, (9) kettlehole. B) NEXTMap hill-shaded digital elevation model of the Ardersier Peninsula, (A) Contorted Silts, (H) Hillhead section, (K) Kirkton section, (J) Jamieson's Pit.

The original section [NH 7939 5616], which has become known as **'Jamieson's Pit'**, was re-excavated in September 1991 (Fig. 30 & 14). It revealed 2 m of stiff, poorly stratified clayey diamict (*Baddock Till Mb of the Finglack Till Fm*) resting on a 3.2 m-thick, imbricated stack of subhorizontal thrust bound slices of micaceous sand intercalated with thin seams of sheared silty clay (Fig. 31). This diamict overlay 3.4 m of sand with steeply dipping thrusts lined by sheared silty clay and folded seams of silty clay (Fig. 32). The sands were variably homogenised, buckled into sinusoidal folds with amplitudes of about 1 m, wavelengths of 2.5 m and axes aligned at N035^{o}. The most prominent thrust dipped at 52^{o} towards N305^{o}. Sub-till tension fractures or hydrofractures filled with thinly laminated silt and clay dipping steeply towards N020-040^{o} penetrated into the sands from the Baddock Till. The whole assemblage of structures are of glacitectonic origin and indicate that the sandy deposits were pushed towards the south-east and then partly overridden by the readvancing glacier that deposited the Baddock Till. No shells were recovered in any of the beds, but olive-grey clay lining thrusts 1.6 m below the Baddock Till had slickensided partings and contained well rounded, polished pebbles. This compares favourably with descriptions of the shell-bearing sediment recorded by Horne (1923), suggesting that it too was also emplaced during thrusting, probably after being ice-rafted from the Inverness Firth.

Another long-abandoned clay pit in the bluff of a Late Devensian raised shoreline at 21.6 m OD, east of Kirkton, was re-opened for the QRA in September 1990 (Fig. 30 & 14). This **'Kirkton Section'** [NH 7849 5647] revealed 1.5 m of thinly interbedded clay, very fine-grained sand and silt occurring as graded couplets and stacked into discrete beds (Fig. 33). This unit overlay 5 m of thinly interbedded and interlaminated clay, silty clay and very fine sand with graded bedding. The base of the excavation revealed over 1.9 m of grey silty clay, mainly massive, but with some graded beds. The 11.4 m-thick succession dipped gently towards N220^{o}, but showed little evidence of glacitectonic disturbance. No faunal remains were recovered from the deposits.

Figure 31. Baddock Till resting on tectonised sand at Jamieson's Pit in 1990. Excavated into the 'Main Postglacial Cliff Line'.

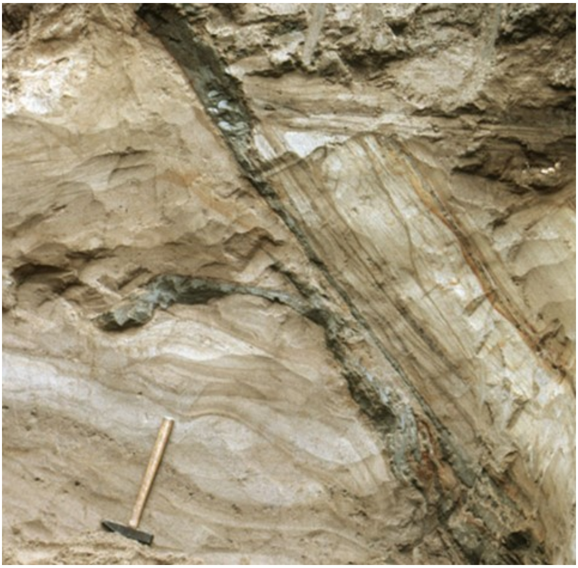

Figure 32. Clay-lined thrusts cutting folded and glacitectonically disrupted silty sand about 1.7 m below the base of the Baddock Till (hammer 37 cm long).

Figure 33. Rhythmically graded bedding in the Kirkton Clay Mb towards the top of the Kirkton Section (hammer 25 cm long).

