Excursion 3 The Upper Jurassic of the Helmsdale area

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Purpose

To illustrate sections across the Helmsdale Fault zone and examine the boulder beds and other Upper Jurassic lithologies deposited in response to fault movement at the western boundary of the Inner Moray Firth Basin. The excursion is divided into the following four itineraries.

Itinerary 3.1 Kintradwell. The Kintradwell Boulder Beds with slump and slide features and an intruded sandstone dyke.

Itinerary 3.2 Lothbeg Point area. The Allt na Cuile Sandstone, and Lothbeg Silt-stone. Sand from a delta transported to deep water.

Itinerary 3.3 Portgower. Boulder beds with giant clasts; the 'fallen stack' locality, and changes in clast types within the boulder beds.

Itinerary 3.4 Helmsdale. The Helmsdale Boulder Beds, rockfall breccias, and Helmsdale Fault outcrop.

General access

Details of access are given with each of the itineraries but the following notes are generally applicable. The itineraries cover most of the major features seen in exposures between Kintradwell and the Ord of Caithness. The whole excursion requires about 2 days and is best carried out in the spring or early summer when vegetation is at a minimum. The shore sections are tide dependent, thus it is best to plan the trip when low tide occurs during midday and visit the localites in an appropriate order. The use of a car or minibus will allow fairly easy access to all localities. If a coach is used the party will have to be dropped at the main road and a little more walking will be needed. The sequences crop out along the rocky foreshore, in river gullies and on raised beaches. Where appropriate, permission should be sought from farmers or landowners to cross agricultural land. Two short itineraries from the first edition of this guide have been omitted due to safety and access problems. Do not attempt to visit exposures in rail cuttings (illegal and dangerous), and take great care crossing the rail line at the designated crossings. Trains are infrequent, but surprisingly silent, and many are not timetabled. The locations of the areas covered by the itineraries are shown on (Figure 3.1) and the main stratigraphic features in (Figure 3.2).

General introduction

The sequences are exposed in a narrow coastal strip up to 1.5 km in width between Kintradwell and the Ord of Caithness. The sediments are downfaulted against Moinian granulites, Helmsdale Granite and Old Red Sandstone to the west, and are bounded by the Moray Firth to the east. There is an overall younging of the sequence from SW to NE, from Kimmeridgian *cymodoce* Zone at Kintradwell to Middle Volgian *albani* Zone near the Ord of Caithness (Lam and Porter, 1977; Riley, 1980).

The late Jurassic of the Inner Moray Firth was characterised by rapid subsidence and the formation of half-grabens (Figure 8 in Geological History section). The sediments exposed in the Helmsdale area were deposited at the western active margin of one of the major half-grabens controlled by downthrow on the Helmsdale Fault. These excursions illustrate the spatial and temporal distribution of lithologies in this fault-bounded basin-margin setting and highlight some of the unusual sedimentary features which developed on the fault-controlled submarine slope.

It is difficult to measure accurately the thickness of the sequence because of discontinuous outcrops, folding, small-scale faulting and disconformities. The Kimmeridgian to Middle Volgian sequences probably total more than 900 m (data in Wignall and Pickering, 1993). In well 11/30–1 of the nearby Beatrice Oilfield the basal Kimmeridgian to late Volgian sequence is approximately 750 m thick and dominantly of shale. The accumulation of these thick sequences illustrates the rapid fault-controlled basin subsidence during the late Jurassic.

From the Lias through to the Oxfordian the Jurassic sequences of East Sutherland are of shallow marine to freshwater origin. Large-scale differential movements on the Helmsdale Fault began during the early Kimmeridgian and led to the establishment of a deep-water submarine slope environment on the downthrown side to the SE of the fault, and a relatively stable shallow-water platform area on the upthrown side to the NW. A spectacular submarine fault-scarp developed between the shallow and deep-water areas. Debris from the fault-scarp formed a submarine talus slope, and sand, shell fragments and land-derived plant debris were washed over the fault from the shallow-water shelf environment into the deep-water environment where suspension settling of mud was the background sedimentation. At the foot of the talus slope, formed largely of rockfall breccias, accumulation took place of boulder beds emplaced by debris flows and other gravity-flow mechanisms. Initiation of gravity flows was probably triggered by earthquakes caused by movements on the Helmsdale Fault. It is thus reasonable to hypothesise that tsunamis would have resulted from sea-floor movements and the narrow shallow shelf bordering the Scottish Landmass would have been severely affected. The great mix of material in the individual beds, including both marine organisms and land-derived plants, would support initiation of debris flows following tsunamis. This scenario has been woven into a time-travel excursion by Trewin (2008) which may be of interest to promote further debate on the origins of the boulder beds.

The boulder beds are interbedded with siltstones, mudstones and thin sandstones. The sand was probably swept off the adjacent shelf by storm, wave and tidal action. The thin sand beds and laminae in the shales between the boulder beds greatly exceed the boulder beds numerically, and were clearly the result of frequent events such as storms.

The displaced fossils in the deep-water deposits include a variety of shallow marine bivalves, brachiopods, echinoid debris and corals. Land-derived debris in the form of wood and leaf material (Seward, 1911; Van der Burgh and Van Konijnenburg-Van Cittert 1984; Van der Burgh 1987) became waterlogged and sank into deep water to be preserved in shales along with an open marine fauna of ammonites and belemnites (Figure 3.3). Bottom conditions on the downthrow side of the fault were reasonably well oxygenated during deposition of the Kintradwell Boulder Beds and a diverse bivalve fauna is present (Wignall and Pickering, 1993). Later in the Kimmeridgian oxygenation was poorer and the benthic fauna is greatly reduced.

Clasts within the Boulder Beds reflect the strata that were exposed on the active fault scarp at the time of deposition. The youngest clasts, possibly reworked from the Jurassic, together with sandstones, probably from the Upper ORS, occur in the oldest (*cymodoce* Zone) boulder beds in the south and Middle ORS flagstone clasts in the youngest boulder beds at the north of the outcrop.

Submarine fans were not extensively developed along the fault-margin. Sand-rich sequences are limited to *cymodoce* Zone and were deposited contemporaneously with the initiation of the large-scale faulting episode. These complex sequences may represent a localised submarine canyon and fan body which was fed from a small delta on the adjacent shelf (Figure 3.4). Generally, the development of submarine fans was precluded by the lack of coarse-grained sediment supply to the high-energy rocky shelf area which developed to the NW of the fault scarp. The term 'submarine fan' is used here in the most general sense. It is not possible to define the shape of the sand body, or to say whether it was multi-sourced from the fault scarp, or channelled through one or more point sources. It seems probable that sand supply was control led both by the positions of valleys and rivers draining the Scottish landmass, as well as delta distributaries and the morphology of the fault scarp. The Helmsdale Fault is not a single line of fracture, and sediment transport to deep water was probably controlled by ramps and terraces between fault segments (Figure 3.4).

Visitors to the area should find time to read Bailey and Weir's article of 1932, which is one of the classics of early sedimentological work. It gives a fascinating overview of the research history, and correctly, through a series of logical assertions, reconstructs the palaeogeography at the time of deposition of the boulder beds. More recent studies on the area by Linsley (1972), Neves and Selley (1975), Pickering (1984), MacDonald (1985), Wignall and Pickering (1993) and Macdonald and Trewin (1993) have added detailed sedimentology and palaeontology to the picture.

Biostratigraphic work based intially on ammonites (Lee, 1925; Linsley, 1972) and more recently on palynology (Lam and Porter, 1977; Riley, 1980; Barron, 1986) has shown that a virtually complete zonal sequence is present from *cymodoce*

Zone of the Kimmeridgian to *albani* Zone of the Middle Volgian (Figure 3.2). Further information (Wignall and Pickering, 1993) has helped tie the palynological and ammonite zonal schemes.

Similar fault-controlled sedimentation of late Jurassic age occurred adjacent to the margins of many North Sea Mesozoic grabens. The best-documented offshore examples are the reservoirs of the Brae Oilfield area at the western margin of the South Viking Graben where Jurassic is faulted against probable Devonian rocks (Stow *etal.,* 1982; Turner *et al.,* 1987). These papers contain illustrations of typical core material. Some of the Brae sequences are similar to those seen in this excursion. The main oil-bearing sandstone and conglomerate reservoirs, however, were deposited as parts of a complex submarine fan system, and the sequences differ from those developed along the Helmsdale Fault. Brief summaries of oilfields in the Brae area can be found in Gluyas and Hitchens (2003). Some fields have reservoirs with breccias and conglomerates adjacent to faults, but others are more distal with respect to source and comprise sandstones similar to the Allt na Cuile Sandstone (e.g. Miller Field).

Variation in the type of sediment supply was probably the most important factor which led to the development of different sedimentary sequences. Fan-deltas apparently supplied abundant coarse-grained material to the western margin of the South Viking Graben, which was then available for transportation and re-sedimentation in deeper water by gravity flows. In contrast, little coarse-grained material was supplied to the western margin of the Inner Moray Firth basin. The occurrence of displaced thick-shelled bivalves, colonies of the *coral Isastraea,* attached worm tubes, brachiopods and sea urchins on the downthrown side of the fault (Itineraries 1, 3, and 4) indicates that the shelf area to the west was a shallow marine, high energy, rocky platform during the deposition of most of the boulder bed sequences.

Itinerary 3.1 Kintradwell shore

Purpose

To examine the Kintradwell Boulder Beds of the *cymodoce* Zone together with features indicative of slumping and sliding of sediments on a submarine slope. A good example of an intrusive sandstone dyke is also seen.

Access

Cars or minibuses can be parked by the road near the entrance drive to Kintradwell House. Cross the railway carefully by means of the gates provided and descend to the shore. The localities to be visited are shown in

Introduction

The Kintradwell deposits are the oldest of the 'Boulder Bed' deposits and were deposited on the downthrown side of the Helmsdale Fault. The shales, siltstones, sandstones and boulder beds of Kintradwell lie within the *cymodoce* Zone and are, from both structural and palaeontological evidence, in part the equivalents of the sandstones and breccias of Allt Choll and Allt na Cuile (Wignall and Pickering, 1993). Thus there is rapid lateral facies variation along the line of the Helmsdale Fault.

The 'shales' are dark in colour due to the presence of mud and plant debris. In terms of grain size they are mainly siltstones, and Wignall and Pickering (1993) describe them as 'paper siltstones'. They are reasonably fossiliferous, and ammonites of *cymodoce* Zone are common. The bivalve fauna includes *Liostrea, Buchia, Parainoceramus, Solemya, Nicaniella* and *Palaeonucula,* and the gastroprod *Semisolarium* is also present. Thus, bottom conditions were quite well oxygenated (Wignall and Pickering, 1993). Abundant plant debris gives evidence for the presence nearby of the Scottish landmass. Sandstone beds are sharp-based, some are graded, and they contain fragments of shallow marine bivalves as well as belemnites. Parallel lamination and ripple lamination are common and examples of convolute lamination can usually be seen. Burrows are preserved on the bases and within some beds; these may have been made by animals swept into the environment rather than by an indigenous fauna.

The soft-sediment deformation structures are varied and include both tensional and compressional features. Tensional features include pull-aparts, low angle normal faults and fractures into which sand has been injected. Compressional features include overfolds and thrusts. Large scale bedding dislocations might represent slump scars, and contorted beds and slide planes are present beneath slump sheets. Some of these structures have been described by Pickering (1983), and Roberts (1989) has published a more detailed anlysis of the soft sediment deformation features. Of particular interest is a good example of an intrusive sandstone dyke.

These sediments at Kintradwell clearly accumulated on an unstable slope at the foot of the Helmsdale Fault scarp which lay about 300 m to the west.

Locality 1. [NC 923 074]

Interbedded sandstones and shales crop out (sand cover permitting) on the lower foreshore with some prominent sandstones extending to the upper foreshore. The siltstones and shales are dark in colour, micaceous, and contain abundant plant debris. Crushed ammonites are common at some levels and benthonic molluscan faunas (see above) are present. The sandstones are generally less than 30 cm thick, display sharp bases, and are parallel and ripple laminated. Scour structures occur on bed bases and some examples of unroofed burrows may be seen. Ammonites and belemnites are also incorporated in some sand beds as clasts, and along with pebbles, acted as tools to produce prod and groove marks beneath sandstone beds emplaced by turbidity currents. Thicker sandstone beds are more massive and have deformation features such as convolute lamination, as well as faults and folds which affected the sediments prior to lithification. A strong lineation is present on some surfaces due to the soft sediment deformation; a feature well displayed on the most southerly outcrops on the shore. These beds also contain sandstone clasts, occasional rounded quartz pebbles and fairly common belemnites. The sandstone beds were formed from material swept off the shelf on the upthrow side of the fault and deposited in the deep water on the downthrow side of the fault by gravity flow mechanisms.

