Lugar, East Ayrshire

[NS 599 216]–[NS 601 213]

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Introduction

It is widely held that many of the alkaline basic sills and sill-complexes in the west of Scotland are probably comagmatic with the Early Permian Mauchline Volcanic Formation (see Howford Bridge GCR site report). Almost all the sills are olivine-bearing doleritic rock-types. Some are thick, differentiated, composite bodies showing a layering attributed to a variety of magmatic processes such as gravitational settling and upward volatile enrichment, elutriation (flow differentiation) and multiple intrusion.

A classic, textbook example of just such an intrusion is the Lugar Sill in the south-west of the Midland Valley. It is exposed in the valley of the Lugar and Glenmuir waters (Figure 5.12) and takes its name from the nearby village of Lugar, 3 km north-east of Cumnock. Historically this sill has played a very important role in developing the concept and mechanisms of magmatic differentiation and is regularly visited for the purposes of education and research. A field excursion was described by Weedon and Mykura (in Lawson and Weedon, 1992).

Although much of our knowledge of this sill is due to the early work of G.W. Tyrrell, his descriptions and interpretations were not the first published accounts. In a paper dealing with the classification of post-Carboniferous intrusions in the west of Scotland (Tyrrell, 1909a), he presented an outline of the Lugar Sill, but fully acknowledged the '...valuable and comprehensive paper on the Lugar intrusions...' by Boyle (1908). The petrography and field relationships of the sill, based upon the Glenmuir Water section, were described by Tyrrell (1917b), and his later papers (1948, 1952) concentrated upon nearby boreholes at Mortonmuir and Craigston House respectively. Tyrrell's work was augmented by the Geological Survey memoir (Eyles *et al.,* 1949), and later mineralogical and geochemical studies by Phillips (1968) and Henderson and Gibb (1987) have resulted in more refined models for the petrogenesis of the sill. Radiometric dates obtained by De Souza (1979) and Henderson *et al.* (1987) suggest an earliest Permian age.

Description

The Lugar Sill comprises two principal lithological units. Marginal analcime-dolerites (formerly termed 'teschenites') are separated by a central thick composite unit of nepheline-dolerite, kaer-sutite nepheline-dolerite and picrite (formerly termed 'theralites'). In detail, the analcime-dolerites are made up of a number of separate intrusions or magmatic pulses. Henderson and Gibb (1987) recognized four such pulses in each of the upper and lower units that form 'mirror images' on either side of the central unit, which was emplaced later as a single pulse. Hence the full composite section comprises nine units, which represent at least five separate intrusive pulses. Later differentiates cut all of these units.

The stream section

The best natural section is afforded by steep cliffs in the Glenmuir Water (Figure 5.13), which cuts through the sill between [NS 6006 2134] and the confluence with the Bellow Water at [NS 5988 2152]. After this confluence, the stream is known as the 'Lugar Water'. Most units of the sill are exposed here and, although access is difficult in places, boulders in the stream bed provide excellent examples of most lithologies. The sill is here about 43 m thick and intrudes arenaceous strata of the Namurian Passage Formation, which dip regionally to the west or NNW at about 10°. The details of the Glenmuir Water section given by Tyrrell (1917b) remain the most comprehensive. They are not repeated here and should be consulted for specific locations. The following short descriptions are mainly taken from Weedon and Mykura (in Lawson and Weedon, 1992).

The basal contact of the sill, which is chilled against pale baked sandstone, is seen in the bed of the stream at [NS 6006 2134]. The basal facies of the sill is some 3 m thick and comprises basalt and analcime-dolerite with numerous layers of differing texture and colour, but there appears to be an upward gradation into more granular analcime-dolerite.

Downstream, to the north-west, this is followed up the sequence by peridotite and picrite, which form extensive, but deeply weathered cliff exposures, mostly on the outer bends of the stream (Figure 5.13) down to the disused railway viaduct [NS 5991 2142]. No contact between the dolerite and the ultramafic facies is visible. North-west of the viaduct, the picrite is in contact with a dark-grey nepheline-dolerite. Neither the top nor the base of the nepheline-dolerite is well exposed. The lower part contains abundant amphibole (kaersutite) and is slightly coarser grained. The upper part is veined by a paler analcime-bearing variety. The contact with the overlying analcime-dolerite is not visible here, though elsewhere it is known to be sharp and chilled.

