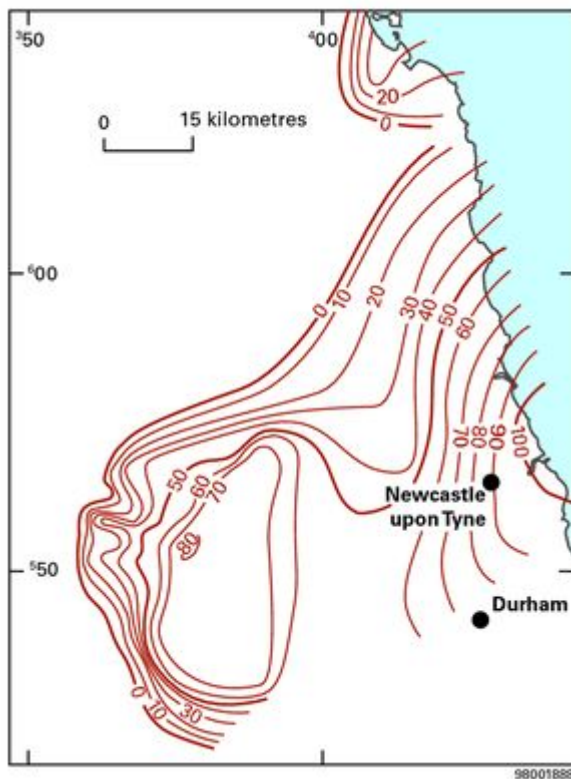




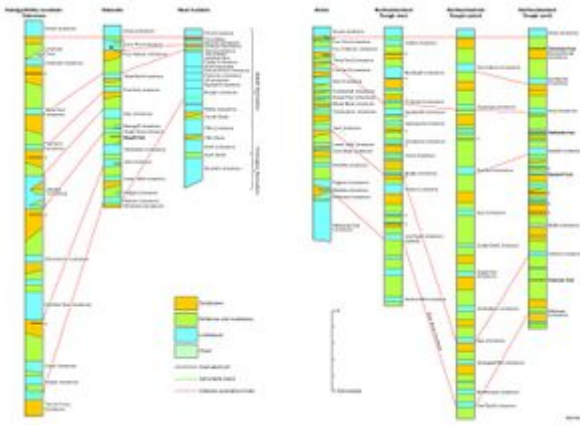
Th Throckley; WB Whitley Bay; Wo  
Woodland. P916081.



Columnar jointed dolerite in the Alnwick Sill at Cullernose Point on the Northumberland coast. In the foreshore is a 'whaleback' anticline in the Four Fathom (Sandbanks) Limestone. (P643594).



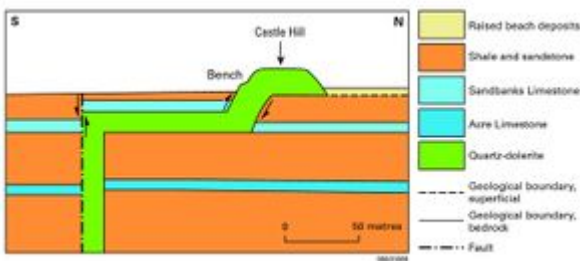
Isopachytes, in metres, on the Whin Sill-swarm. Where more than one leaf of dolerite is present, the total thickness is given. P916082.



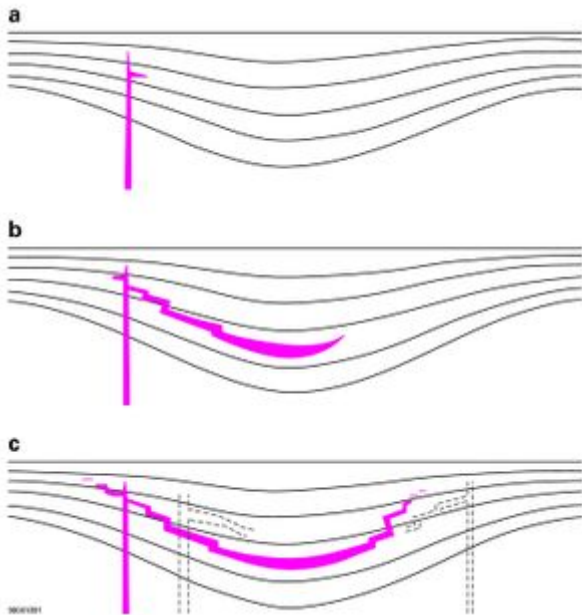
Representative sections and correlations for the Alston Formation, Yoredale Group, showing correlation with the Eskett Formation of west Cumbria. P916073.