The silt-clay couplets in the Kirkton Clay are comparable to cyclopels described by Cowan and Powell (1990), stacked into discrete packages 0.3-0.8 m thick. Such bedding typically results from rapid accumulation of silt and clay flocculates in brackish water close to a glacier snout (Mackiewicz et al., 1984). The more massive beds of silty clay also contain wispy laminae of silt. The thick rhythmic bedding probably results from seasonal influxes of meltwater during summer months, whereas the thinner packages of laminated sediment were probably deposited when sea-ice was prominent during the rest of the year. As the sequence recorded at Kirkton is truncated by a raised shoreline, some 20 m or so of the original succession may have been removed by subsequent marine erosion. However, the absence of thrusts and folds indicates that it may not be contiguous with the tectonised deposits occurring at Jamieson's Pit and the Contorted Silts section described below, and is probably younger. It is consequently assigned to a separate allostratigraphical unit, namely the *Kirkton Clay Mb* of the Ardersier Silts Fm (Fletcher et al., 1996).

Firth (1989b) described other sections in the cliff line north of Ardersier village, including at Hillhead [NH 7821 5565], where a thin unit of diamict ('Hillhead Till') rests on a sequence of very compact, silty fine-grained sand dipping at 15° towards N008° (Merritt et al., 1995). Beneath the diamict the tilted sands have been sheared to form a stack of thin, sub-horizontal thrust slices, like at Jamieson's Pit.

Figure 34. Graded bedding and soft-sediment deformation structures at the Contorted Silts section, looking northwards. Thrust faults displace the upper limb of the anticline westwards. Hammer 40 cm long.

Soft-sediment deformation in the form of flame, dish and ball-and-pillow structures, together with convolute bedding, commonly affect graded beds of silt and very fine-grained sand within the Ardersier Silts. A particularly good example of such phenomena, together with post-depositional overfolding and thrusting, is displayed in a cliff section known as the **Contorted Silts of Ardersier** [NH 7803 5598] (Firth, 1989b, 1990b; Gordon and Merritt, 1993). Visible from a small carpark and picnic area [NH 779 557], the section in the 'Main Postglacial Cliffline' reveals 20 cm to 35 cm-thick beds of massive silt interbedded with thinly laminated, very fine-grained sand, laminae of clay and sparse lenses of fine gravel. Well-developed, asymmetrical ripple-drift cross-lamination in the sand indicates south-westward or south-eastward palaeocurrents. The deformed beds exposed in the main section are folded into two asymmetrical synclines separated by an asymmetrical anticline (Fig. 34). The folding has an amplitude of about 3 m and a wavelength of about 6 m. The axis of the anticline plunges 16° towards N150°. The hinge and upper limb of the anticline have been back-thrusted north-westwards along a thrust plane dipping steeply south-eastwards.

Figure 35. Shearing in cross-bedded sand beneath a capping of Baddock Till at the Hillhead Section (spade 0.9 m long).

Shearing within cross stratified sands with low amplitude symmetrical ripples was recorded by Merritt et al (1995) beneath the Baddock Till at the **Hillhead Section** [NH 782 556] (Fig. 35). These shears were interpreted as forming small-scale thrust slices, suggesting ice push from the south-west. Convoluted graded beds of silt and very fine-grained sand are occasionally exposed along the raised cliff line towards Nairn, backing the Carse of Delnies at [NH 8322 5590] and [NH 8286 5570] where shear planes indicate push towards the east (Fletcher et al., 1996). Syn-depositional soft-sediment deformation appears to decrease progressively, both in scale and intensity, eastwards from the Ardersier push moraine suggesting that the deformation resulted from loading induced by ice pushing into water-saturated sediments rather than being triggered by paleoseismic events (cf. Davenport and Ringrose, 1987; Ringrose, 1989).

Interpretation

Jamieson believed that the marine clay he discovered was the remnant of a more extensive deposit that had been destroyed during a later glacier advance. J.S. Smith (1968, 1977) interpreted the deposits, together with complementary features on the north side of the Inverness Firth at Fortrose, as a readvance moraine of the last ice-sheet. Smith suggested that the shelly clay was translocated from the floor of the firth during the *Ardersier Readvance* and deformed with associated deposits to produce the high ground of the peninsula. As supporting evidence for an ice readvance, he adduced a significant drop in the marine limit west of Ardersier.