The quartz pebbles were possibly derived from earlier Jurassic sandstones, such as the Brora Sandstone which could have been exposed on the fault scarp at this time, and the matrix sand could be reworked from the same source. There is still some doubt as to the ages of the sandstone clasts in these beds, but most are feldspathic, and were derived from a sandstone with features of fluvial deposition. A source in the ORS is likely, the clasts having been bleached of typical red and green colours in the reducing environment of early burial (see Locality 6 below).

Locality 2. Sandstone dyke [NC 925 074]

The sandstone dyke (Figure 3.6) is composed of calcite-cemented sandstone and is up to 70 cm wide and near vertical. It can be traced for about 100 m over the tidal platform. This feature has been commented on by several authors since first being recorded by Murchison in 1827. It is clearly intrusive and is the result of mobilisation of sand, probably caused by earthquake shock associated with movement on the Helmsdale Fault. Pickering (1983) considered that it was intruded from below, citing evidence of upturned edges of adjacent shale beds, but this could be a compaction feature.

The reefs in the area around the dyke are worth examining in some detail. By following the strike of individual beds many discordances become apparent, which can be followed for tens of metres. Some of these may be relics of slump scars infilled with sediment; others are clearly slide planes which are frequently parallel to bedding, but change horizon to produce the discordances seen. Examples of slump folds are also present which lie on slide planes; Crowell (1961) studied these and other structures to show that derivation was from the NW Roberts (1989), in a detailed analysis of the deformation features in this area, recognised three categories of deformation related to soft sediment movement on a palaeoslope directed away from the Helmsdale Fault. The categories are: (1) small syn-depositional normal faults throwing down to the S or SE; (2) slump folds directed to the S and produced by movement within the wet sediment pile; (3) 'thrust' faults and related low-angle slides and extensional faults related to the movement of a gravity slide away from the Helmsdale Fault.

The most resistant sandstone reef in this area contains a great concentration of well-rounded quartz and quartzite pebbles mainly of 5–15 mm diameter, together with occasional sandstone clasts, belemnites, and shallow-water marine bivalves (Figure 3.7). The well-rounded, spherical pebbles are also common in sandstone and boulder beds in the Allt Choll/Allt na Cuile area. They are typical of, and restricted to, *gmodoce* Zone sequences. The pebbles were rounded prior to the brief transport episode that brought them into deep water. They closely resemble those found near the top of the Brora Sandstone Member and could have been derived from that source by reworking. Likewise the matrix sand could be largely reworked from older Jurassic strata. The sporadic distribution of the pebbles suggests that the pebble source was not tapped by all events that introduced sediment to deep water. The pebbles might have been beach material channelled through gullies to the edge of the fault scarp.

Locality 3. [NC 926 074]

Near the point a large (c.2 m) boulder is seen resting on, and deforming, a bed of laminated sandstone which varies in thickness when followed along the strike. The boulder consists of a breccia of sandstone blocks in a matrix of coarse sand with small quartz pebbles. This lithology closely resembles the breccias seen adjacent to the Helmsdale fault to the north at Allt Choll and provides evidence for early reworking of material in the Helmsdale fault zone (see (Figure 3.4)). One requirement is early lithification of the breccia so that it could withstand transport. Preferential cementation is seen along fractures in the Allt Choll area and this could have been due to hot fluids rising in the active fault zone and producing near-surface lithification.

Locality 4. [NC 926 075]

The shore section is approximately coincident with the strike of the beds to locality 3 where an isolated outcrop on the foreshore, usually protruding from sand, shows an excellent slump overfold in sandstones which have a concentration of rounded quartz pebbles, together with large angular clasts of sandstone (Figure 3.8). Clearly there were at least two sources of material, the rounded pebbles being reworked from a poorly lithified sandstone, and the angular sandstone clasts from a better lithified sandstone which probably formed the footwall of the exposed fault scarp.

Locality 5. [NC 927 076]

Cross the sandy bay and stream to the next outcrop, which is a sequence of interbedded sandstone and shale capped by a sandstone bed showing excellent convolute lamination. If exposure and seaweed permit, examine the shales at the base of the outcrop. There are two or more dislocation or slide planes present, and the shales between these planes are intensely deformed with thin sandstone beds distorted into flat-lying isoclinal folds (Figure 3.9). This feature represents a slide plane beneath a sheet of sediment that slid downslope away from the Helmsdale Fault. Sand cover frequently obscures the base of this slide.

Locality 6. [NC 928 076]

At this locality impressive boulder beds are interbedded with siltstones, shales and thin sandstones. Many compaction features occur around the large boulders, and soft-sediment deformation features are common in the interbedded strata.

The boulders in the beds are angular to rounded and are composed of parallel laminated and cross-bedded white or grey sandstone. Small eroded slits in the sandstone resemble bivalve moulds, but on close examination most represent weathered-out clasts of clay flakes. Read *et al.* (1925, Frontpiece photo) considered these clasts to be of Devonian rocks, and the feldspar content is consistent with an ORS origin. However, MacDonald (1985) favoured a Jurassic age, as some undoubted bivalve casts have been reported in similar clasts in the Allt na Cuile/Lothbeg area. One large 6 × 7 metre boulder is prominent on the shore and comprises bedded sandstone with some beds showing cross-bedding and with concentrations of small green mudstone flakes; this boulder is typical of Devonian fluvial facies and unlike any of the rocks of the Triassic–Jurassic sequence. It appears that many of the clasts could have been quite poorly lithified at the time of incorporation into the boulder beds, as they show signs of disintegration and veining by the matrix muds; such features could give support to a Jurassic rather than a Devonian age for some of the clasts. However, the fluids that bleached the sandstone clasts may also have opened up joints, causing the clasts to break up during early burial and compaction. This might explain the generally angular nature of the fragments (Figure 3.9).

The majority of clasts are derived from a fluvial sandstone of probable Devonian age. The clasts are of feldspathic sandstones and thus differ both in lithology and sedimentology from known Jurassic sandstones in the area.

Itinerary 3.2 Lothbeg Point area

Purpose

To examine breccias, sandstones, siltstones and shales which were deposited during the initial stage of basin deepening in the *cymodoce* and *mutabilis* Zones of the Kimmeridgian. The Allt na Cuile sandstone represents a point source of sand entering the basin from a small delta fed by a river draining the Scottish landmass.

Access

Car or minibus access is from the A9 through Crackaig Farm and under the rail bridge to the Crackaig Links camp and caravan site (Figure 3.10). Localities 1–3 can be accessed along the beach, locality 1 being about 2.5 km from the parking access. The walk involves crossing the Loth Burn. Unless the burn is in spate this may involve a shallow paddle, or some rock-hopping at locality 4. Localities 1–3 can also be reached by following a track from the A9 to the south of Loth Burn (see (Figure 3.10)). Localities 3 and 6 should be visited within 2 hours of low tide. Locality 7 occurs beside the overgrown Lothbeg Bridge on the old road over the Loth Burn. The road crosses the burn about 200 m upstream from the point where the present A9 crosses the burn. Take the turning north to Loth on the east side of the burn where a car can be parked. Descend to the east bank of the burn on the south side of the old bridge. The excursion can be shortened by omitting localities 1–3 and 7, which are not suitable for large parties.

Introduction

Localities 1 and 2 display breccia-rich sequences close to the Helmsdale Fault. The precise age of the sandstones and breccias is uncertain. Brookfield (1976) obtained ammonite casts of *cymodoce* Zone age from loose blocks of sandstone, and Wignall and Pickering (1993) have proposed an early *mutabilis* Zone age for the top of the sandstone at Allt na Cuile, but most of the Allt na Cuile Sandstone is of *cymodoce* Zone age. This age is in accordance with the overall geological setting, and the sequences are thus lateral equivalents of the Kintradwell Boulder Beds (*see* Wignall and Pickering, 1993, Figure 15).

The sandstones are variably bioturbated, cross-bedded, normally graded, and apparently structureless. MacDonald (1985) proposed that a possible depositional environment for these complex sequences could be a large submarine valley or canyon where tidal currents reworked the sand into dune structures, and high-density turbidity currents deposited the graded beds. The sequences clearly represent a point of considerable sand supply to the fault-margin. Possibly a river entered the sea near this point or a cross-fault channelled sand into deeper water.

Localities 4 and 5 display the best available exposures of the Allt na Cuile Sandstone of *cymodoce* Zone. They show sandstone facies at a greater distance from the Helmsdale fault than those of Allt Choll and Allt na Cuile. The exact relationship between the sandstones exposed at Lothbeg and in the Allt na Cuile area is not clear because of the discontinuity of outcrop. Both sequences directly overlie bioturbated mudstones (Locality 3) and are apparently lateral equivalents on opposing limbs of a gentle northwards plunging anticline.

The sandstones at Lothbeg are better sorted and lack sandstone clasts, but occasional quartz pebbles are present. They have been made more resistant to erosion by the presence of a network of quartz cemented crush zones along the line of a cross-fault. The *mutabilis* Zone shales (Lothbeg Siltstone of Wignall and Pickering (1993)) of this area show the best examples in the Helmsdale area of black, deep-water, organic rich siltstone and shale deposition with very few thin turbidite beds included in the shales.

Locality 1. Allt Choll gorge [NC 936 091]

The NE face of the gorge is a spectacular exposure of a compound boulder bed sequence (Figure 3.11). The Helmsdale Fault lies approximately 100m to the NW but is poorly exposed and access is difficult, particularly in summer when vegetation is high.

Poorly defined bedding dips to the SE. The clasts, up to 2 m long, are mostly friable, buff-coloured quartzose sandstones. This is a very common clast type in the *cymodoce* and *mutabilis* Zone breccias of East Sutherland. Also typical of breccias of this age at this locality are the well-rounded quartz granules and pebbles which are a common matrix component of the boulder beds, and are also seen in equivalent beds at Kintradwell (Itinerary 1). It is possible that some of the clasts are reworked older Jurassic sandstones similar to the Brora Arenaceous Formation, and that matrix material of sand and pebbles is also reworked from the same source. However, it is more likely that the sandstones are extensively altered Old Red Sandstone. At the top of the cliff cross-bedded sandstones overlie the breccias. A prominent ridge at the entrance to the gully consists of more strongly cemented breccia. The ridge is parallel to the Helmsdale Fault and the cementation was probably the result of fluids ascending fractures associated with the fault.

Locality 2. Stream gully to NE of Allt Choll [NC 938 092]

The SW face of the gully is composed of an interbedded sequence of breccias, sandstones and large isolated boulders of sandstone up to several metres in diameter. Other breccias and sandstones are well exposed higher up in the gully. Access is difficult in summer when vegetation is high.

The sandstones are fine-grained, thin-bedded and in places are cross-laminated and cross-bedded. The large isolated blocks of sandstone have deformed the underlying sandstones. The blocks clearly created a variable depositional topography, as the overlying sandstones have been ponded into depressions between the boulders. The overlying sandstones were deposited from relatively low-energy flows, as there is no scouring around the large sandstone blocks. This outcrop has important implications for the interpretation of depositional environments. The preservation of large angular blocks of sandstone and the lack of scouring suggests that the environment was relatively low-energy and below wave base.

Locality 3. Shoreline west of the Loth River [NC 946 095]

At this locality bioturbated sandstones and mudstones underlie the *cymodoce* Zone sandstone-rich sequence exposed at Lothbeg Point (Locality 3), and must be *cymodoce* Zone or older. The bioturbated shales contain a lot of carbonaceous debris and some beds of interbedded porous sandstone. These rocks were deposited in a well-oxygenated, slowly subsiding, shallow marine basin immediately prior to the major episode of faulting and basin deepening. Subsequently, large-scale movements along the Helmsdale Fault led to a deepening of the basin, and the remainder of the Jurassic is characterised by relatively deep-marine sedimentation in a rapidly subsiding basin.

The overlying sandstone-rich sequences (Locality 3) were deposited during a transitional deepening phase and the finely laminated black mudstones exposed at locality 4 were deposited in a deep-water, oxygen-depleted environment.

Locality 4. Loth River at Earls Cut [NC 952 099]

Large cliff exposures occur on the east bank of the Loth Burn on both sides of the railway bridge. Upstream of the bridge a sandstone bed is present in a siltstone- and shale-dominated sequence (Loth Burn Siltstone of Wignall and Pickering (1993)). At first sight, the sandstone at river level appears to be a channel, but the lower surface is concordant and the top is truncated by low-angle faulting. In the continuation of the exposures downstream of the bridge (Figure 3.12) two 2–3 m thick sandstone beds are seen, interstratified with siltstones, shales and thin sandstones. Two large, and several small curved fault planes downthrow to the SE. They affect discrete units of sediments and probably formed soon after deposition, during failure of the sedimentary pile on a SE-dipping slope. An intensely folded slump horizon is present about half way up the cliff and numerous small syn-sedimentary normal faults cut the sequence, many of which can be traced into bedding-parallel slip planes.