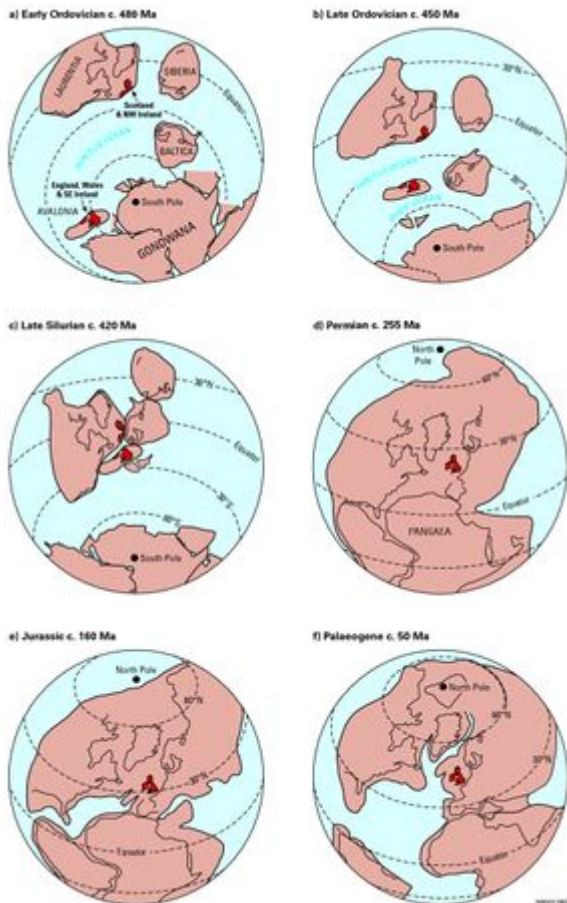
Ropy flow-structure on the lower, inner surface of a large, flattened vesicle at the top of the Farne Islands Dolerite Sill at Harkess Rocks, Bamburgh, Northumberland coast [NU 177 358]. The hammer head is 17 cm long. (P637452).



Sketch of a south-to-north section through the centre of Castle Hill, Holy Island, showing the alternating dyke-like and sill-like segments of the Holy Island Dyke (after Goulty et al., 2000). Castle Hill and the bench feature are illustrated on the front cover of this book. The bench feature is interpreted as part of a step-and-stair transgression of bedding during dyke intrusion.) P916083.



Diagrams illustrating the mechanism of intrusion of the Whin Sill-swarm. a dykes are intruded to within 1 kilometre of the surface; b lateral intrusion of magma leads to gravitational flow down-dip and ponding of the magma in the centre of the basin; c to achieve hydrostatic equilibrium, magma advances up-dip on the other side of the basin with interfingering at the leading edge. Broken lines denote variation introduced where there are multiple dyke sources (after Francis, 1982). P916084.



Series of palaeogeographical reconstructions showing continental movements from the Ordovician to the Palaeogene (after Woodcock and Strachan, 2000). P916033.

The tholeiitic basaltic intrusions emplaced in northern England during earliest Permian times comprise the Whin Sill-swarm and east-north-east-trending dykes of the Northern England Tholeiitic Dyke-swarm. These intrusions have played an important role in the early development of geological science in Great Britain. In northern England, the word 'sill' was used to describe a flat-lying layer of rock, and 'whin' meant hard. Hence, the term 'Whin Sill' may have been in use long before the origin of the rock was known and is most likely the first geological use of the word 'sill'. The Great Whin Sill was recognised to be of igneous origin early in the nineteenth century, but there was debate as to whether it was an intrusive sheet or a lava flow. Its intrusive origin was finally established through investigations in Northumberland, and the Great Whin Sill became regarded as the type example of a sill.

## Whin Sill-swarm

The Whin Sill-swarm underlies about 4500 km<sup>2</sup> of northern England, extending from the southernmost outcrops in Lunedale, west as far as the Pennine escarpment, and north to Holy Island ([P916081](#)). Four separate sills have been identified from the outcrop distribution, magma-flow directions, and differences in petrology and palaeomagnetic signatures. These are the Farne Islands and Alnwick sills in the north, the Great Whin Sill, which crops out in Teesdale, the Pennine escarpment and along the Roman Wall, and the Little Whin Sill in Weardale. The volume of magma intruded was at least 215 km<sup>3</sup> and possibly much more, as the sills appear to thicken and extend eastwards for some distance under the North Sea.