Synge (1977b) and Synge and Smith (1980) integrated the Ardersier evidence into a regional model of Late Devensian shoreline changes and ice-sheet retreat stages. Aspects of this model were questioned by Firth (1984, 1986, 1989a, 1989b), who concluded that the 'Ardersier Readvance' could not be substantiated and that deformation structures in the Contorted Silts section were probably caused by loading, slumping or minor ice-front movement. The shingle ridges on the peninsula (30.6 m OD) correlate with the highest of ten Late Devensian shorelines identified in the region, which Firth associated with an ice limit at North Kessock, near Inverness (Fig. 16; IL-1). Firth postulated that sea level dropped from at least 37.8 m to about 30 m OD while the ice retreated from Ardersier to Inverness. Although the geomorphological evidence presented by Firth (Fig. 30) could be interpreted to indicate that relative sea level stood no higher than 16 m OD during the Ardersier Oscillation (Merritt et al., 1995), the evidence at **Alturlie Point** suggests that it was higher.

The folds and thrust planes recorded at Jamieson's Pit, together with the presence of diamict at the top of the sequence, have a significant bearing on the question of ice readvance (Merritt *et al.*, 1995). The diamict may be interpreted either as a subaerial (or possibly glaciomarine) mass-flow or subglacial traction till, but in either case requires the close proximity of ice following subglacial shearing of the underlying fine-grained sediments. A readvance of the ice front is clearly indicated, although the shoreline evidence presented by Firth (1989b) appears to preclude an event of the magnitude suggested by both Smith and Synge.

The lateral glacial limit of the Ardersier Oscillation can be followed south-westwards where the ground is highest at the coast and shelves inland towards the Gollanfield Depression, now largely occupied by Inverness Airport. This feature was identified as a push moraine by Merritt et al. (1995) (Fig. 14), an interpretation that has been strengthened by the subsequent discovery of thrust blocks formed of silt and fine-grained sand in a temporary exposure at Balnaglack [NH 745 513] (Fig. 36), now landscaped within the golf course at Castle Stuart.

Figure 36. Ice-thrust Ardersier Silts in a temporary section in a Late Devensian raised cliff line at Balnaglack, looking eastwards.

The characteristics of the Ardersier Silts Formation along its outcrop.

Regional surveying has now established that the Ardersier Silts extend eastwards from Inverness to just beyond Forres (Fig. 37). This included logging all of the exposures in the coastal area, as well as interpretation of hundreds of borehole and site investigation reports. This data has enabled the three dimensional extent of the unit to be modelled throughout most of its outcrop (Arkley et al., 2014; Arkley and Callaghan, 2014). The location of the most significant exposures in the coastal area are shown in Fig. 38 and listed in Table 3. These have enabled significant changes in the character of the unit to be recognised along its outcrop.