The upper marginal facies of the sill is, like the base, an analcime-dolerite or gabbro. Both medium- and coarse-grained varieties are exposed downstream from the viaduct and the upper contact with white thermally altered sandstones is exposed on the south bank of the stream, where it is joined by the Bellow Water to become the Lugar Water [NS 5986 2151].

This section is also the type locality for an unusual rock-type. This is a kaersutite- and/or augite-rich nepheline-gabbro or nephelinolite that has been termed 'lugarite'. In hand specimen it can be very striking as it is essentially a coarse-grained pegmatitic rock (Figure 5.14). It is exposed in the west bank of the Glenmuir Water 15 m north of the viaduct, close to the picrite–nepheline-dolerite contact, where it occurs as segregation patches up to 1.2 m thick. It also occurs as irregular, anastomosing veins, 2–12 cm wide, which cut the picrite.

Boreholes

Most of the detailed descriptions and interpretations of the Lugar Sill are based on the examination of borehole core. To date, three holes have specifically intersected the sill (Figure 5.12). These are at Mortonmuir [NS 5984 2337] (Tyrrell, 1948), Craigston House [NS 5908 2130] (Tyrrell, 1952) and Lugar Water [NS 5990 2150] (Henderson and Gibb, 1987). There is overall internal consistency between the boreholes in both the relative positions and the thickness of the majority of lithologies (Figure 5.15). However, they show that the sill has a much more complex internal structure than is revealed by the natural exposures alone. In detail, there are clear differences within the nepheline-dolerite facies and in the presence and position of lugarites (kaersutite-augite-rich nepheline-gabbro).

The Lugar Water Borehole, detailed by Henderson and Gibb (1987), was located at the junction of the Glenmuir and Bellow waters and hence the section closely resembles and significantly augments the natural section. Important additional details seen in the borehole core concern the complexity and nature of the internal contact relationships. The thicknesses of the upper and lower marginal analcime-dolerites are 4.45 m and 8.90 m respectively. Each comprises several distinct units of layered analcime-dolerite, which show chilled internal contacts with one another. Superimposed upon an overall inward-coarsening profile through the analcime-dolerites, these smaller units also coarsen individually into the sill. The 35.5 m-thick central part of the sill comprises a complex unit of nepheline-dolerite and picrite. The upper part of this consists of 2.25 m of relatively fine-grained nepheline-dolerite, which has a sharp, chilled contact with the overlying analcime-dolerite. Below, but gradational into the nepheline-dolerite, is a substantial unit of kaersutite nepheline-dolerite that extends downwards for a further 13 m or so. With a downward increase in olivine and a concomitant decrease in kaersutite, this passes into picrite. The picrite unit is about 20 m thick. The lower few metres, though showing mineralogical changes and a slight downward decrease in grain size, are not chilled like the top of the central unit. Lugarite is present as four thin units interbedded within the upper part of the kaersutite nepheline-dolerite unit. These comprise both kaersutite- and kaersutite-augite-rich variants and each has a sharp contact with adjacent rock. They occur in the same position within the sill as in the exposed stream sections. Pink aplitic veins (probably microsyenitic) cut all the analcime-dolerite units.

The profiles of the other boreholes illustrate an apparent slight increase in overall thickness eastwards, from Craigston House (44.7 m), through Lugar (50.2 m; cf. Tyrrell's field estimate of 42.7 m) to Mortonmuir (51.4 m). These are considered real, but in part they could also be attributed to the effects of varying dip. There are thickness changes in some of the units, for example the lower analcime-dolerites also thicken eastwards. The principal contrasts in lithology between the Lugar Water and Mortonmuir bore-holes are seen in the relationship between the nepheline-dolerite and its kaersutite-bearing variant. In both boreholes these dolerites have similar thicknesses, but in the Mortonmuir Borehole, there are two kaersutite-bearing units and their total thickness is considerably less than at Lugar Water. Also, there are no lugarites in the Craigston House section as opposed to the complex multiple unit at Lugar and the three at Mortonmuir; at the latter, the upper two units are augite-rich varieties and the lower unit is a 'normal' kaersutite-augite-rich variety.