Ammonites and well-preserved plants are found associated in the dark siltstones. The ammonites indicate an open marine environment and the plants were probably derived from a vegetated delta on the upthrow side of the fault. Nineteen species of plants representing 14 genera have been described from the siltstones and shales of Kintradwell, Lothbeg Point and Crackaig Links by Van der Burg and Van Konijnenburg — Van Cittert (1984) who consider the dominant species to be typical of brackish swamps (*Gleichenites cycadina*)and freshwater swamps (*Taxodiophyllum* *scoticum*)of a delta. Less abundant representatives of heath, moist lush vegetation and upland forest were also recognised (Figure 3.13).

Locality 5. Lothbeg Point [NC 960 096]

On the lower shore between localities 4 and 5 there are exposures of sandstone with some interbedded carbonaceous siltstones. These are best seen when cleaned after storms, but become algae-covered in summer. The sandstones show interesting soft-sediment deformation features (Figure 3.14) including sand injection into pull-aparts in the dark siltstones.

The sequence underlying the white sandstones exposed near the high water mark at Lothbeg Point is generally covered in seaweed and is only exposed at low water. It is composed of interstratified sandstone and mudstone with a general increase in the sandstone proportion upwards towards high water mark. The sandstones are 2–5 m thick and are apparently lensoid. The mudstones near low water mark are bioturbated and similar to those better exposed at locality 3. The bioturbation generally decreases upwards and is replaced by finely laminated mudstone.

The sandstones at Lothbeg Point are generally friable, highly quartzose, have porosities up to 28%, and permeabilities up to 3D; thus they have potential as oil reservoirs. Some of the sandstones are clearly graded and have carbonaceous material concentrated at bed tops. The thicker sandstones at first sight appear massive, but scour features with coarser grains at the base are present. Also, cross-bedding can occasionally be observed in sandstones exposed on wave-scoured platforms.

The massive nature of most of the beds, their scoured bases and occasional grading, along with their overall stratigraphic context and interstratification with dark laminated mudstones is suggestive of deposition from high-density turbidity currents in a submarine slope or fan environment. The cross-bedding is of more problematic origin and some may be the result of localised wave or tidal reworking, but most is probably due to traction processes within submarine channels. Wignall and Pickering (1993) favour a sandy slope environment overspilling the Helmsdale Fault; they avoid use of the term 'fan' since radial organisation cannot be demonstrated.

The sandstone exposures at Lothbeg Point are crossed by numerous pale upstanding 'veins' which, on microscopic examination, are seen to be quartz-cemented granulation seams formed by microfaults; slickensides can be seen on fault surfaces (Figure 3.15). The granulation seams are due to faulting that has hardened the sandstone over a wide zone and made them more resistant to erosion, resulting in the formation of Lothbeg Point.

Granulation seams such as those at Lothbeg Point, pose problems for extraction of oil from reservoirs since they divide the rock into compartments that lack effective permeable connection. They can greatly reduce the production potential of a reservoir.

Locality 6. Exposure north of Lothbeg Point [NC 961 096]

A thick sequence of *mutabilis* and *eudoxus* Zone siltstones and shales is exposed, which comprise the Loth River Shales of Lam and Porter (1977) and the Lothbeg Siltstone of Wignall and Pickering (1993). The siltstones are organic-rich, frequently calcareous and highly fossiliferous. They contain well-preserved ammonites, belemnites, bivalves, brachiopods and drifted plants; some of the better fossil specimens occur in carbonate concretions that also yield rare fish and reptile remains. The fine lamination contrasts with the abundant bioturbation seen at locality 3, and the water depth within the basin is interpreted as having increased. Contemporaneously, the sediment–water interface was frequently, but not permanently, oxygen-depleted. The fauna at the base of the siltstone includes *Buchia, Parainoceramus* and *Leiostrea* and indicates moderate oxygenation. Higher in the shales oxygen levels become more depleted and pseudoplanktonic oysters attached to ammonites are the only bivalves present (Wignall and Pickering, 1993).

This organic-rich lithology is similar in appearance to the Upper Jurassic Kim-meridge Clay Formation shales which were deposited over much of the NW European continental shelf and include the organic-rich source rocks for oil in most of the North Sea oilfields. The siltstones and shales at Lothbeg and throughout the Helmsdale sequences are, however, generally more rich in terrestrially derived organic material such as plant fragments than their North Sea oil-prone counterparts, and consequently are poorer quality oil source rocks. The abundance of terrestrial material is a consequence of the basin-margin setting and testifies to a highly vegetated land area nearby.

Thin sandstones are also well exposed at this locality; these have sharp bases and tops, may be parallel-sided, or can pinch and swell across the outcrop. Some of the beds are graded and contain parallel lamination, cross lamination and waning-flow sequences of structures. The cross lamination demonstrates that these turbidite sandstones were emplaced from NW to SE by currents flowing away from the Helmsdale Fault scarp. A folded and boudinaged slump sheet of interbedded sandstone and shale is sometimes exposed at the southerly end of the exposures.

Locality 7. Helmsdale Fault zone at Lothbeg Bridge [NC 945 105]

Follow directions in the 'access' section to Lothbeg Bridge. Descend to the east bank of the burn on the south side of the old bridge. Under the bridge and upstream are exposures of shattered Helmsdale Granite within the Helmsdale Fault zone. Numerous faults are present and blocks of several different lithologies are caught up in the fault zone. Blocks of red to green laminated sandstone and mudstone, presumably from the ORS, are present and can also be seen on the west bank downstream of the bridge at river level. Extensive veins of pink and grey calcite are present in the fault zone. This exposure marks the most southerly extent of the Helmsdale Granite along the fault line. To the south of the bridge Moinian metamorphics occur on the upthrow side of the fault.

Downstream of the bridge a breccia is exposed with blocks of sandstone up to a metre in length. The boulders are generally medium-grained sandstones and contain green clay clasts and kaolinite pseudomorphs of feldspar grains. Parallel lamination and cross-bedding are present in the boulders, which are most probably of Devonian origin. The matrix is micaceous, fine sand with occasional quartz pebbles and carbonaceous material.

Itinerary 3.3 Portgower

Purpose

To see the upward transition from sandstone-rich sequences to mudstone and boulder-bed dominated sequences and visit the Portgower giant clast locality popularly known as the 'fallen stack'. To examine changes in clast and matrix types within the boulder beds.

Access

Turn off the A9 in Portgower (car or minibus only) and park near the last houses on the lower road at the western end of the village at Craig Loisgte Place (Figure 3.16). A track from this point runs to the cliff edge and continues down the slope to the south, reaching the shore about 200 m north of the 'fallen stack' (Locality 4). Take care crossing the rail line. To examine the sequence in ascending stratigraphic order, walk SW along the shore to locality 2. Low tide is required; the sandstones of locality 2 should be visited within 2 hours of low water.

Introduction

The sandstones at the base of the sequence (Locality 2) have been dated to *mutabilis* Zone by Barron (1989). They are very similar to the sandstones of Lothbeg Point but lie higher in the zonal sequence. (Itinerary 2, Localities. 4–5). The sandstones pass upwards into a thin mudstone sequence which is overlain by a breccia and sandstone-rich sequence which Linsley (1972) recognised as being of *mutabilis* Zone (Figure 3.16). These lithologies contrast with the thick *mutabilis* Zone siltstones which overlie the Allt na Cuile Sandstone at Lothbeg Point. The lack of boulder beds at Lothbeg Point may also be due to greater distance from the Helmsdale Fault; thus it is implied that boulder beds did not extend far into the basin. The upward sequence from locality 2 to locality 4 reveals a change in clast types (Figure 3.17), with clasts of trough cross-bedded sandstones of probable Upper ORS at locality 3, and Middle ORS flagstone clasts between localities 3 and 4. The misnamed 'fallen stack' of locality 4, which is in the *eudoxus* Zone, is a giant clast of Middle Old Red Sandstone flagstones.

Locality 1. [NC 997 123]

Boulder Beds in the region of locality 1 contain some sandstone clasts greater than 2 m in length. These larger clasts are red in colour in their centres but bleached to 3.18 Cross-bedding in sandstone clast within boulder bed near Locality 1, Portgower. Lens cap 52mm.

brown and green around the margins and along fractures. The sandstone of the clasts is moderately sorted, medium-grained and trough cross-bedded (Figure 3.18), with some evidence of distorted cross-bedding due to liquefaction. Rip-up clasts of red mudstone and occasional subrounded quartzite pebbles are present. Clasts with parallel lamination display primary current lineation. These clasts are from a sequence of fluvial origin and are probably Devonian in age rather than Permo-Triassic, since no characteristic Permo-Trias lithologies (e.g. aeolian sandstone, caliche carbonates) have been seen, and the petrographic features (mineralogy and textures) are consistent with an origin from the ORS. The large clast size and minimal matrix suggest a very local derivation, probably by rockfall. Boulder bed matrix is generally sandy with coarse shell debris, including oysters and echinoids, derived from a well oxygenated shallow shelf on the footwall side of the Helmsdale Fault.

Locality 2. [ND 000 125]

The base of the sequence is exposed in the core of a gentle anticline. The sediments are friable, medium to coarse-grained quartzose sandstones with excellent porosity and permeability. Graded sandstone beds are present with highly carbonaceous shale interbeds. These sandstones are similar to the Allt na Cuile Sandstone exposed at Lothbeg Point. The lack of any carbonate cement or carbonate bioclasts in this sandstone can be explained if the sand came direct from a delta, rather than from a shallow marine shelf. Mudstones with thin sandstone beds overlie the massive sandstone, which are in turn abruptly overlain by a breccia and sandstone-rich sequence, which marks the local base of the Helmsdale Boulder Beds. The lowest boulder beds contain clasts of pale-coloured laminated and cross-bedded sandstones, the matrix is shelly, and sea urchin spines, pectinid bivalves and oysters can be recognised. It appears that the delta had ceased to supply sand direct to deep water, and marine shelf conditions had re-established on the footwall.

From a petroleum geology perspective this exposure shows that good quality reservoir sandstones occur within the boulder bed sequence, and that there is a potential seal of shales and carbonate-cemented boulder beds to such a reservoir. The key to finding such reservoirs might be to identify possible point sources of sand (rivers and deltas) being supplied to the fault scarp in the late Jurassic. Walk back along the shore towards locality 3 noting the clast types present.

Locality 3. [ND 003 127]

Clasts in the basal breccias at Midgarty (between Localities. 2 and 3) are predominantly light-coloured and relatively friable sandstones, and although some are similar in colour and grain size to the older Jurassic sandstones exposed at Brora, they differ in being feldspathic. These clasts are derived from a fluvial sandstone facies, probably of Devonian age. In the region of locality 3 the first clasts of typical Middle ORS flagstone facies are found. The varying clast types may reflect the progressive erosion of older lithologies on the upthrown side of the fault, but this picture is probably complicated by changes in basement geology along the line of the Helmsdale Fault where it intersects older cross-faults. Possibly the fault scarp outcrop changed from Middle ORS flagstones to Upper ORS fluvial sandstone at this point.

Locality 4. The giant clast or 'fallen stack of Portgower' [ND 004 128]

Between localities 2 and 3 a wide variety of breccias and sandstones are very well exposed and it is worthwhile to spend some time studying the textures of these beds. Exposed near the top of the beach (sometimes covered under pebbles and boulders) is a sequence of beds up to 30 cm thick and with sandstone clasts up to 10 cm, but a few reach boulder size. The interbedded shale contains sandy laminae and lenticles rich in bioclastic and carbonaceous debris. The thin boulder beds contain some excellent examples of calcitic clasts bored by the bivalve *Lithophaga,* together with oysters, and urchin spines. The latter have their long axes oriented between 130° and 150° on several surfaces. Calcite veins cut the outcrop, mostly oriented between 220° and 240°, but with some at 180°.

The famous misnamed 'fallen stack of Portgower' is a giant flagstone clast 30 m long which occurs in a breccia bed along with several other giant clasts (Figure 3.19).

Bailey and Weir (1932) measured the clast as 100 ft long. The flagstones are very similar to those exposed *in situ* in the Middle ORS Caithness Flagstone Groups throughout much of Caithness. The 'stack' shows many features typical of the Middle ORS including a dark grey laminated fish bed horizon with scattered fish scales near the landward end of the 'stack'. This lithology was deposited in a deep lacustrine environment and is described in detail in Excursion 5. Shallower water lacustrine facies include ripple lamination, some cross-bedding, and the base of one sandstone bed shows good flute moulds. Subaqueous desiccation cracks are common and some horizons of polygonal desiccation cracks are present; the latter indicating exposure and drying of the lake sediments in a playa-like environment. Thus, a full range of lithologies representing Devonian environments ranging from deep to shallow lake and exposed playa are preserved in the stack. Hugh Miller (Miller, 1854) collected Devonian (Middle Old Red Sandstone) fish fragments from this locality, and clasts of fish bed laminites still yield incomplete specimens of *Dipterus.* (However, please do not destroy such clasts in a search for the fish, which are not very well preserved; much better material can be seen at Achanarras Quarry, Excursion 5).

