Water Swallows Quarry, Derbyshire

[SK 084 750]

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Introduction

Water Swallows Quarry, now disused, about 3 km to the north-east of Buxton (Figure 7.3), has been selected as an excellent exposure of a thick olivine-dolerite sill, with spectacular examples of columnar cooling joints. The site is significant in that the Water Swallows Sill is seen to intrude the Lower Miller's Dale Lava, which is Visean in age, whereas the sill has been dated radiometrically to be around 10 Ma younger, of Namurian age (Figure 7.2). Numerous descriptions of the site have been published, notably on the geometry, petrography, geochemistry and radiometric age of the sill (Moseley, 1966; Stevenson *et al.,* 1970; Stevenson and Gaunt, 1971; Ineson *et al.,* 1983). The latest published description, by Miller (1986), provides a review of previous literature and field descriptions from exposures revealed by quarrying operations from 1971 to 1985.

The Water Swallows Sill has been intruded at the same stratigraphical level as the sill at the Tideswell Dale GCR site and may be genetically related.

Description

The sill has an approximately semicircular outcrop about 800 m across (Figure 7.6) and with a thickness of up to at least 80 m in the west-central part of the intrusion (Ineson *et al.,* 1983). It is the thickest sill proved in the area. The upper contact has been removed by erosion and quarrying, though Stevenson and Gaunt (1971) recorded that the top of the sill is gently discordant and is overlain by basalt of the Lower Miller's Dale Lava. Ineson *et al.* (1983) established that the lower contact is saucer-shaped, broadly undulating, gently discordant to the east and strongly transgressive to the west. The succession shown below (from Moseley, 1966; Stevenson *et al.,* 1970; Stevenson and Gaunt, 1971) was taken from a drainage cut in the quarry, which is no longer exposed. It shows that the sill is also underlain by basalt of the Lower Miller's Dale Lava.

	Thickness (m)
Water Swallows Sill	
Dolerite, dark grey, commonly spheroidally weathered and with prominent columnar joints, typically medium grained; local presence of smectite-filled vesicles; sharp irregular base	24.4 seen
Lower Miller's Dale Lava	
Basalt, dark grey, locally hard and white where calcitized or soft and green where chloritized; the lower part commonly decomposed yellow-brown, amygdaloidal with chlorite- and calcite-filled vesicles; pyrite veins and pyrite amygdales present near to the top with euhedral crystals up to 2 mm; sharp base	0–2.0
Bee Low Limestones	
Limestone, pale grey, with slight marmorization	0–3.0
Limestone breccia with clasts strongly altered	0–0.8
Tuff, pale green, calcareous	0–3.0

The sill comprises a coarse-grained, relatively altered, upper unit and a fine-grained, relatively unaltered, lower unit with columnar jointing. In the lower part of the quarry, where the base of the sill is approximately horizontal, columnar joints within the sill are vertical (Figure 7.7). Where the basal contact dips steeply below the deepest levels of the quarry the columnar jointing is horizontal with thin calcite veins along these joints (Moseley, 1966). The columnar joints were also described as horizontal in the north-east of the quarry, in the vicinity of a north-trending fault (Stevenson and Gaunt, 1971).

The rock of the sill is an olivine-dolerite, generally lacking the ophitic texture common in other intrusions of the area. meson *et al.* (1983) have shown that there is a systematic grain-size variation. The lower unit, 20–30 m thick, is fine grained and contains euhedral and partly rounded microphenocrysts of olivine, partly pseudomorphed by smectite, and labradorite feldspar. The groundmass, locally chloritized and carbonated, comprises pale-green to pale-brown anhedral augite and flow-aligned laths of labradorite. Anhedral grains of iron-titanium-manganese oxide are present and the interstitial areas include apatite and partly devitrified glass. There is a gradation toward a middle unit, 40 m thick, slightly coarser and showing an increase in content of groundmass plagioclase and a reduction in augite content relative to the lower unit. Olivine microphenocrysts and interstitial areas have been completely replaced by smectite (Walters and Ineson, 1983). Towards the top of this unit there are spherical amygdales filled with smectite. The upper unit, of unknown thickness, is coarse grained with olivine phenocrysts, pseudomorphed by smectite, forming 25% of the rock. Miller (1986) has described the presence of rounded inclusions (5 mm to 50 cm diameter) of fine-grained basalt with some vesicles, comparable in appearance to the lower unit of the sill.