Internal variations in mineralogy and geochemistry

The gross petrographical variation from top to base through the Lugar Sill is, not surprisingly, mirrored by variations in both mineralogy and whole-rock geochemistry. These systematic variations have been documented comprehensively by Henderson and Gibb (1987). The following summarizes some of the essential points of their study.

The mineral compositions reflect an overall evolutionary trend from picrite, through kaersu-tite nepheline-dolerite and nepheline-dolerite to the kaersutite-augite-rich nephelinolite (lugarite) in the thick, central part of the sill. The earlier, marginal analcime-dolerites are even more evolved. The mafic phases (olivine, clinopyroxene, kaersutite and biotite) are compositionally zoned and, generally, all show maximum magnesium content within the picrite and kaersutite nepheline-dolerite of the central unit. Biotite and amphibole compositions show markedly symmetrical distribution patterns throughout the sill, becoming less magnesian towards both upper and lower margins (Henderson and Gibb, 1987, fig. 4). The main feldspar in the sill is a zoned plagioclase. The range of zoning, from anorthite-rich (*c.* $An_{70–80}$) to orthoclase-rich (*c.* Or_{42}) compositions, is considerable, but similar, in the marginal layered analcime-dolerites, the kaersutite nepheline-dolerite and the lower parts of the picritic unit. There is a much more restricted range in the rest of the picritic unit. Alkali feldspar occurs in the more marginal units (Henderson and Gibb, 1987, fig. 8) and it is likely that primary nepheline was originally present in all lithologies.

Alteration of both mafic and felsic minerals is common. Olivines are typically pseudomorphed by serpentine minerals, especially in the analcime-dolerites, and the feldspars, nepheline and interstitial areas are converted to analcime, zeolite and chlorite associations. Pyroxenes are generally unaffected, except in the lower analcime-dolerites.

The general pattern of variation in whole-rock chemistry with position in the sill is fairly symmetrical for most elements, with the marginal analcime-dolerites having the most extreme values (Henderson and Gibb, 1987, fig. 11; (Figure 5.16)). The main control over the major element trends is the variation in modal olivine during the early fractionation, with clinopyroxene controlling formation of the analcime-dolerite and later differentiates. The highest MgO contents occur near the middle of the central picrite-nepheline-dolerite unit, with progressive decreases in concentration from the centre outwards. The total Fe (FeO + Fe_2O_3) trend closely parallels this but the other major element trends are antipathetic to the MgO trend, i.e. with lowest concentrations in the middle of the picrite-nepheline-dolerite unit and increasing outwards. The lugarites have evolved compositions with low MgO and CaO and high Al_2O_3 and Na_2O values. These, the last-intruded rocks, represent a late-stage liquid. However, the most evolved compositions, in terms of major-element chemistry, are the first-intruded, upper and lower marginal analcime-dolerites.

The variation patterns for Ni and Cr in the central unit are also controlled by the olivine and chrome-spinel inclusions within the olivine and hence follow the MgO trend. Other trace elements, for example Zr, Sr, Rb, Ba, Nb, La, Ce and Nd, show patterns similar to that of Al_2O_3 (i.e. antithetic to the MgO trend; (Figure 5.16)). There are discontinuities and some complications in the marginal facies, but overall, these incompatible elements increase towards the margins of the sill. Since Sr, Ba and Rb contents are normally controlled by feldspar composition and distribution, their incompatible behaviour suggests that feldspar played only a subordinate role during fractionation (Henderson and Gibb, 1987).

Age

Henderson *et al.* (1987) presented a new Ar-Ar plateau age of 288 ± 6 Ma for a kaersutite separated from the main picrite–nepheline-dolerite unit of the Lugar Sill. This age is preferred to the 'total gas' ages in the same study. These gave a result of 292 ± 7 Ma, which is broadly in agreement with the earlier K-Ar determinations, on kaersutite from a 'lugarite' vein, by De Souza (1979), which yielded ages of 297 ± 7 Ma (as recalculated by Wallis, 1989). The preferred age is Early Permian, but very close to the Carboniferous–Permian boundary.

Interpretation

The Lugar Sill is a complex, multiple intrusion that has contributed significantly to theories of magma evolution and emplacement over the past century. The following summary is based largely upon the most recent petrogenetic model of Henderson and Gibb (1987), who also include a comprehensive review of earlier models.