Early workers thought that the giant boulder was a sea stack which had fallen on its side; rather like a collapsed Old Man of Hoy. Although the massive piece of Old Red Sandstone was clearly derived from a nearby cliff, Bailey and Weir (1932) explained that it is unlikely to be a fallen stack, as it forms part of a boulder bed that is interstratified with deep-water marine shales. Bailey and Weir then correctly surmised that the giant clast was derived from the submarine Helmsdale Fault scarp. It is noticeable that in the 'stack' bed, and in many of the other nearby boulder beds, there is little matrix between the clasts. It appears that the clasts avalanched from the fault scarp into their present position, rather than being transported by any sort of debris flow process. On the basis of the 30 m stratigraphic thickness present in the giant clast, combined with the reasonable assumption that the Middle ORS in the fault scarp had a low dip, the exposed submarine fault scarp must have been at least 30m high.

Locality 5. Westgarty [NC 989 124]

Immediately upstream of the road bridge there are exposures of Helmsdale Granite on the upthrown side of the Helmsdale Fault.

Locality 6. Westgarty [NC 989 123]

Breccias, downthrown side of Helmsdale Fault.

In the stream bed and banks both upstream and downstream of the point where the cart track crosses the stream there are poor exposures of breccias that contain large blocks of ORS lithologies. There is no evidence in this area for the continuous fault-bounded slice of Old Red Sandstone shown on the Geological Survey Golspie geological map (Sheet 103). Middle ORS fish fossils can be found in large clasts, which were thought to be *in situ* Devonian when the map was originally surveyed. In the stream between localities 5 and 6 there are poor exposures of sheared granite with a hydrocarbon-bearing vein near the contact. Parnell (1983) describes this and other minor occurrences of hydrocarbon-bearing veins in the area.

Itinerary 3.4 Helmsdale to Dun Glas

Purpose

To examine the Helmsdale Boulder Beds, rock-fall breccias and the Helmsdale Fault zone at the northernmost end of the Jurassic exposure.

Access

This itinerary can be tackled on foot from Helmsdale Harbour (Figure 3.20), in which case the return walking distance is 7 km if the party wishes to walk as far as Dun Glas. Low tide is required for all localities.

Introduction

The strata exposed on the shore range in age from *pectinatus* Zone at the harbour to *albani* Zone near Dun Glas, the latter being based on palynological comparison with the ammonite zonation (Riley, 1980; Barron, 1986, 1989) (Figure 3.2).

The section displays a fine range of boulder bed lithologies with many interesting structures, mainly associated with deposition by matrix-poor debris flows. Clasts in the boulder beds are of Middle Old Red Sandstone flagstone facies and occasional clasts of fish-bed lithologies (see Excursion 5) yield Devonian fish fragments. *Dipterus* is the most common genus, but *Coccosteus cuspidatus* has also been found, and is indicative of a source high in the Lower Caithness Flagstone Group according to the zonal scheme proposed by Donovan *et al.* (1974).

The boulder beds are now faulted against the Helmsdale Granite, but no clasts of granite are present within the boulder beds. There has clearly been considerable post-depositional movement on the fault with downthrow to the SE. Calcite veins are oriented parallel to the fault and were formed after lithification of the boulder beds. Movement on the fault took place in Kimmeridgian times when the fault controlled sedimentation, but later movements in the Cretaceous and again in the Tertiary took place after the sediments were lithified. The boulder beds show gentle folding into anticlinal closures against the fault. These structures are well seen in the reefs of the intertidal platform, which form a protection to headlands from coastal erosion. The folds have been related to stresses set up by opposed strike-slip motion on the Helmsdale Fault (sinistral) and Great Glen Fault (dextral) during the Tertiary (Thomson and Underhill, 1993).

At the time of deposition, the active fault scarp in this area exposed Middle ORS flagstones, and the narrow shelf to the west of the fault was apparently dominated by exposed rock. A rich, shallow marine fauna of bivalves, including thick-shelled cemented forms and boring forms, colonies of the coral *Isastraea,* attached worm tubes, brachiopods and cidaroid sea urchins, lived on this shallow marine high-energy rocky shelf (Figure 3.3).

Interbedded with debris flows derived from the fault scarp are siltstones and shales with thin beds rich in bioclasts and quartzose sand. The shales contain ammonites, belemnites and occasional fish debris. Drifted plant debris, some in the form of calcitised logs and rare reptile (crocodile, turtle, plesiosaur) remains have also been found. The deep-water environment was generally anoxic during deposition of the Helmsdale Boulder Beds; hence a bottom-dwelling fauna is absent. Even ammonites are absent from much of the sequence, a feature which Wignall and Pickering (1993) suggest was due to reducing conditions in the lower part of the water column where nektobenthonic ammonites might have lived. The general features of the fault scarp in this area are illustrated in (Figure 3.21).

Locality 1. Harbour area [ND 031 151]

Entering Helmsdale from the south on the A9 cross the bridge, take the first right into Dunrobin Street and then turn right again to the harbour and park at the eastern end of the harbour. The boulder beds are exposed low on the beach and good surfaces can be seen where they have been abraded by movement of beach pebbles.

Typical debris-flow textures are seen with angular to sub-angular, and also rounded, clasts of Middle ORS flagstones matrix-supported by coarse bioclastic debris (Figure 3.22). Detailed examination reveals that rounded and angular bivalve shell debris dominates the matrix, with scattered examples of belemnites, corals, sea-urchin spines and other bioclastic debris. Clearly, there was little siliciclastic detritus available on the shelf at this point, and bioclastic debris accumulated on a rocky shelf. The variable rounding of the larger clasts reflects their derivation from shelf (rounded by wave action) or fault scarp (angular). With careful searching, clasts may be found with typical boring crypts of bivalves (cf. *Lithophaga*)(Figure 3.23) showing that rock was exposed in the shallow marine environment.

About 150 m from the harbour some large blocks of ORS are seen, the largest measuring about 17 x 11 m in outcrop area, and others are 5–10 m in size. These blocks were probably detached from the fault scarp along joints during earthquakes, and slid the short distance (about 300 m) from the scarp to their resting place. The large block of ORS dips seawards and is inverted. Within the block examples of load structures, ripple lamination, polygonal desiccation cracks and subaqueous shrinkage cracks can be seen, all typical of the shallow lake phase deposits of the Caithness Flagstone Group (see Excursion 5).

Locality 2. [ND 035 153]

Continue along the beach, noting the variety of boulder beds and interbedded shaly lithologies. Between the shed and the concreted outfall, exposures of grey-black shales with thin, white to pale yellow sandstones up to a few centimetres thick are exposed. Sandstone beds and laminae are graded and others have ripple lamination. This thin-bedded association is similar to the so-called 'tiger-stripe' facies and has been described from the Brae Oilfield by Stow *et al.* (1982). The sand was probably deposited following storms that stirred up sediment on the shallow shelf and swept it over the fault scarp and down into deep water. There is no sign of bioturbation or a benthonic fauna and amorphous sapropelic organic material is preserved; bottom conditions thus appear to have been reducing. Drifted plant debris and ammonites may be found. Some lenticular boulder beds are seen here, demonstrating that individual flows were of small volume. Boulders in the beds exceed 1 m in diameter; indeed the clasts may be thicker than the 'bed' that contains them, and protrude from the tops of beds. Beneath the boulder beds there is frequently a zone of siltstone and shale up to 10 cm thick which has been deformed during the emplacement of the boulder bed.

Locality 3. [ND 038 154]

Proceed to about 150 m beyond the modern house where a 2 m thick boulder bed with a coarse Shelly matrix can be seen. The bed wedges out down the beach, away from the Helmsdale Fault. Calcite veins, which run subparallel to the Helmsdale Fault, cut both clasts and matrix, indicating that the rock was fully cemented prior to the veining. Sandstone at the top of the bed can be seen apparently draped over boulders, but this is likely to be a compaction effect (Figure 3.24).

In the next dark siltstone and shale sequence, about 100m further along the beach, some thin beds of sandstone with bioclastic material have spines of cidaroid sea urchins on their top surfaces which have their long axes aligned perpendicular to the Helmsdale Fault. The sea urchins probably lived on a rock substrate at the top of the fault scarp. A few ammonites and belemnites are found in the shales.

The interlaminated shale and sandstone in this area is rich in carbonaceous debris and shows complex syn-sedimentary faults and zones with laminae deformed into ptygmatic folds. A coarse sandstone bed is present that wedges out down the shore, and isolated boulders which slid into the muds from the fault scarp are found within shale.

Locality 4. [ND 040 155]

Near the point, there are usually good exposures of boulder beds, sandstones and shales in which lateral discontinuity of the sandstones and boulder beds can be demonstrated. About 100 m south of the point, sandstone and boulder bed lithologies occur in dyke-like bodies discordant to the bedding of the enclosing strata. Colonies of the coral *Isastraea* (Figure 3.25) occur as boulders in some beds in this area — please do not hammer good colonies — loose material can usually be found on the shore. Logs of calcitised conifer wood are also reasonably common. Examples of beds with boulders larger than the bed thickness, boulder beds overlying disrupted shale, and small sandstone dykes are also present. From the point (Sron a Chrochair) there is a good view northwards to Dun Glas (also known as Green Table) where the Helmsdale Fault crosses the shore and leaves the coast (Figure 3.26).

It is a 10 minute walk back to the harbour from this point, and Dun Glas is a brisk 40 minute walk further along the shore.

Locality 5. [ND 045 161]

Continue into Navidale Bay noting the seaward plunging anticlinal closure in the boulder beds exposed on the shore beneath the Navidale House Hotel. Locality 5, at the north side of the bay beyond a ruined building, is a small cliff in boulder breccia which contains very little matrix and is interpreted to be a rockfall breccia. Rare examples of clasts bored by bivalves are present, so confirming the submarine origin of the breccia. Shales and boulder beds with bioclastic debris are interbedded with the rockfall breccias.

At the end of the cliff bedding becomes vertical against a large, subsequently fractured, block of shaly ORS some 20 m thick. The clasts in this region are all very similar ORS of local derivation, and further down the shore the typical boulder bed facies with a calcareous matrix is present. Prominent calcite veins trend at 030–050° across the outcrop, filling fractures parallel to the Helmsdale Fault. Fracturing is interpreted to have taken place after the boulder beds were fully lithified because the fractures pass straight through both clasts of ORS flagstones and Jurassic matrix, rather than going around the clasts.

Locality 6. [ND 047 167]

The reefs of boulder beds on the shore form a seaward-plunging anticlinal fold around the point and protect the point from erosion. The waterfall formed by the Sput Burn cascades over the rockfall breccia close to the line of the Helmsdale Fault. At the back of the bay a prominent rusty outcrop in a gully cutting the cliff marks the position of a lens of fractured yellow sandstone caught up in the fault zone. This sandstone is medium-grained, and contains moulds of marine bivalves including pectinids and small oysters. Bailey and Weir (1932) considered that these could be 'Corallian' sandstones that had collapsed into a chasm along the line of the fault. Both Lee (1925) and Bailey and Weir (1932) compared this sandstone with that of the Loth area (Allt na Cuile Sst.) and in particular the Allt Choll breccia. The sandstone is certainly no older than Jurassic and is possibly of Lower Cretaceous age. Lower Cretaceous crops out on the seafloor close by, so the presence of a slice caught in the fault zone is not surprising. It is also possible that the sediment was intruded as a clastic dyke, or represents part of a fissure filling in the fault line as suggested by Bailey and Weir (1932).

Locality 7. [ND 052 171]

The Helmsdale Fault zone is exposed on the shore at this locality near the mouth of Allt Briste (Figure 3.26). Rocks in the fault zone are intensely fractured, sheared and veined. Cherty crush veins are prominent and original lithologies are hard to recognise, but it appears that most of the fault zone consists of altered granitic material. Veins with calcite and pyrite are also present. Typical boulder beds are seen on the SE side of the fault on the foreshore. The fact that the granite is so intensely deformed when compared to the softer Jurassic provides evidence that the granite deformation took place at great depth, and that the Helmsdale Fault is an older structure reactivated in the Jurassic. Bailey and Weir (1932) considered that 'a foot or two' of white sandstone at this locality rests unconformably on Helmsdale Granite. It is, however, difficult to distinguish small fault slices, vein infills and unconform-able relations in such disturbed rocks.