The underlying vesicular to non-vesicular lava is extensively albitized, chloritized and calcitized, and is considerably more altered than the sill. The top of the lava is irregular, commonly bulging upward into the overlying sill (Moseley, 1966).

The tuff seen at the base of the section was described by Ineson *et al.* (1983) as comprising a basal coarse tuff-breccia with rounded and iron-stained limestone clasts, on average 1 cm in diameter, overlain by lapilli-tuffs. The tuffs thicken up to 25 m beneath the north-western part of the sill, with graded beds dipping at 7°.

Mineralization is dominated by the presence of calcite amygdales and veins in the basalt; smectite and subordinate haematite, quartz and amethystine quartz veins in the sill; and pyrite in the tuffs (Miller, 1986). Moseley (1966) described the lowermost 0.6 m of the sill, containing narrow calcite veins that are parallel to its irregular basal contact. Marmorization (thermal alteration) of the limestone country rock of the sill is slight (Stevenson and Gaunt, 1971).

The olivine-dolerite sill is hypersthene-olivine-normative, with tholeiitic affinities. The lower and middle units of the sill show only minor geochemical variations, whereas the upper unit is depleted in Ca, Na, Si, Y, Zr and Sr and enhanced in Mg and total Fe (Ineson *et al.,* 1983).

Regionally, the Lower Miller's Dale Lava is underlain and overlain by beds of the Bee Low Limestones, which contain fauna indicative of late Lower *Dibunophyllum* (D_1) Zone (Stevenson and Gaunt, 1971). This shows the lavas to be Asbian in age (around 334–330 Ma on the timescale of Gradstein and Ogg, 1996). Whole-rock K-Ar age determinations of the sill gave an average date of 311 ± 6 Ma (*c.* 317 Ma with new constants) from three analyses (Stevenson *et al.,* 1970). Other, much younger dates from the same study and from a subsequent study by Ineson *et al.* (1983) were discounted as unreliable, probably due to argon loss. More recently, an Ar-Ar plateau age of *c.* 321 ± 8 Ma has been obtained from groundmass plagioclase of the sill (M. Timmerman, pers. comm., 2002), re-inforcing the suggestion of a Namurian age.

Interpretation

The presence of a sill at Water Swallows Quarry was first recognized by Arnold-Bemrose (1907) and it subsequently became well exposed through quarrying operations. Moseley (1966) provided a detailed description of the geometry of the igneous body, though he did not adequately distinguish between the sill and the underlying lavas, which he considered were both part of the same igneous event. The geological re-survey of the district established the distinct identities of the lava and sill and provided detailed petrographical and geo-chemical information (Stevenson and Gaunt, 1971). The discrepancy between the strati-graphical age of the Lower Miller's Dale Lava and the K-Ar radiometric age of the Water Swallows Sill led to the interpretation that the two are genetically unrelated (Stevenson *et al.,* 1970). Both the published K-Ar and the unpublished Ar-Ar radiometric dates for the sill suggest a Namurian or younger age. However, regionally the majority of dolerite sills only intrude at or below the level of the Upper Miller's Dale Lava and no intrusions are found in strata of Namurian or Westphalian age (Figure 7.3). It has been proposed that at Water Swallows Quarry the Lower Miller's Dale Lava acted as a barrier to upward migration of magma, so that the sill developed through the lateral migration of magma at or near the base of the lava (Stevenson *et al.,* 1970).