It has long been supposed that the lithologies that make up the Lugar Sill were all derived from a common parent. This is reasoned to have been a primary, relatively alkali-rich, picritic magma, likely to have originated in the upper mantle. It rose through the crust before fractionating in a low-level magma chamber. Here, gravitational settling of olivine, accompanied by ascent of the lower density residual melt, produced a vertically stratified column, with the denser, more mafic and therefore less-fractionated magmas, towards the bottom.

The earliest intrusion was formed when the more-fractionated magmas, towards the top of the chamber, were evacuated in a series of pulses. These had an analcime-dolerite composition. A final larger pulse emplaced the less-fractionated olivine-rich magma from deeper in the chamber to form the picrite–nepheline-dolerite unit. This has regionally transgressive margins in contact with the analcime-dolerites, the top margin being notably chilled, but has gradational internal contacts. The proportion of suspended olivine crystals increased during emplacement, as the magma chamber was purged of progressively more olivine-rich magma, so that the central part of the unit, the last to be emplaced, is the most olivine-rich. Thus, in simple terms, the profile of the sill was formed in sequence from more evolved analcime-dolerite, through nepheline-dolerite, to less evolved picrite.

Differentiation then continued *in situ* with gravitational settling and equilibration of the olivine crystals that were suspended in a liquid phase of nepheline-dolerite composition. This later settling explains the zonation of the unit from nepheline-dolerite to picrite and the fact that the greatest concentration of magnesium-rich olivines in the sill occurs just below the middle part of the central unit.

The segregations and veins of lugarite (kaersutite-augite-rich nepheline-gabbro or nephelinolite) were interpreted by Henderson and Gibb (1987) as auto-intruded, late-stage fractionation products of the central unit, involving in-situ differentiation and upward enrichment in residual liquid and volatiles. The aplitic veins cutting the analcime-dolerites were similarly interpreted as late-stage, in-situ differentiation products from the earlier analcime-dolerite magma.

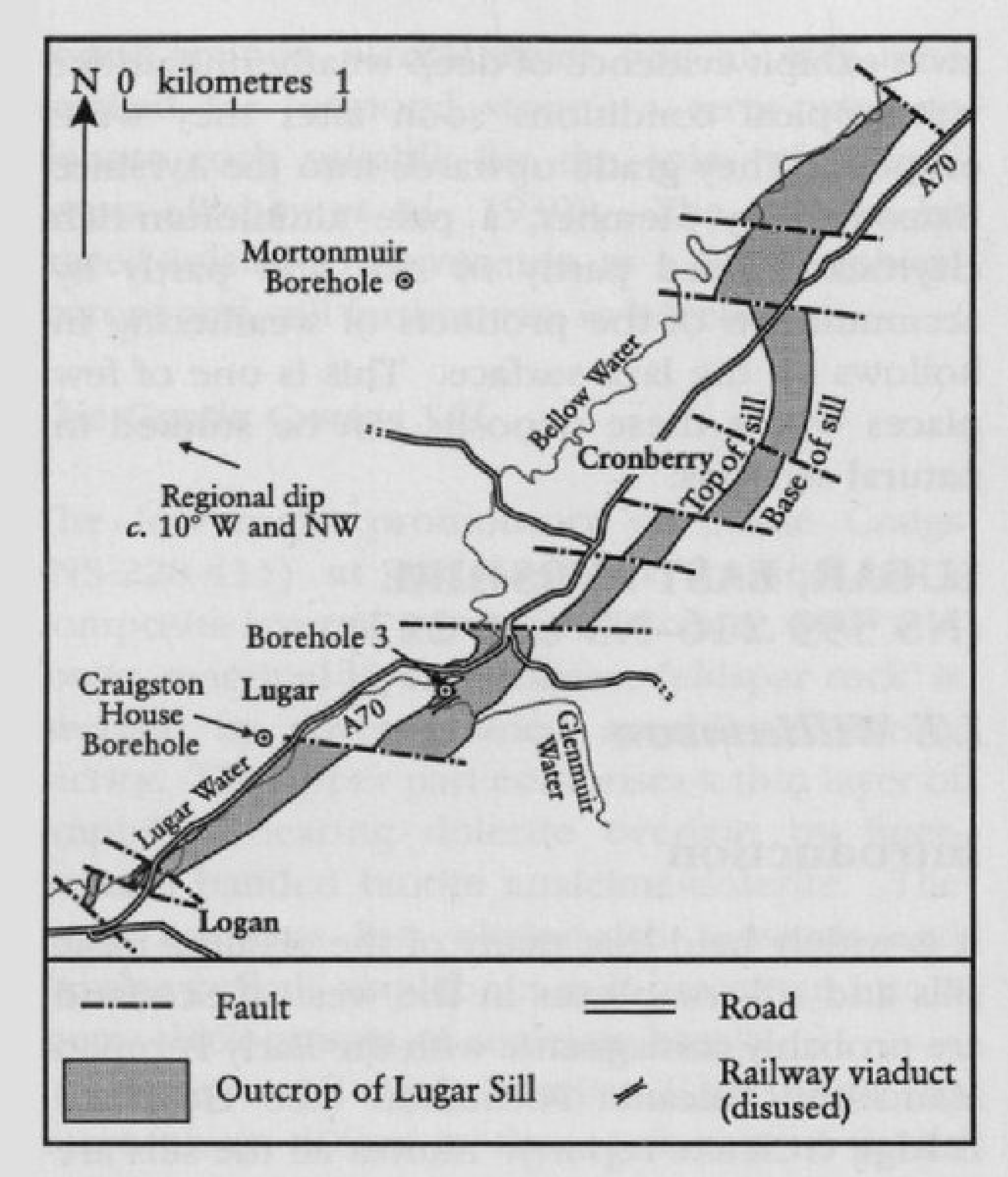
Post-magmatic alteration is common across the entire sill. However, this phenomenon is most prominent and pervasive within the lowermost units. Henderson and Gibb (1987) suggested that circulating, super-heated groundwater below the sill may have accounted for this.