Locality 8. [ND 056 173]

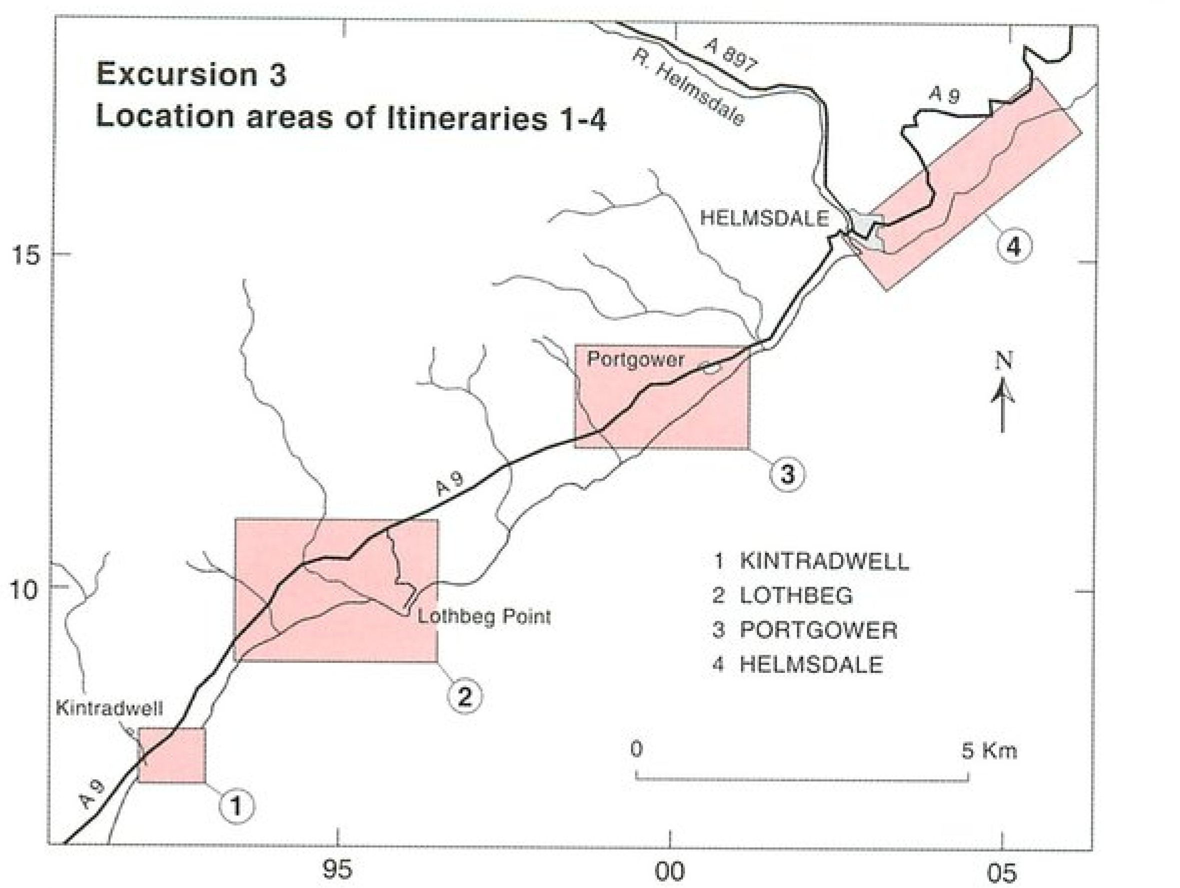
The Ord Burn forms a waterfall at the sharp transition from the Helmsdale Granite to the Helmsdale Fault zone. The fault zone is exposed in a NE-facing cliff adjacent to the burn and mostly comprises sheared granitic lithologies. This contrasts the situation in the Garbh Allt to the south of Helmsdale where a slice of ORS is present between the granite and the Jurassic strata. In general there is little evidence for ORS lithologies in the footwall of the fault to the NE of Helmsdale. However, in the raised beach cliffs to the SE of locality 8, some probable ORS conglomerates with rounded granitic clasts and arkosic sandstones are poorly exposed. Clearly, there are many lithologies of various ages incorporated as fault slices within the Helmsdale Fault zone.

Locality 9. Dun Glas [ND 058 172]

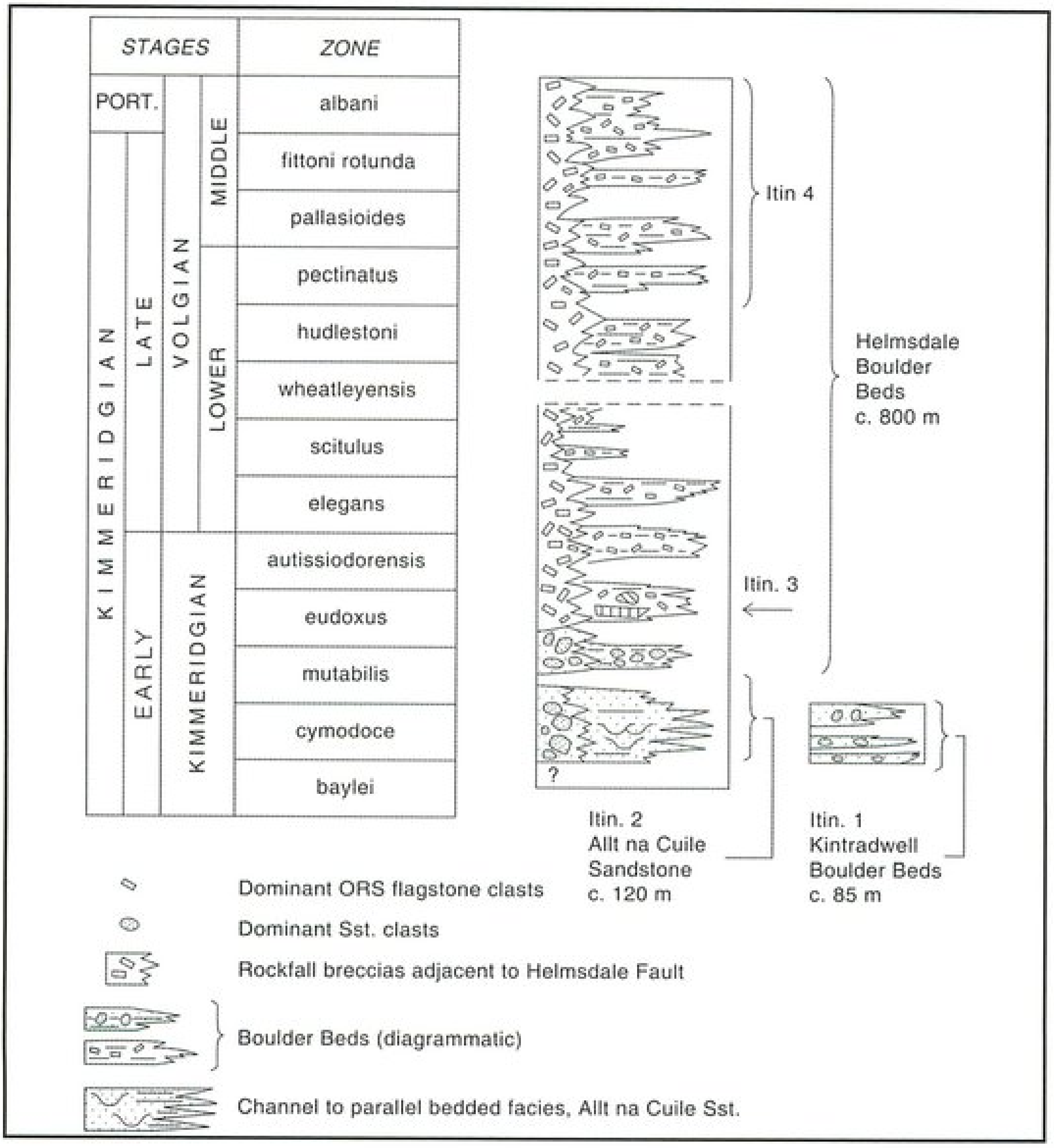
Spectacular cliff exposures of rockfall breccias dipping steeply to the SE are exposed here (Figure 3.27). The fault is not exposed but runs adjacent to the breccias. The steep south-easterly dip is partially due to drag effects during later movements on the fault. Note the variety of sandstone and flagstone clasts and the lack of inter-stratified mudstone.

Compound amalgamated breccia sequences are typical of a narrow zone lying immediately to the SE of the Helmsdale Fault. These breccias are the deposits of fossilised submarine fault-scarp talus slopes. The sequences of interstratified mud-stone, sandstone and boulder beds which are exposed at Portgower and Helmsdale were deposited further from the fault, where settling of suspended mud particles was the background sedimentation. Occasional catastrophic rock avalanches, debris flows and turbidity currents transported coarser-grained sediment into this deeper marine low-energy environment.

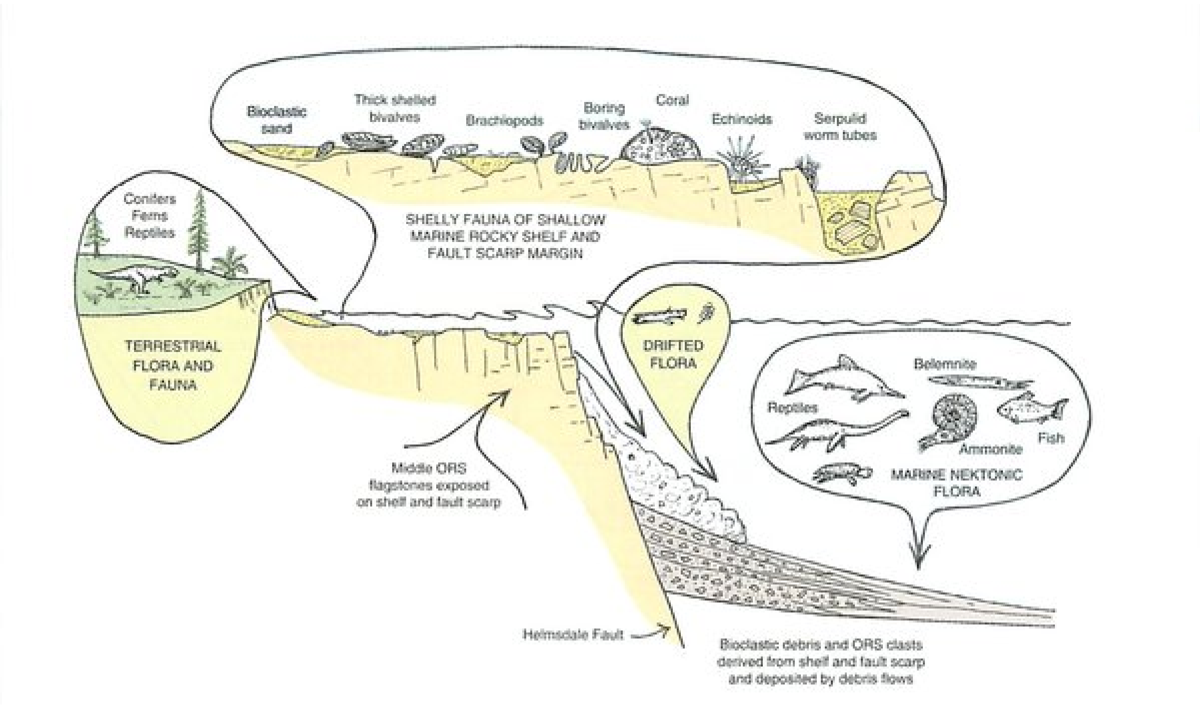
Dun Glas has a capping of glacial till. If one climbs to the col at the back of Dun Glas the line of the Helmsdale Fault can be seen at low tide in the shore reefs to the NE, where the fault passes out to sea.