Ineson *et al.* (1983) concluded that the whole-rock K-Ar radiometric dates do not represent cooling ages, and have been reset to a younger age by argon loss, possibly during hydrothermal or deuteric alteration. They therefore proposed that the intrusions are no younger than Brigantian in age, thus reopening the possibility that the eruption of the Lower Miller's Dale Lava and the intrusion of the sill were near-contemporaneous events. However, the recent, unpublished Ar-Ar plateau age should not have been affected by any argon loss and would appear to confirm the time gap.

Moseley (1966) considered both the Lower Miller's Dale Lava and the sill to be lavas. He proposed that the geometry of the igneous body, in part determined from the orientation of the cooling joints, is indicative of formation within a vent, with the lava rising up a central pipe and spreading laterally as the extrusion of the Lower Miller's Dale Lava. The subsequent drilling of boreholes ascertained the saucer-shape geometry of the base of the intrusion, discounting the presence of a central pipe (Ineson *et al.,* 1983). However, Ineson *et al.* used the presence of the lapilli-tuff beneath the Lower Miller's Dale Lava, which shows a great thickening towards the north-west, to propose the presence of a tuff-cone associated with a nearby vent. This vent, as yet unlocated, was proposed to occur towards the north-west of the site. The association of the tuff-cone with the Lower Miller's Dale Lava and with the area of maximum discordance and thickness of the sill led Ineson *et al.* (1983) to suggest that this vent fed both the extrusive and intrusive igneous phases.

Arnold-Bemrose (1907) and Moseley (1966) recognized variations from fine grained to coarse grained within the sill. Ineson *et al.* (1983) determined that this grain-size variation is systematic, the lowest unit being finest and the uppermost unit being coarsest. Miller (1986) suggested that the relationship is more complex, with the coarse-grained gabbroic rocks not confined to the upper part of the sill. Geochemical variations in the sill have been attributed to the increase in proportion of olivine phenocrysts in the upper unit (Ineson *et al.,* 1983). This olivine-enriched unit cannot be a product of in-situ crystal settling as it occurs above the bulk of the intrusion. Ineson *et al.* (1983) proposed that the differentiation initially occurred in a magma chamber at depth. As the magma moved upwards, the upper olivine-poor magma was intruded first, forming the lower unit of the sill. Then, a final intrusion of the lower olivine-rich magma occurred into the top of the sill.

Although the sill lacks modal quartz, Stevenson and Gaunt (1971) indicated that it is quartz-normative, i.e. silica-saturated, and falls within the range of tholeiitic basalts. Ineson *et al.* (1983), however, suggested that these normative values do not take account of the deuteric alteration and calculated that the sill is hypersthene-olivine-normative, with tholeiitic affinities transitional to alkali basalt, and having geochemical affinities with the Lower Miller's Dale Lava.

The mineralization seen at Water Swallows Quarry has a mineral assemblage similar to that seen at the Calton Hill GCR site, lacking the phases more typical of hydrothermal mineralization in Derbyshire, e.g. galena, chalcopyrite and fluorite. As with Calton Hill, the mineralization is thought to be a late-stage, deuteric or low-temperature hydrothermal alteration (Walters and Ineson, 1983; Miller, 1986).