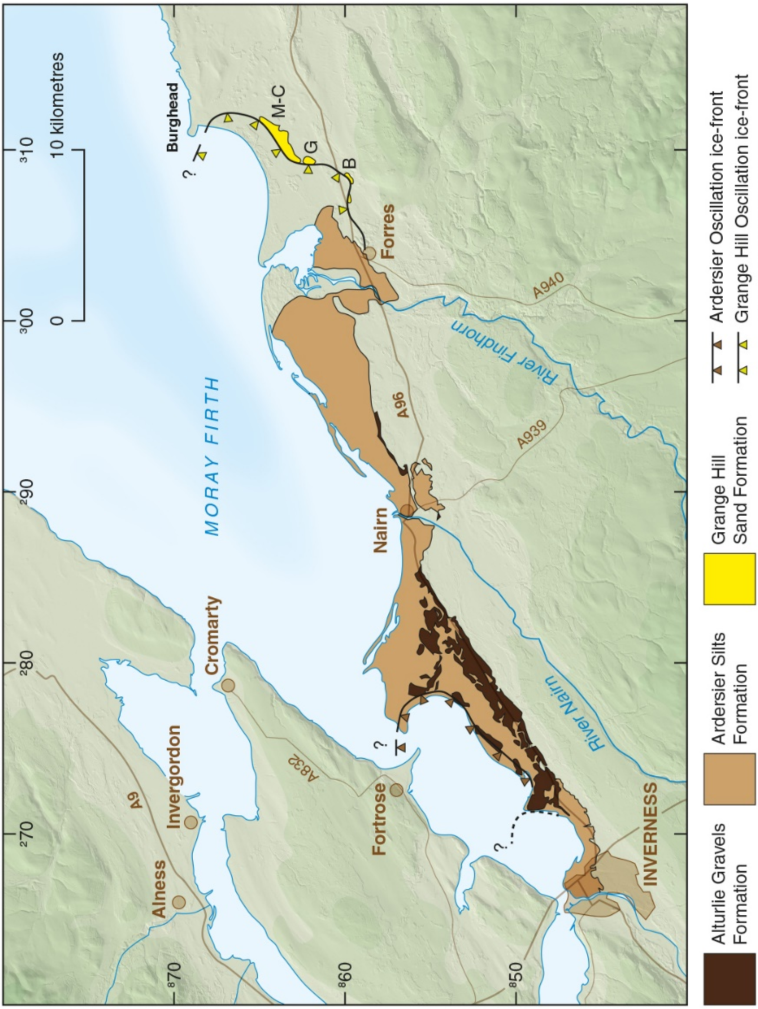

Figure 37. The onshore outcrop of probable glaciomarine successions on the southern side of the Moray Firth between Inverness and Burghead and their relationships to readvance and stillstand positions during late stages of the retreat of the Moray Firth glacier; (B) Burgie Lodge, (G) Grange Hill, (MC) Miltonhill-Coltfield Ridge.

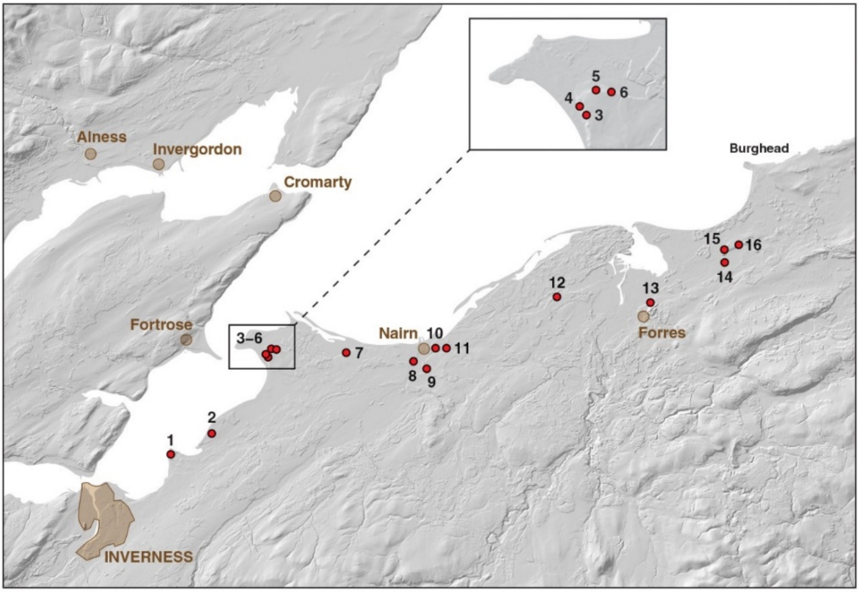

Figure 38. Main logged field localities in the Alturlie Gravels, Ardersier Silts and Grange Hill Sand Formations (see Table AR1 for details).

Table 3. Principal units present at the main field localities (sites in the itinerary are in bold).