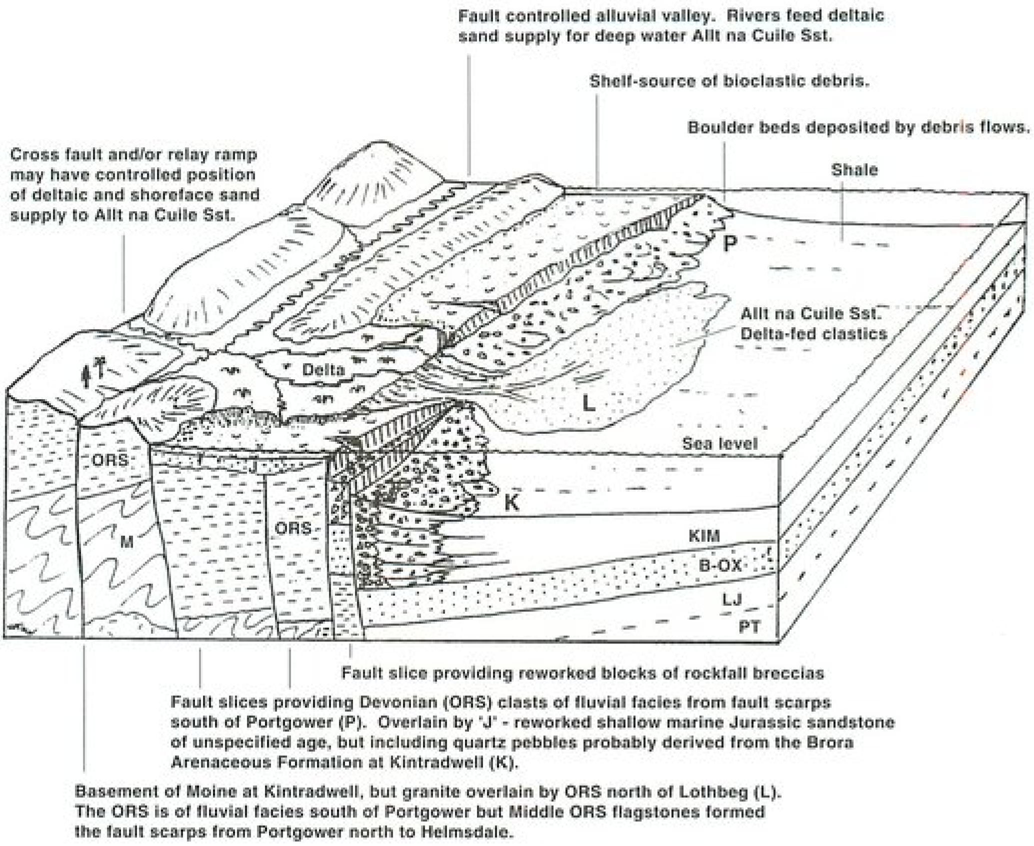
(Figure 3.1) Location areas of itineraries 1 to 4 of Excursion 3.



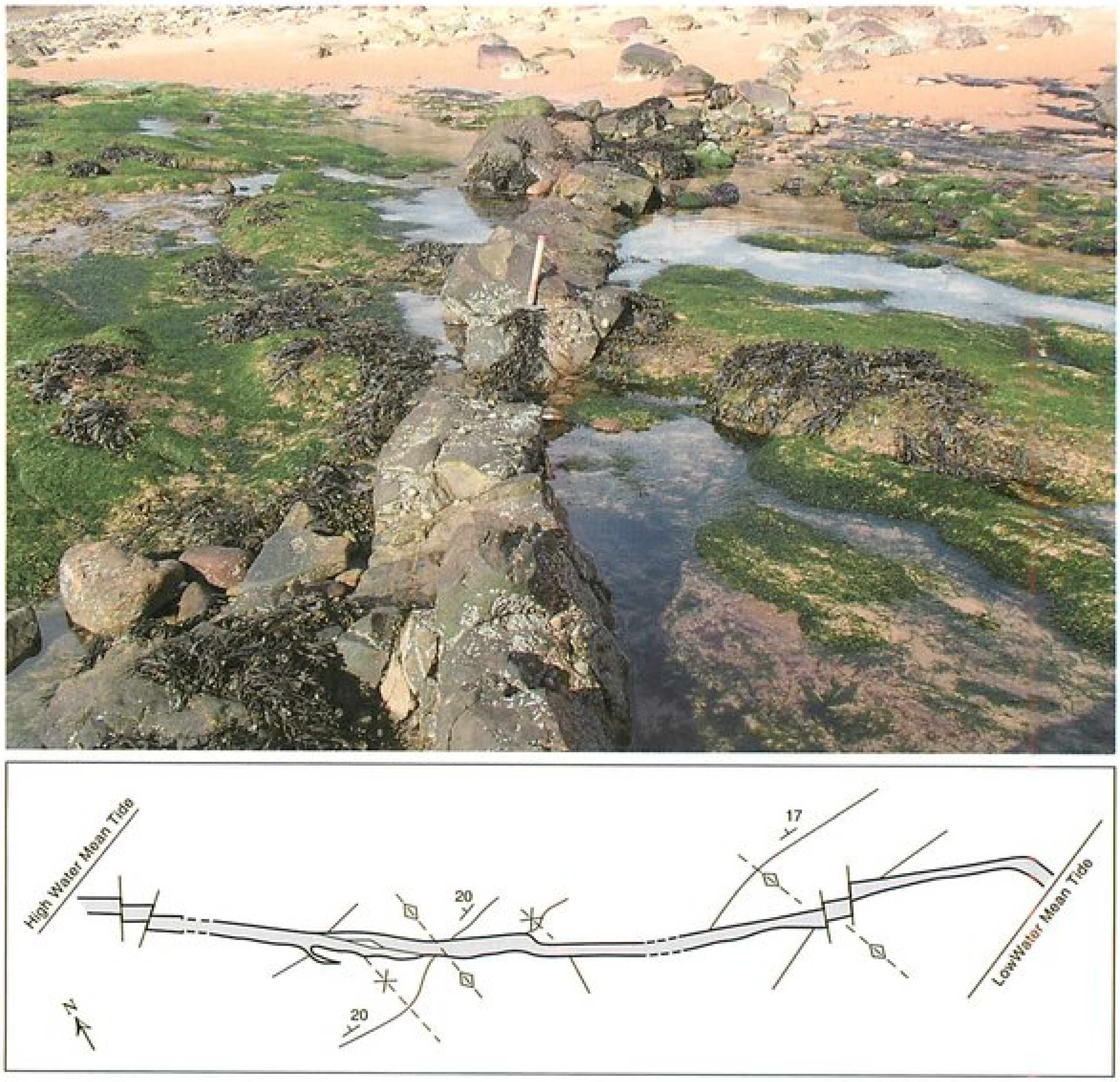
(Figure 3.2) Basic stratigraphy of the Kimmeridgian section with approximate stratigraphic positions of localities described in the excursion.



(Figure 3.3) Cartoon showing origin of fauna and flora associated with the Helmsdale Boulder Beds.

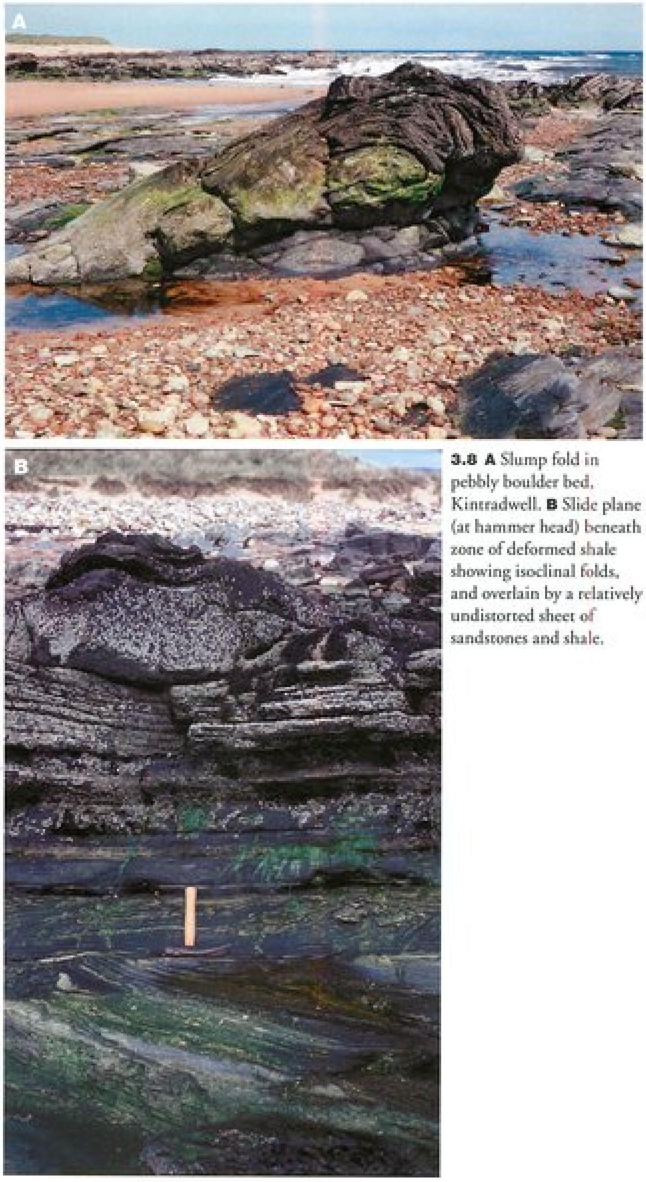


(Figure 3.4) Reconstruction of the Helmsdale Fault zone in the early Kimmeridgian to show factors associated with the derivation of the Kintradwell Boulder Beds and the Allt na Cuile Sandstone.



(Figure 3.6) Photo and sketch plan of the intrusive sandstone dyke, Kintradwell (plan modified from Jonk, 2003).

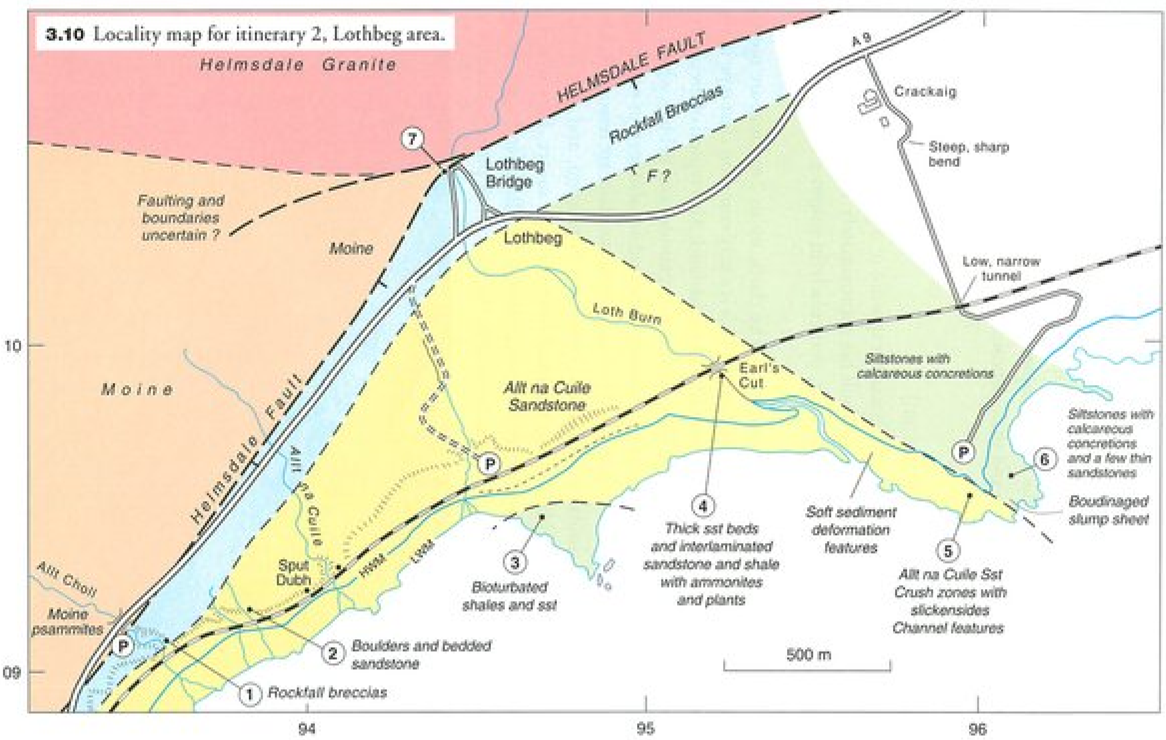
(Figure 3.7) Rounded quartzose pebbles and a belemnite in boulder bed, Kintradwell. Coin 28mm.