The sill-swarm is composed of quartz-dolerite and this tough rock typically forms picturesque crags and scarps that dominate the landscape of parts of north-east England. In Northumberland, the Farne Islands are almost entirely made of dolerite. North of the Tyne valley, the Romans built an important segment of Hadrian's Wall along the impressive dolerite scarp that runs for a distance of 25 km. In upper Teesdale, the Great Whin Sill forms waterfalls on the River Tees at High Force (NY 880 284) and at Cauldron Snout (NY 814 286), where the river cascades spectacularly over columnar-jointed crags. Columnar cooling joints are well developed in many other places, for example at Sewingshields Crags (NY 800 700), Longhoughton Quarry (NU 231 153), and Cullernose Point (NU 259 221) ([P643594](#)); Low Force (NY 903 277) is a series of rapids where the river flows over columnar-jointed dolerite. Both sills and dykes provide solid foundations for castles at Dunstanburgh, Bamburgh and Holy Island.

The Farne Islands and Alnwick sills were emplaced within Carboniferous rocks overlying the Cheviot Block. From the Farne Islands and Budle Bay to the Kyoel Hills, the Farne Islands Sill is up to about 30 m thick and was intruded into five horizons that range from the upper part of the Fell Sandstone Formation, in the north of the outcrop, to the Eelwell Limestone within the Alston Formation on the Farne Islands. To the south of this, in Beadnell Bay, the horizon of the Alnwick Sill is some 120 m higher in the stratigraphy within the lower part of the Stainmore Formation. The sill's horizon thence falls stratigraphically southwards to lie at a level within the Tyne Limestone Formation at its most southerly outcrop near Newton Burn (NU 145 068). The Alnwick Sill varies from about 6 to 21 m thick.

The Great Whin Sill is on average about 30 m thick. The thickest single leaf has been recorded in borings in West Allendale (81 m) and Weardale (90 m, but this was near a small horizon change and may be anomalous). The sill tends to thin towards its northern, western and southern margins ([P916082](#)). Along the Roman Wall, the thickness of the sill varies from 20 to 50 m. Multiple sheets occur at outcrop only east of Thockrington (NY 970 800), though in boreholes more than one sheet has been recorded at depth: for example, three dolerite sheets recorded in the Harton Borehole (NZ 3966 6563) total 90 m. In upper Teesdale, the Great Whin Sill intrudes its lowest stratigraphical level within the Melmerby Scar Limestone (for lithostratigraphy see [P916073](#)). From here, it thins and rises in stratigraphical level in every direction, forming a 'saucer-shaped' intrusion. This form is also demonstrated along the sill's northern outcrop where its level changes systematically from the Oxford Limestone north-eastwards into lowest Namurian strata and westward to its highest stratigraphical level within the Westphalian B (Duckmantian) Coal Measures in the Midgeholme coalfield. The presence of the sill in Coal Measures strata here suggests that before intrusion these rocks had been juxtaposed against Dinantian strata by displacement on the Stublick Fault. The changes in stratigraphical level occur in transgressive steps, separated by significant distances where the intrusion maintains a constant level. In places, the sill transgressions are fault controlled, for example between Steel Rigg and Sewingshields Crags (NY 751 676 to 813 704), but elsewhere the sill rises either gradually or by short steps.

At outcrop near Stanhope in Weardale, the Little Whin Sill is a flat-lying, columnar-jointed dolerite sheet, up to 13 m thick, intruded into the Three Yard Limestone of the Alston Formation. The sill thins westwards and dies out near Ludwell. To the north, in the Rookhope Borehole (NY 937 427), some 6 km north-west of Weardale, the Little Whin Sill is about 2 m thick and it has been encountered north of the River Wear in mines at Stotfield Burn (NY 943 424) and Stanhope Burn (NY 987 413). In the Rookhope Borehole, the Little Whin Sill lies stratigraphically about 120 m above the Great Whin Sill. In the Woodland Borehole (NZ 091 277), some 15 km to the south-east of Stanhope, the Little Whin Sill is encountered 20 m above the Three Yard Limestone, but it is not present at outcrop in upper Teesdale or in boreholes drilled to this level around Crook to the east.