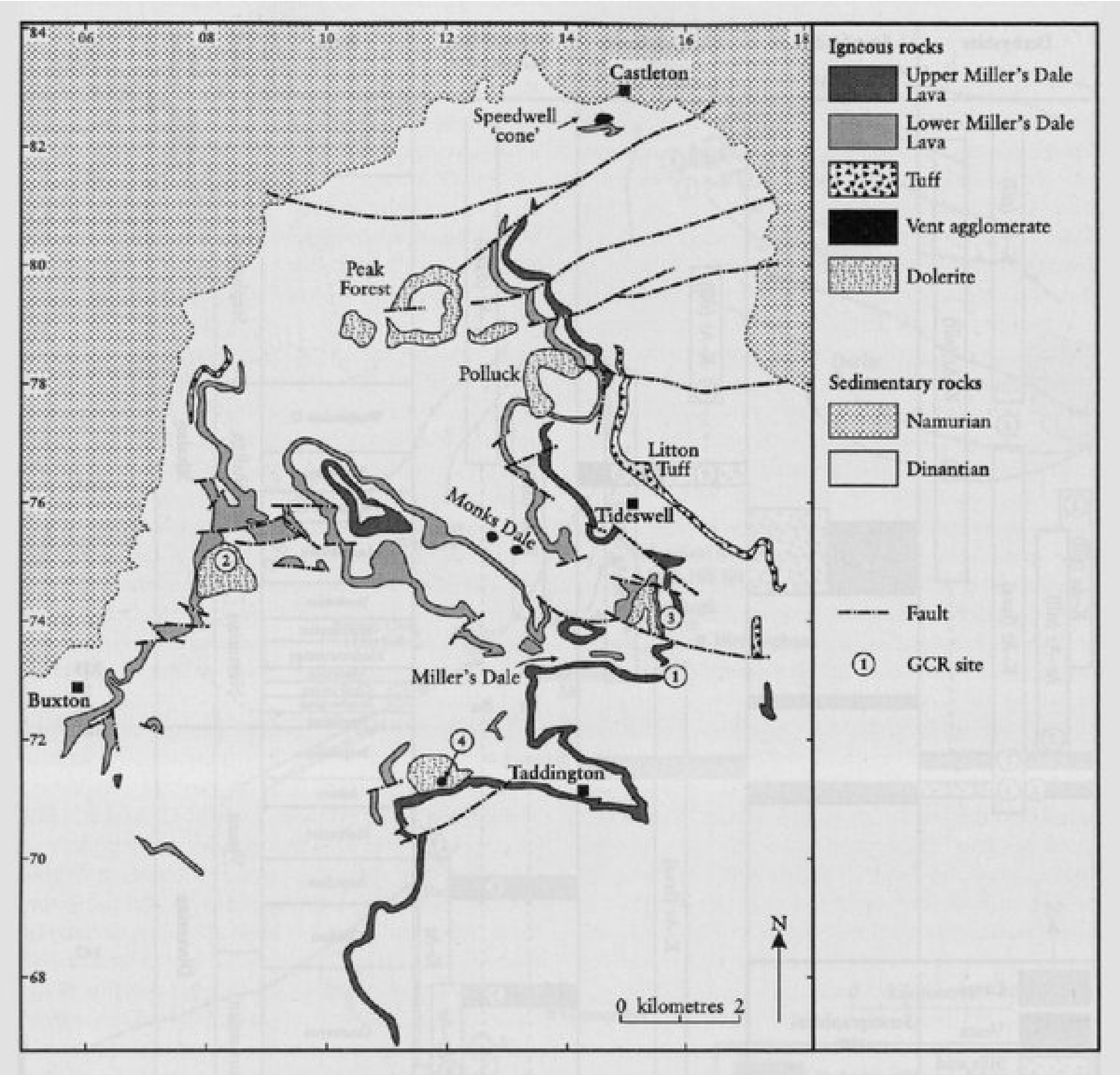
Conclusions

The Water Swallows Quarry GCR site is representative of the Carboniferous age dolerite sills of Derbyshire. It provides an excellent exposure of a thick dolerite sill, the Water Swallows Sill, which intrudes the Lower Miller's Dale Lava and limestones of late Visean age. Infilling of the quarry has greatly reduced the extent of section visible, though the site still provides the opportunity for future research to establish the likely relationships between the lava and the sill.