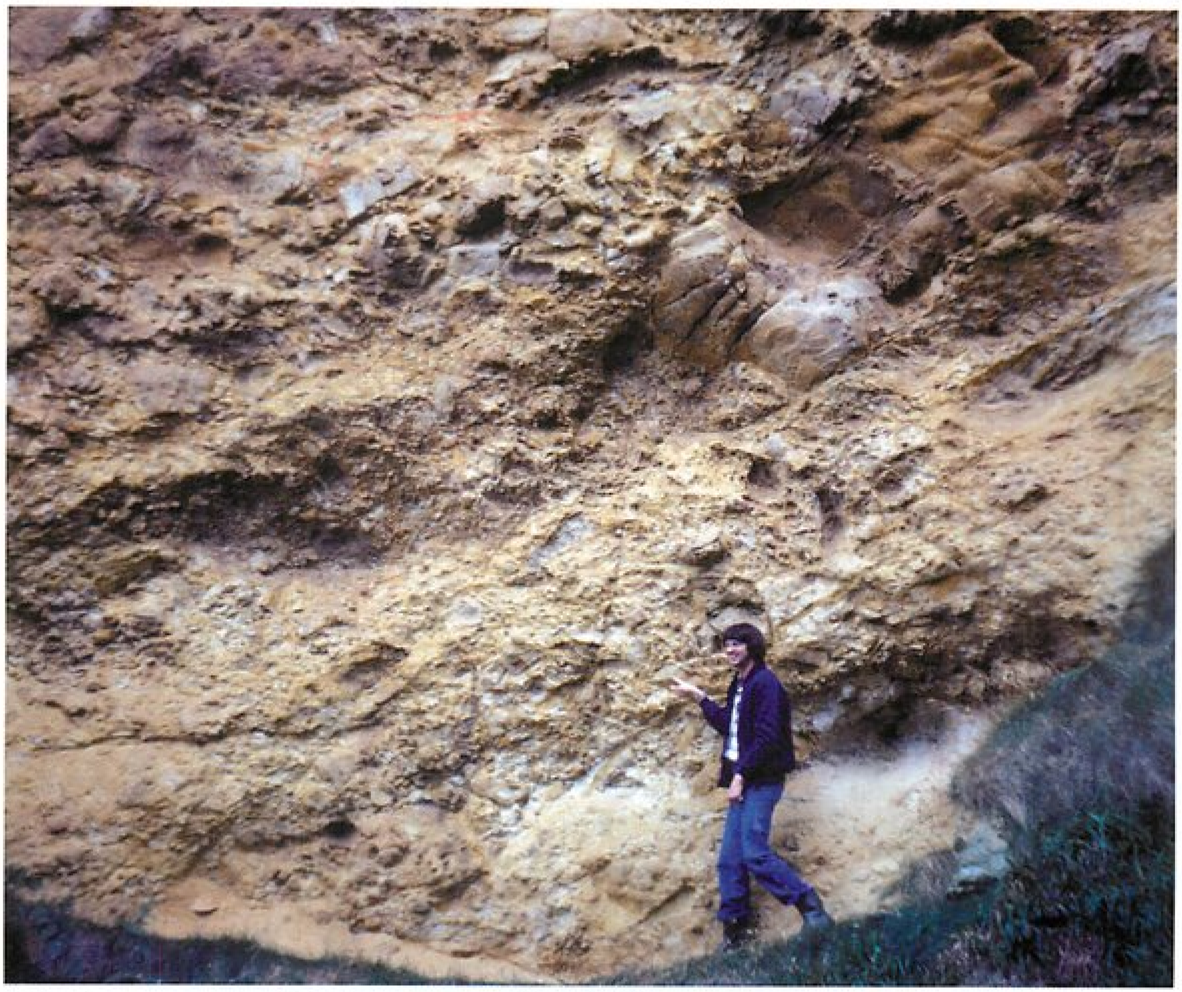
3.8 A Slump fold in pebbly boulder bed, Kintradwell. **B** Slide plane (at hammer head) beneath zone of deformed shale showing isoclinal folds, and overlain by a relatively undistorted sheet of sandstones and shale.

(Figure 3.8) A Slump fold in pebbly boulder bed, Kintradwell. B Slide plane (at hammer head) beneath zone of deformed shale showing isoclinal folds, and overlain by a relatively undistorted sheet of sandstones and shale.

(Figure 3.9) Sandstone clast showing in situ disintegration within boulder bed, Kintradwell.



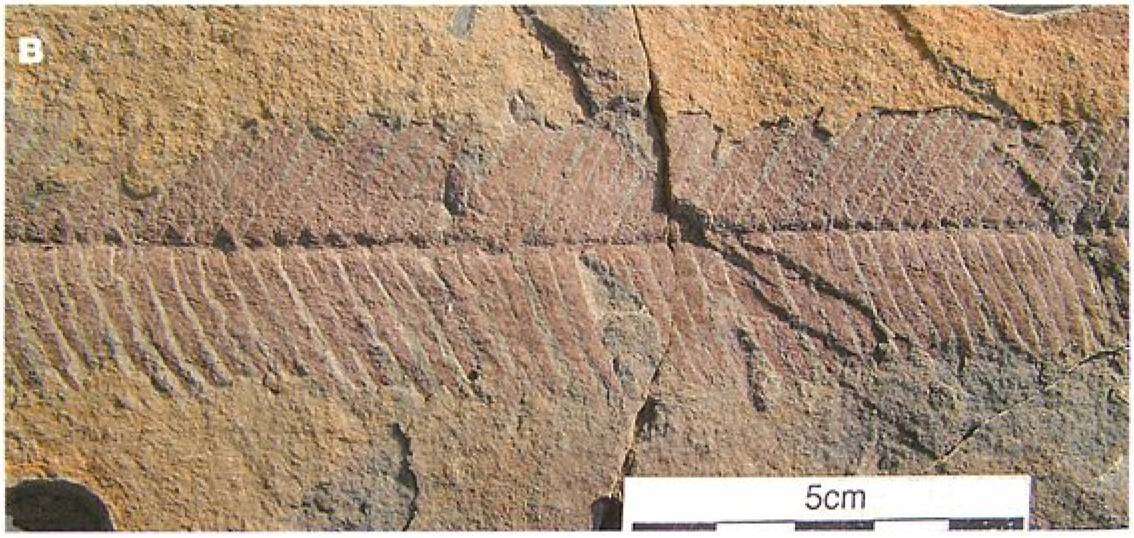
(Figure 3.10) Locality map for itinerary 2, Lothbeg area.



(Figure 3.11) Exposure of rock-fall breccias in Allt Choll.

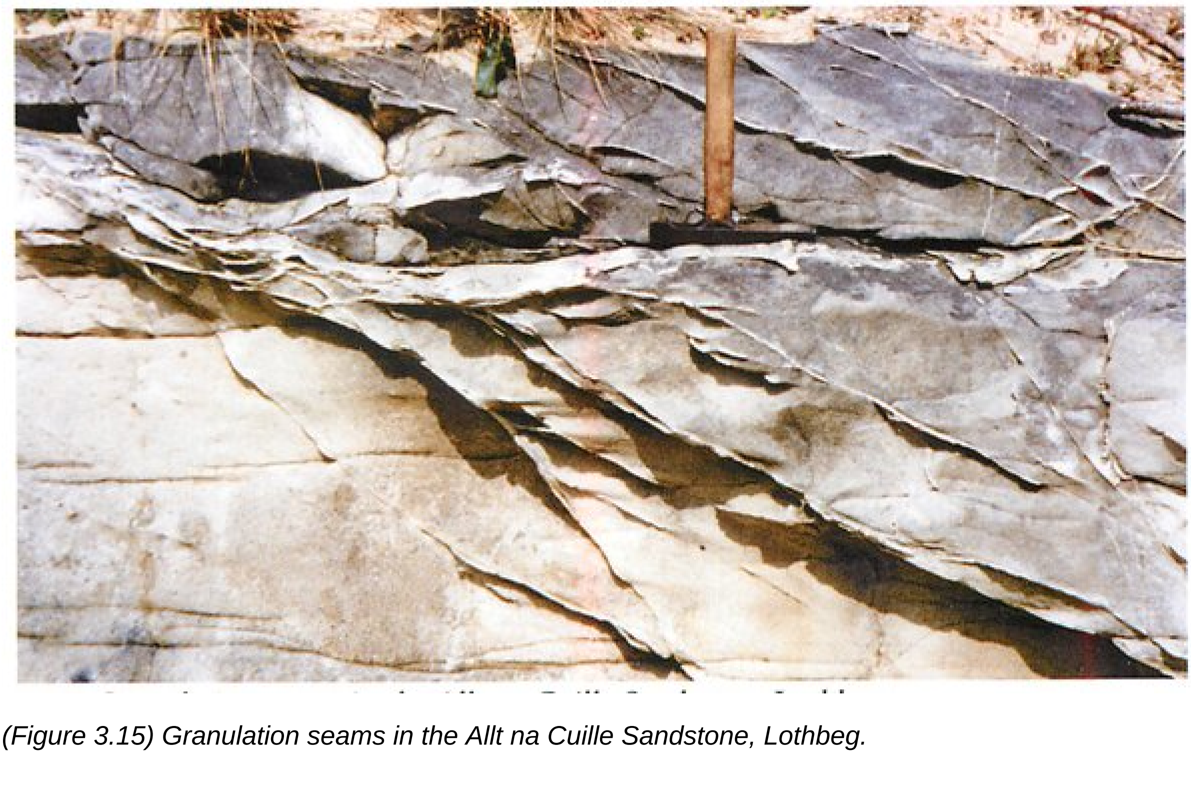
(Figure 3.12) Allt na Cuille sandstones and interbedded shales in cliff at the Earl's Cut, Lothbeg.

3.13 A Ammonite with tiny encrusting bivalves and an isolated fragment of *Gleichenites*. **B** Frond of cycad from carbonate concretion found loose on beach but probably derived from the mutabilis Zone shales.

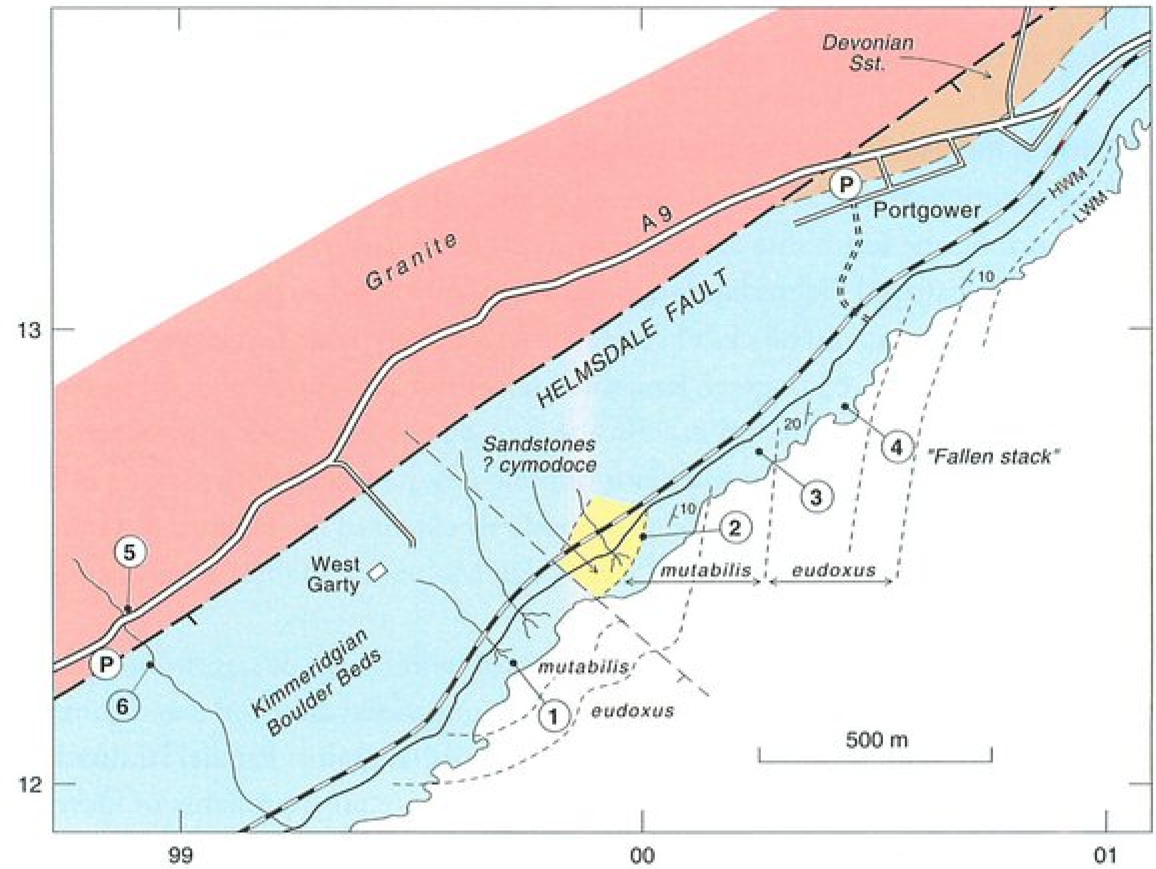


(Figure 3.13) A Ammonite with tiny encrusting bivalves and an isolated fragment of Gleichenites. B Frond of cycad from carbonate concretion found loose on beach but probably derived from the mutabilis Zone shales.