No.	Locality	Principal Unit
1	**Alturlie Point**	Alturlie Gravel Fm
2	Balnaglack Pit	Ardersier Silts Fm
3	Hillhead	Ardersier Silts Fm
4	**Contorted Silts SSSI**	Ardersier Silts Fm
5	Kirkton	Ardersier Silts Fm
6	Jamieson's Pit	Ardersier Silts Fm
7	Ardersier Race Track	Ardersier Silts Fm
8	SW of Nairn Hospital	Ardersier Silts Fm
9	House Hill Mains	Ardersier Silts Fm
10	Loch Loy Avenue	Ardersier Silts Fm
11	**Cloddymoss SSSI**	Ardersier Silts Fm
12	Sueno's Stone	Ardersier Silts Fm
13	**Grange Hill**	Grange Hill Sand Fm
14	Milton Hill	Grange Hill Sand Fm
15	Hempriggs	Grange Hill Sand Fm

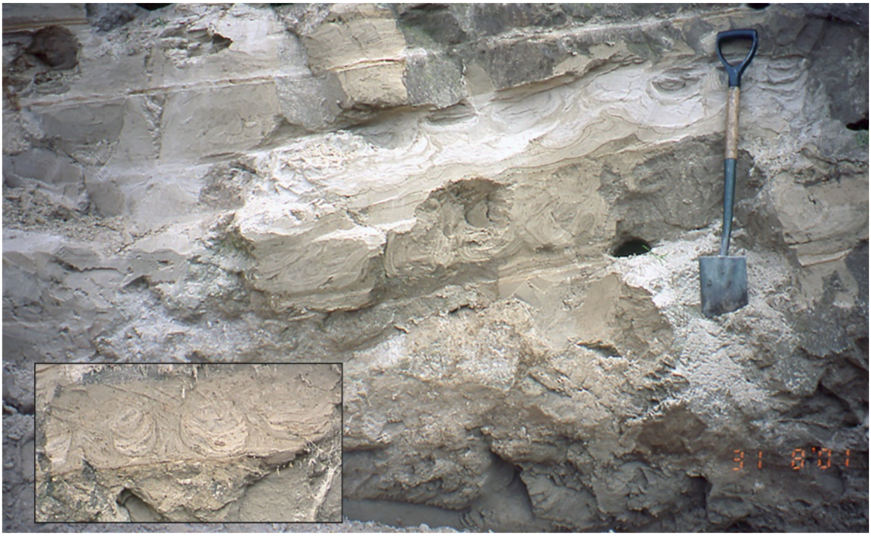

Figure 39. Soft sediment deformation in the Ardersier Silts exposed at the Ardersier Race Tack Site in 2001 (spade 0.9 m long).

The convoluted graded beds of silt and sand exposed along the raised cliff line backing the Carse of Delnies, reported by Fletcher et al. (1996), were better exposed in excavations for a trial bike race track ('Ardersier Race Track' site) at [NH 832 559] in 2001. These sections showed a thickly interbedded sequence of pale olive-grey, finely laminated sandy silt and pale yellow silty sand (Fig. 39). The silt contains a significant proportion of rock flour, similar to that seen at the 'Contorted Silts' site. Many beds show convolute bedding and well developed ball-and-pillow structures. The exposed sequence was greater than 6 m thick and dipped at 10˚ towards the north-east.

A diamict unit, typically up to c. 3 m thick, occurs within the Ardersier Silts between Nairn and Auldearn. It crops out in the Main Postglacial Cliffline between Nairn and Kingsteps Quarry [NH 899 517], was recorded in boreholes sunk for the Auldearn Bypass and was exposed in foundations for buildings on the Balmakeith Industrial Estate [NH 895 856] in 1998 (Fig. 40). In these exposures, the unit comprised up to 1.8 m of firm sandy and silty diamict with a distinctive mottled appearance due to patches of pale yellow silty sand (composed in part of rock flour) within the predominantly reddish brown matrix. It contained isolated rounded clasts, principally of red-brown sandstone. This unit has been named as the *Balmakeith Till Mb* of the Finglack Till Fm, but it may have originated as a subaqueous debris flow rather than as a subglacial till. Isolated silt-lined shear planes dipping towards the north and north-west, are present within the surrounding Ardersier Silts. These shears, which are associated with sparse well rounded, polished pebbles (as they are in Jameson's Pit), are similar to, but much smaller than, those exposed at the latter locality. Nevertheless, the shearing indicates that a minor episode of glaciotectonic movement may have been associated with the emplacement of the diamict.