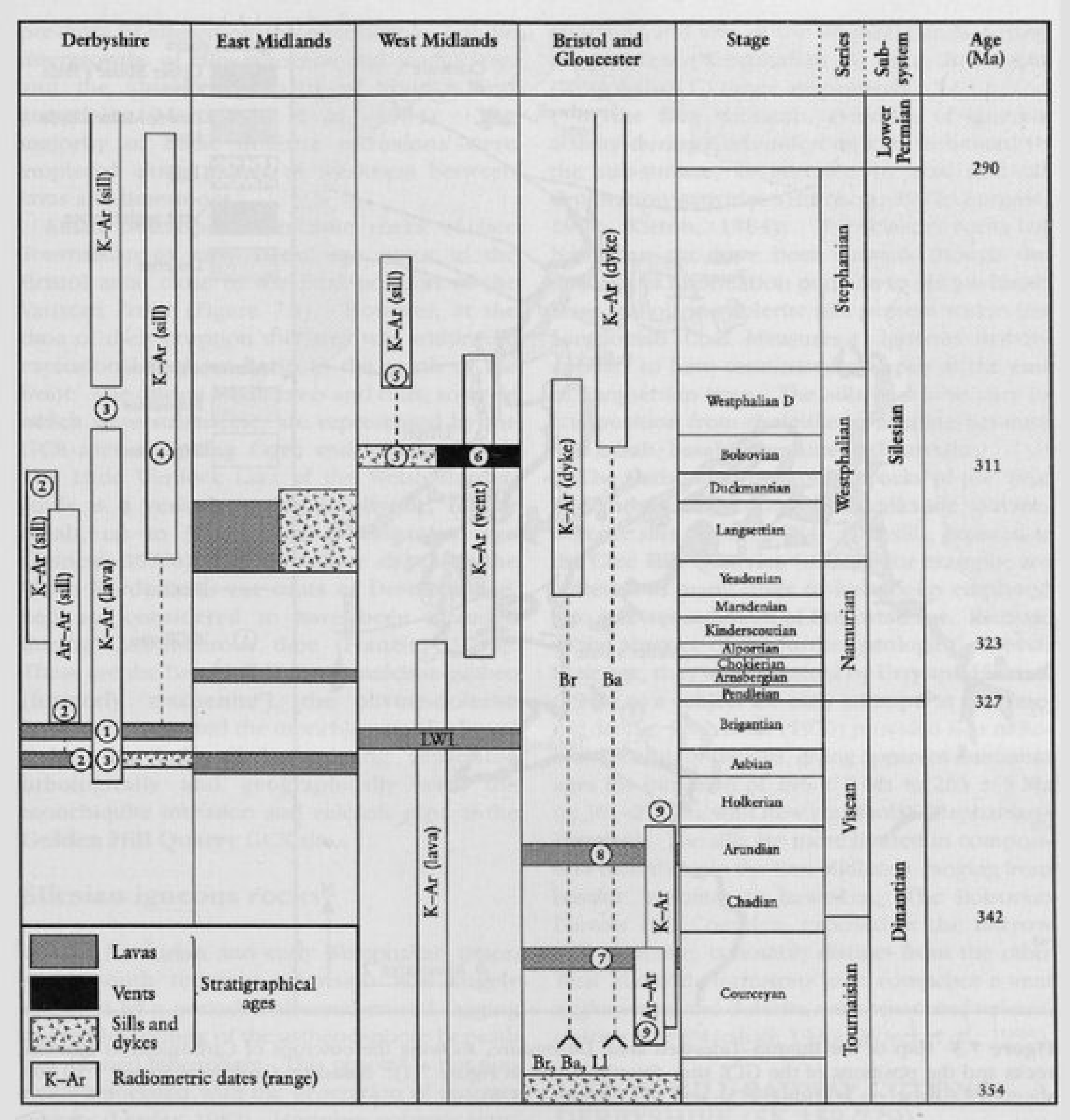
Spectacular examples of columnar joints are developed perpendicular to the sill margin in response to slow cooling of the magma. The orientation of these joints suggests that the base of the intrusion is saucer-shaped (concave-upwards). Variations in the amount of olivine at different levels in the sill have been attributed to pulses of magma from a compositionally zoned (layered) magma chamber at a deeper level.