Conclusions

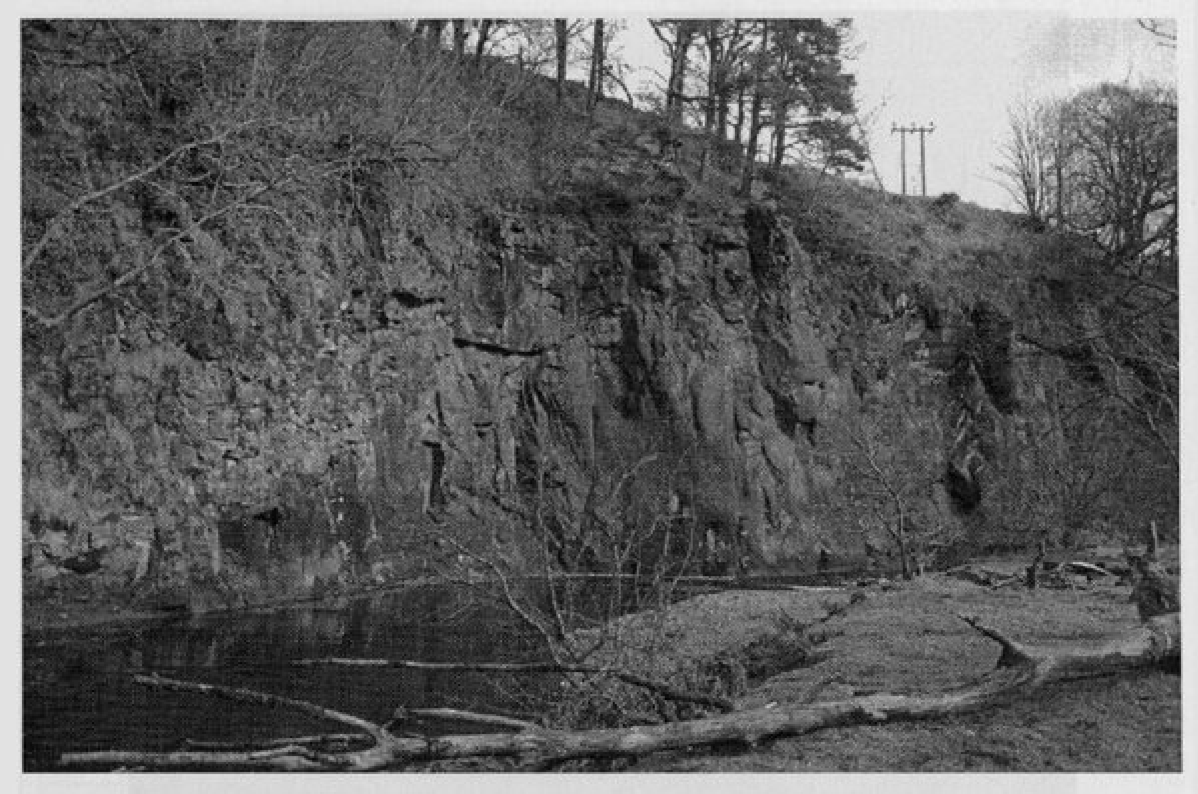
The Lugar Sill has a long-standing, international reputation as an example of a composite, differentiated, basic alkaline intrusion and is frequently visited for both teaching and research purposes.