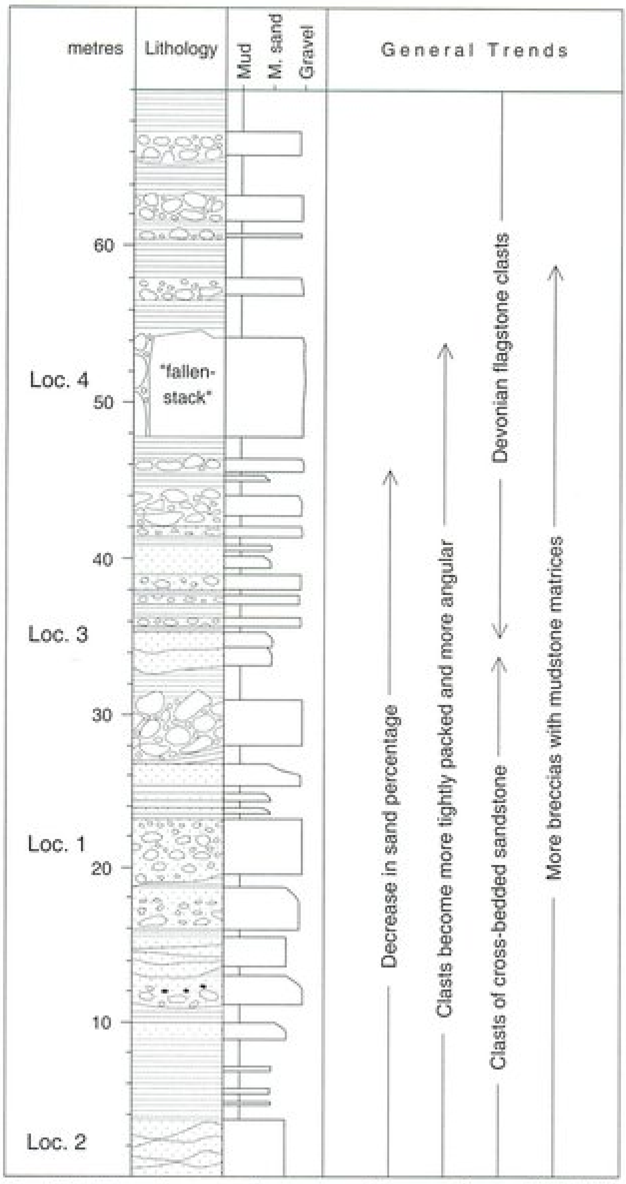
(Figure 3.14) Features in Allt na Cuille Sandstone caused by fluidisation and injection of sand. Shore between localities 4 and 5, Lothbeg.



(Figure 3.15) Granulation seams in the Allt na Cuille Sandstone, Lothbeg.

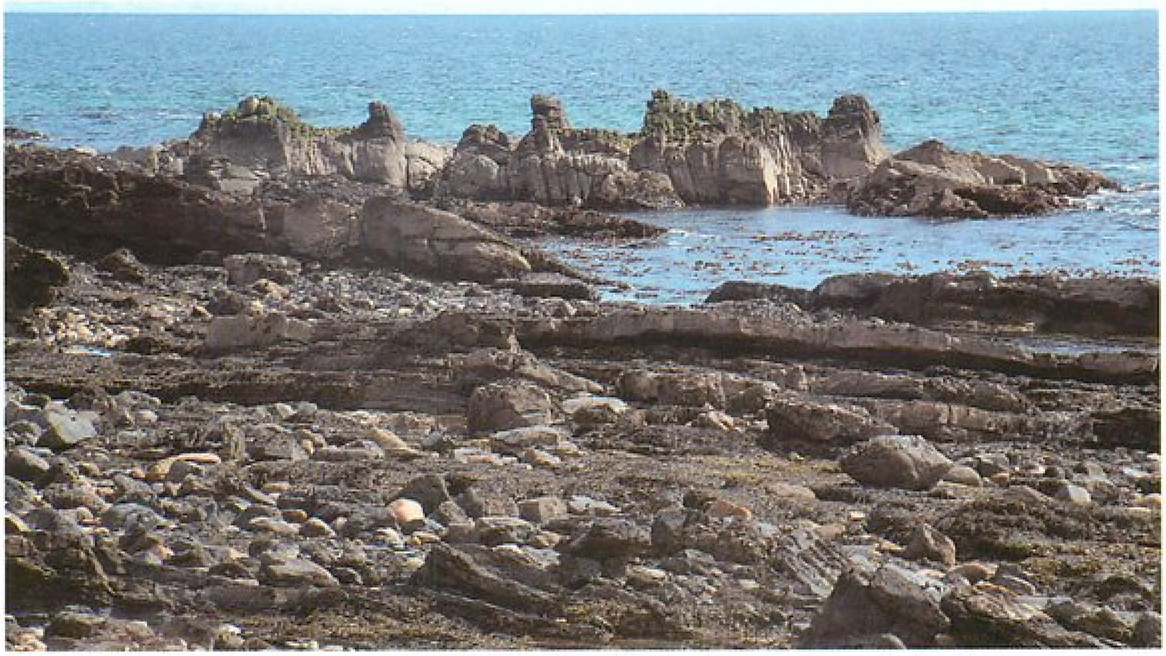


(Figure 3.16) Locality map for itinerary 3, Portgower.

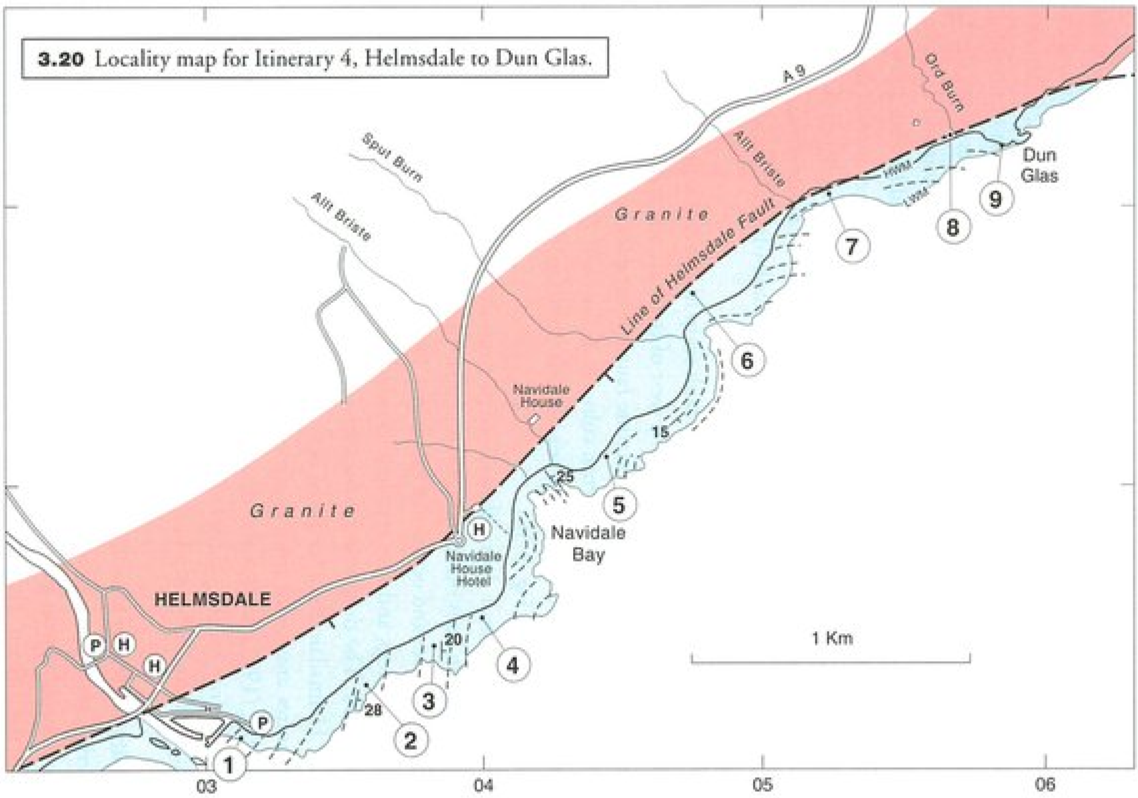


(Figure 3.17) Log of boulder bed section near Portgower with general trends in lithology and clast types (adapted from MacDonald (1985)).

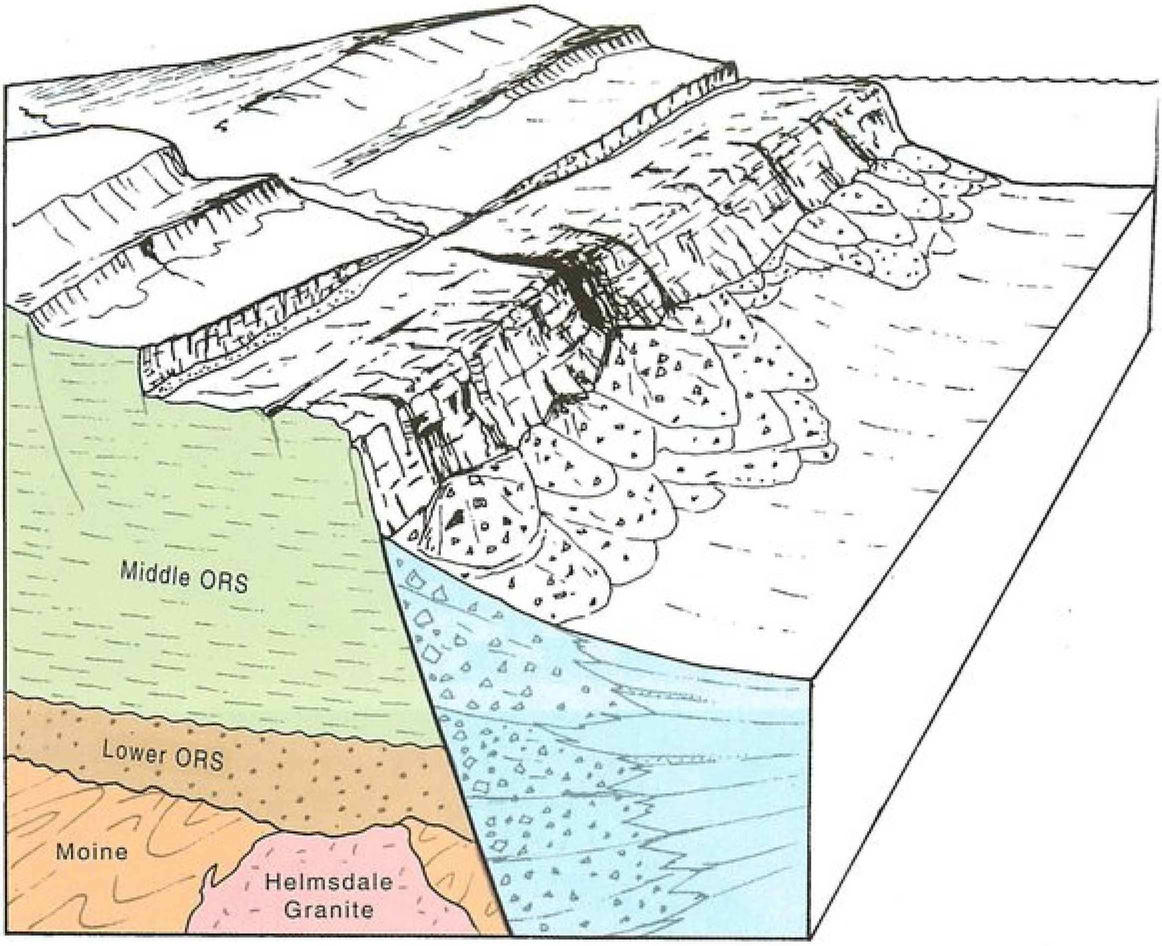
(Figure 3.18) Cross-bedding in sandstone clast within boulder bed near Locality 1, Portgower, lens cap 52 mm



(Figure 3.19) The giant clast known as the 'Fallen Stack' showing near-vertical bedding; strata in foreground show general shallow easterly dip of shales and sandy boulder beds.



(Figure 3.20) Locality map for Itinerary 4, Helmsdale to Dun Glas.



(Figure 3.21) Reconstruction of the Helmsdale Fault zone in the late Kimmeridgian at the time of deposition of the Helmsdale Boulder Beds.

(Figure 3.22) Typical texture of Helmsdale Boulder Beds with Middle ORS flagstone clasts in a bioclastic matrix, locality 1, Helmsdale.

(Figure 3.23) Limestone clast in the Helmsdale Boulder Beds at locality 1 bored by the bivalve Lithophaga, together with example showing the shape of the bivalve crypt.

(Figure 3.24) Example of a boulder bed that wedges out rapidly away from the Helmsdale Fault, Helmsdale shore.

(Figure 3.25) Colony, 25 mm across, of the coral Isastraea from the boulder beds at Helmsdale. The colony was swept into deep water from its living position on a shallow shelf. It may have grown attached to rock on the shelf edge.

(Figure 3.26) View of Dun Glas from SW of the end of Allt Briste. The Helmsdale Fault is exposed on the beach below the granite buttress at the left of the picture, and passes through the col at the back of Dun Glas.

(Figure 3.27) Inclined rockfall breccia of Middle ORS flagstone clasts at Dun Glas, locality 9, Helmsdale excursion.