Figure 40. The Balmakeith 'Till' exposed at the Balmakeith Industrial Estate in 1998 (spade 0 9 m long).

The Ardersier Silts are overlain by the Alturlie Gravels Fm between Alturlie Point and the vicinity of Blackcastle [NH 829 541], 5 km to the west of Nairn (Fig. 37). The Alturlie Gravels are present in scattered exposures to the east of Nairn and were identified in borehole records from the Auldearn Bypass; they thin eastwards and are absent farther east, around Forres (see **Cloddymoss**).

Around Inverness, the Ardersier Silts and the fossiliferous sediments overlying them were first described by Peacock and Wilkinson (1995), from borehole samples collected for the construction of the Kessock Bridge. The borehole records show that they extend across much of the Kessock Narrows and reach to below -60 m OD in boreholes close to the bridge. The Ardersier Silts are not present in any borehole within a second transect between North Kessock [NH 650 480] and South Kessock [NH 655 470], the deepest of which reaches to below -47 m OD (Auton, 2006). This transect is the present western limit of the Ardersier Silts Formation, although it is possible that they are present at greater depths, particularly as seismic surveying evidence suggests that rockhead may occur at depths of between -153 and -162m OD in the Kessock narrows.

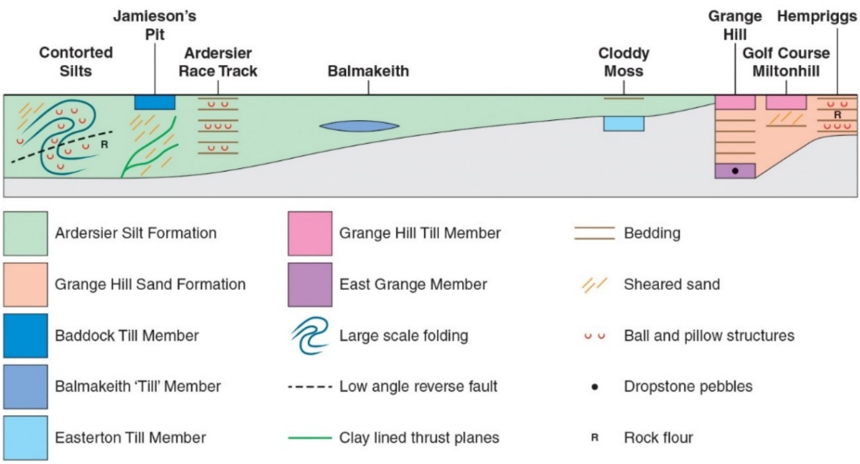

Figure 41. Changes in the character of the Ardersier Silts and the Grange Hill Sand formations along their outcrop between Ardersier and Burghead.

The data presented here suggests that the Ardersier Silts around Ardersier Peninsula are typically greater than 10 m thick, sandy, and contain a significant proportion of rock flour. They are commonly sheared, folded, show pervasive soft sediment deformation and are locally capped by the Alturlie Gravels Fm In contrast, the sediments at **Cloddymoss** and those present in the Forres area are typically only 1.5-2.5 m in thickness and comprise laminated sand, silt and clay. Possibly because they contain little rock flour, these outcrops reveal sparse evidence of soft sediment deformation. They are not glacitectonically disturbed and lie beyond the outcrop of the Alturlie Gravels.

The sequential changes in sedimentary features and deformation structures within the Ardersier Silts eastwards from the Ardersier Peninsula are illustrated in Fig. 41, which shows a decrease in the thickness of the unit and in the intensity of deformation with distance away from the Ardersier Oscillation limit. It is also notable that many of the suite of features recognized within the ice-proximal facies, on Ardersier Peninsula, are similar to those now identified within the Grange Hill Sand Formation, some 33 km farther east (see **Grange Hill**) implying a similar mode of origin for both successions.