It was probably emplaced in very early Permian time as a series of pulses of magma from a compositionally stratified magma chamber situated deep in the Earth's crust, below the final level of the sill. The more evolved, less dense magmas residing at the top of the magma chamber were the first to be evacuated, followed by successive pulses from sequentially deeper levels and hence more mafic magmas. The first phase of sill formation involved the intrusion of progressively less evolved analcime-dolerite magmas. This phase was then followed by the intrusion, into this early sill, of a large-volume pulse of olivine-rich nepheline-dolerite magma. Continued crystallization and settling of crystals *in situ* and an upward enrichment in residual liquids and gases subsequently gave rise to an unusual rock-type, a spectacular nepheline-gabbro with large crystals of pyroxene and amphibole. This has been given the local name of lugarite', from this, the type locality.

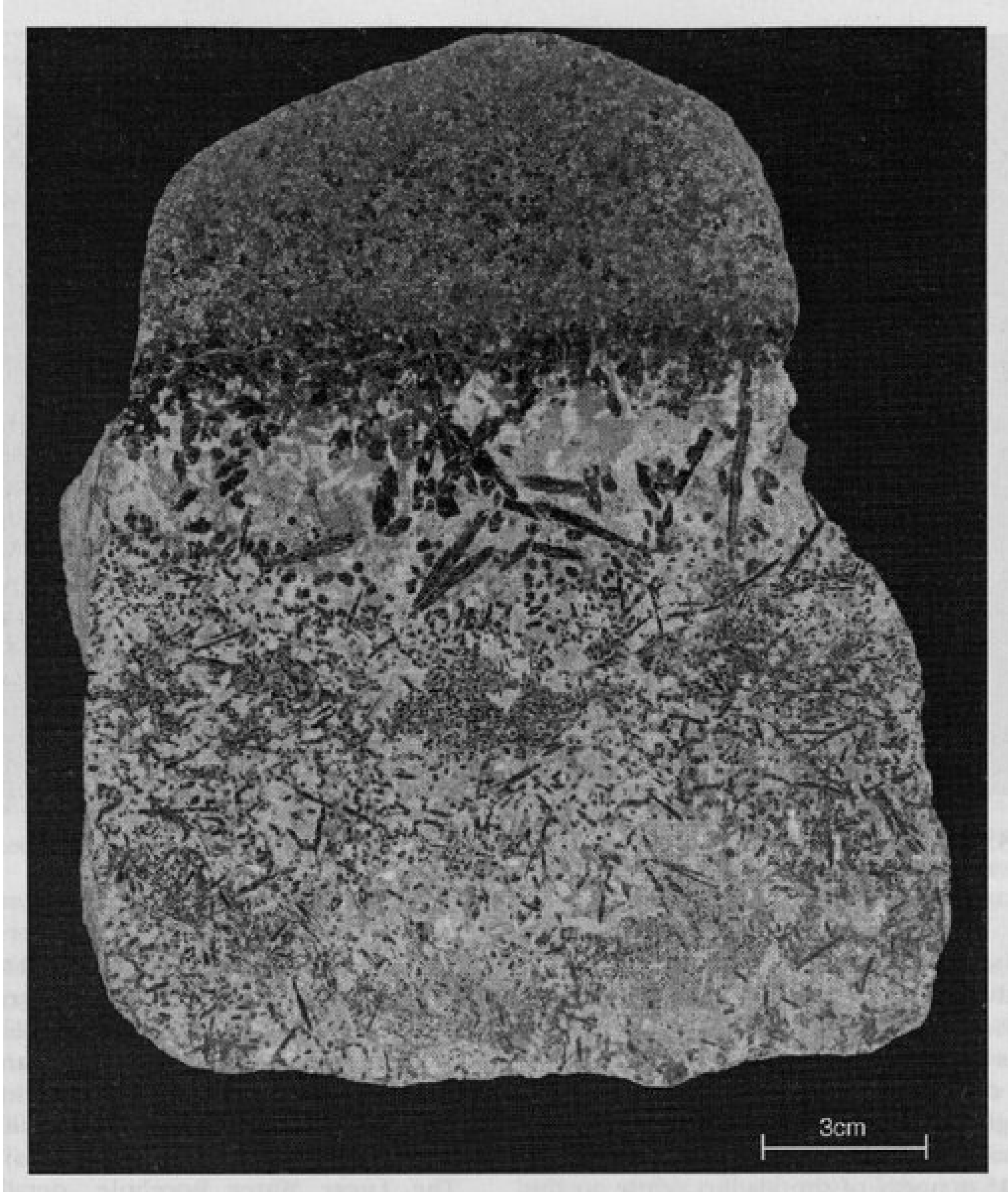
References



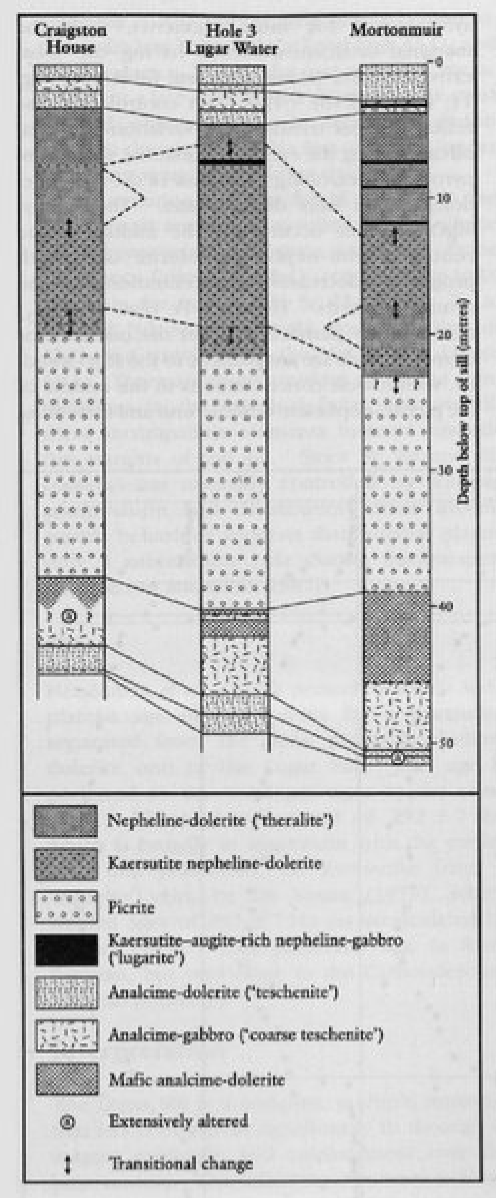
(Figure 5.12) Map showing the outcrop of the Lugar Sill and the locations of boreholes through the sill. After Henderson and Gibb (1987).