It has been proposed that the Lower Miller's Dale Lava and the Water Swallows Sill were near contemporaneous, both having been fed from a nearby vent, which produced a tuff-cone at the surface. In contrast, radiometric dates suggest that the sill was intruded some 10 million years after the eruption of the lavas and hence that the sill and lavas are unconnected. Further study is clearly required in order to clarify the timing and the magmatic relationships, which have a wider significance for the understanding of magmatic evolution in the Carboniferous of Derbyshire.

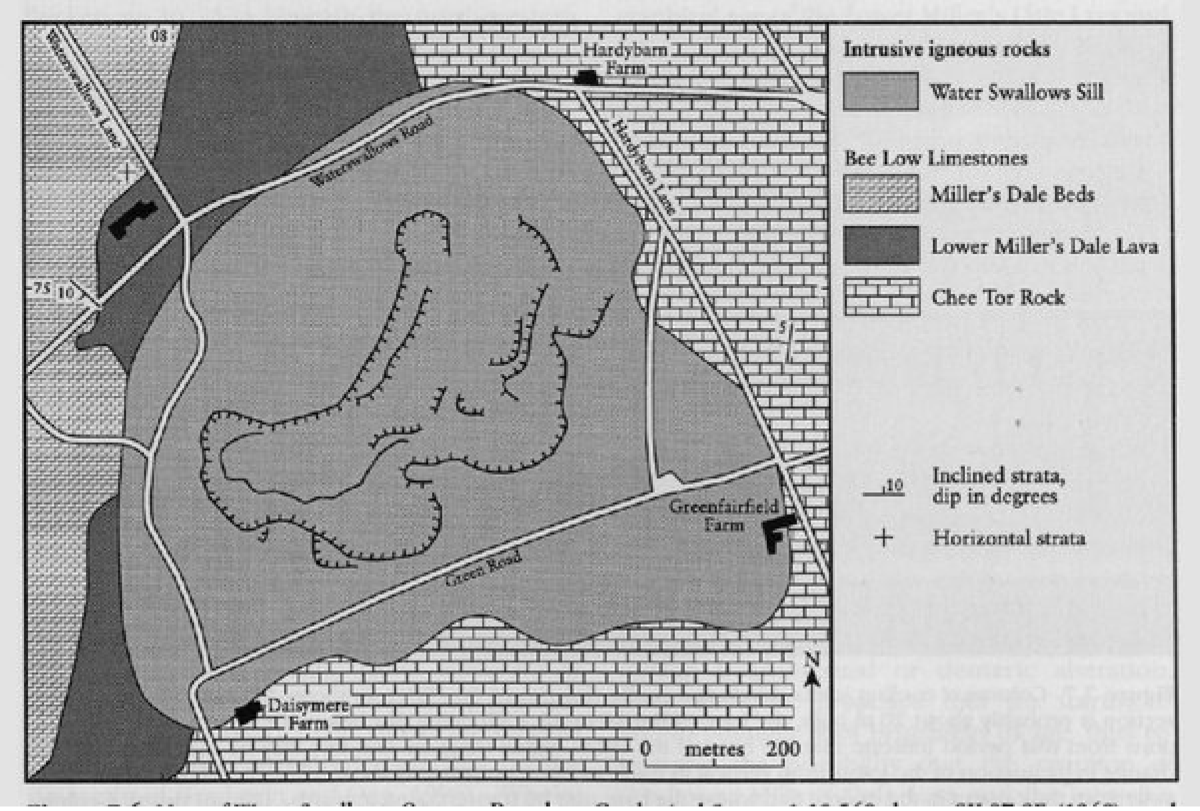
References



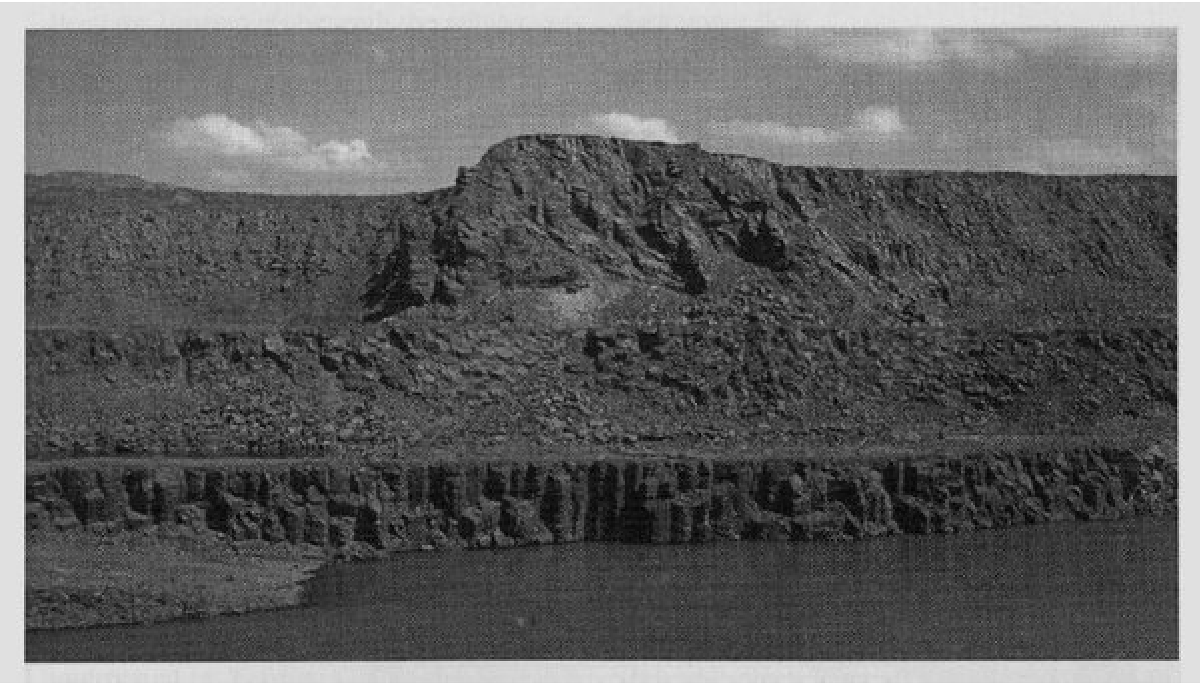
(Figure 7.3) Map of the Buxton-Tideswell area, Derbyshire, showing the outcrops of Carboniferous igneous rocks and the positions of the GCR sites (numbered as in (Figure 7.1)). Based on Geological Survey 1:50 000 sheets 99, Chapel en le Frith (1975); and 111, Buxton (1978).



(Figure 7.2) Approximate ages and stratigraphical distribution of selected igneous rocks from central England and the Welsh Borderlands. The GCR sites are numbered as for (Figure 7.1). (Ba = Bartestree Dyke; Br = Brockhill Dyke; Ll = Llanllywel Monchiquite Dyke; LWL = Little Wenlock Lavas.) After Francis (1970a); and Kirton (1984). The timescale is that of Gradstein and Ogg (1996).



(Figure 7.6) Map of Water Swallows Quarry. Based on Geological Survey 1:10 560 sheets SK 07 SE (1968); and SK 07 NE (1959).



(Figure 7.7) Columnar cooling joints developed in the dolerite of the Water Swallows Sill, taken in 1969. The section is probably about 20 m high, the base of the 24 m-thick sill being just below the quarry floor. Descriptions from this period indicate that the base of the sill is highly irregular and this may be the reason for the change in inclination of the joints from vertical in the lower tier, presumably above a horizontal base, to inclined away from the camera in the middle tier, where the base may be transgressing upwards. (Photo: British Geological Survey, No. L239, reproduced with the permission of the Director, British Geological Survey, © NERC.)