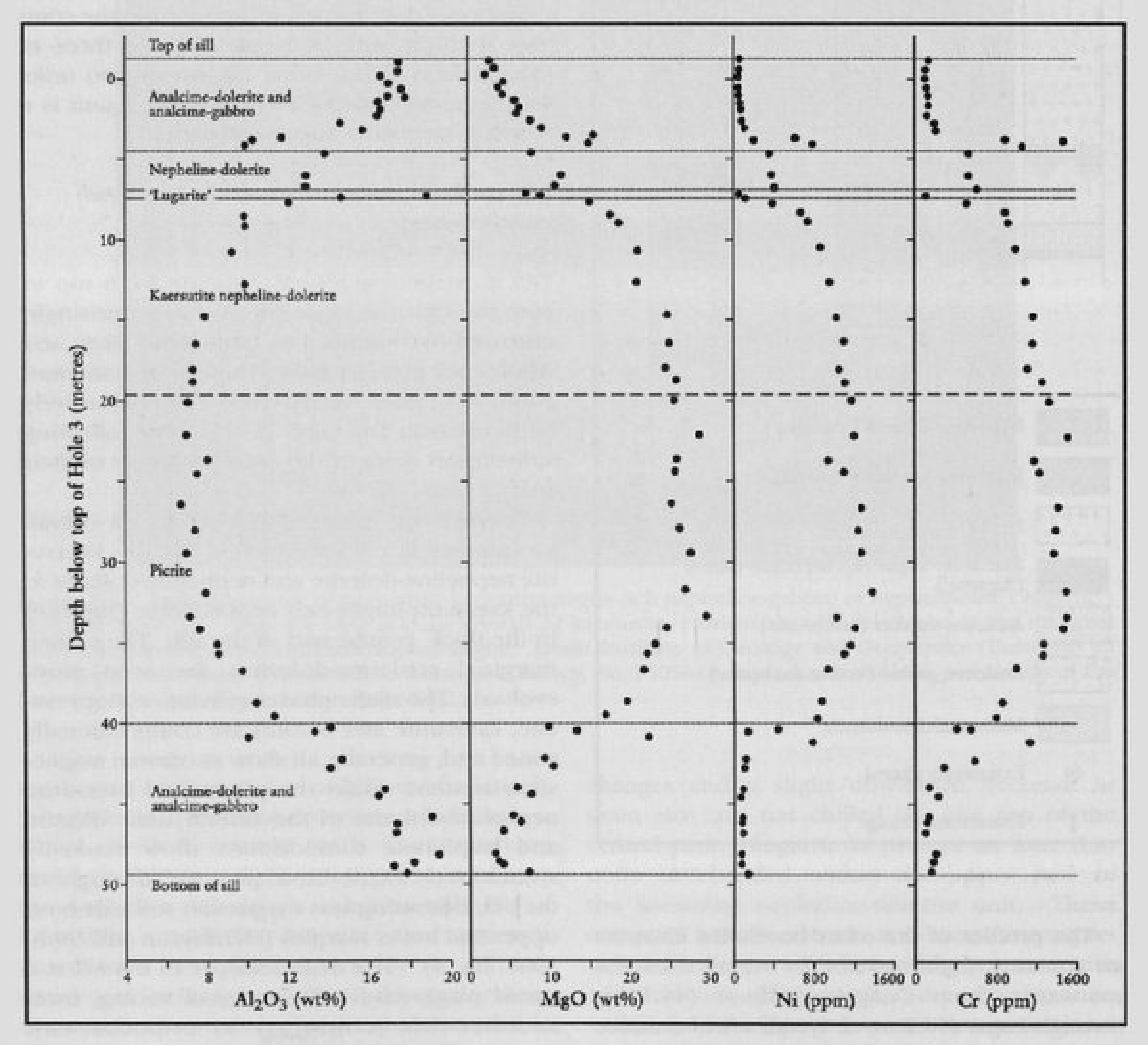
(Figure 5.13) Cliff exposures of the picritic central part of the Lugar Sill in the Glenmuir Water, upstream from the railway viaduct, Lugar GCR site. (Photo: K.M. Goodenough.)



(Figure 5.14) Polished sample of pegmatitic kaersutite-augite-rich nepheline-gabbro or nephelinolite ('lugarite) from the Lugar Sill. Note the long acicular crystals of kaersutite, particularly well developed in the marginal zone, and smaller, more equidimensional augite. Grant Institute of Geology and Geophysics (University of Edinburgh) collection. (Photo: British Geological Survey, No. P505645, reproduced with the permission of the Director, British Geological Survey, © NERC.)



(Figure 5.15) Correlation of borehole sections through the Lugar Sill. After Henderson and Gibb (1987). See (Figure 5.12) for locations.



(Figure 5.16) Variations of key major and trace elements in a vertical section through the Lugar Sill (Borehole 3). After Henderson and Gibb (1987). See text for details.