Sill contacts are sharp though irregular in places, implying that the host rocks were lithified prior to

intrusion. Locally, for example at Barrasford Quarry (NY 910 742) in Northumberland, narrow dyke-like masses protrude from the upper surface of the Great Whin Sill into the overlying strata. More widely in the Northumberland section of the Great Whin Sill, blocks of the underlying sedimentary rock have been levered up into the sill during intrusion and now form xenoliths close to its base. Similarly detached rafts of host strata are seen within the body of the Alnwick Sill, for example near Cullernose and at Longhoughton (NU 231 153), but, by contrast, xenoliths are rare in the north Pennines part of the Great Whin Sill intrusion. Between Budle Point and Harkess Rocks, the relationship between the Farne Islands Sill and the sedimentary country rock is extraordinarily complex, with numerous fragments and blocks of sandstone occurring within the sill. Here, the sedimentary rocks were probably disrupted immediately prior to intrusion by precursory hydroclastic activity.

Vesicles are present in the marginal zones of the Great Whin Sill along its northern outcrop, though none have been recorded from Teesdale. Of particular interest, however, are flattened amygdales up to 1.5 m long and 60 cm wide, close to the upper contact of the Farne Islands Sill, best exposed at Harkess Rocks (NU 177 356). The inner surface of the gas bubbles is revealed where the amygdale has been removed by later erosion. The lower surface of these vesicles has a tachylitic margin up to 2 mm thick and this displays parabaloid ropy flow-structures, similar in miniature to the surface of pahoehoe lava ([P637452](#)). The linings of the large vesicles must have remained plastic for long enough to allow flattening, elongation and the development of flow structures by the still molten magma moving through the intrusion. These are thought to be rare features of sills. Below this zone are further zones of abundant smaller vesicles, along with narrow zones of peperitic breccia.

The maximum thermal metamorphic effect on the country rock is seen in upper Teesdale, where limestones are recrystallised for over 30 m from the contact and mudstones are spotted for almost 40 m. The metamorphic effect of the three sheets of dolerite in the Harton Borehole can be detected in rocks at distances of 425 m above and 180 m below the sills. Generally, the rank of coal increases dramatically towards an intrusion: vitrinite reflectance increases, the texture changes and ultimately the coal becomes a natural coke. Relatively pure limestones, such as the Melmerby Scar Limestone, are recrystallised with a saccharoidal texture, and known from the characteristic weathering as 'sugar limestone'. This rock produces distinctive soils that support a relict arctic alpine flora, including the spring gentian, *Gentiana verna*, on Cronkley and Widdybank fells, for which the area is renowned.

Impure limestone and calcareous mudstone have been metamorphosed into calc-silicate rocks containing such minerals as garnet, vesuvianite, diopside, feldspar, chlorite, epidote and rare wollastonite. Close to the contact, typically dark mudstones become light-coloured, hard porcellanous rocks known as 'whetstones'; farther away they develop spots, mostly of chlorite, quartz and illite, but sporadically also with andalusite and cordierite. In several places, layers of pyrite nodules within country rocks close to the margins of sills and dykes have been altered to pyrrhotite, for example at Barrasford Quarry and Wynch Bridge. The presence in the contact zone and in rafts of sedimentary rock of wollastonite and vesuvianite in particular, indicate temperatures estimated to be as high as 720°C. Multiple episodes of metamorphism around upper Weardale have been cited as evidence for emplacement of the Little and Great Whin Sill magmas at separate times.

In the Alston Block, mineral veins of the Northern Pennine Orefield cut both the Whin sills and their associated dykes. The dolerite acts as a competent wallrock, like limestone and massive sandstone, and hence is a favourable host for mineralisation (see [Northern Pennine Orefield](#)). An unusual occurrence of magnetite and niccolite-bearing skarn mineralisation at Lady's Rake Mine in upper Teesdale has been cited as evidence of the interaction between north Pennine mineralising fluids and Whin Sill contact rocks whilst the latter were still hot.

## Northern England Tholeiitic Dyke-swarm

Basalt and dolerite dykes associated with the Whin Sill-swarm are typically 3-10 m wide and have north-east to east-north-east trends similar to the structural grain in the underlying Lower Palaeozoic basement. The dykes produce pronounced magnetic anomalies. occur in four, widely separated subswarms, three of which could be regarded essentially as discontinuous single dykes with an echelon offsets ([P916081](#)). Some authors have used the term 'echelon' rather than 'subswarm'.

The dextrally offset northern dykes, belonging to the Holy Island Subswarm, lie at the northern margin of the Cheviot Block. The subswarm has similar palaeomagnetic characteristics to the Farne Islands Sill. South of the Cheviot Hills, the High Green Subswarm can be traced for over 80 km, converging slightly on the Holy Island Subswarm to cross the coastline at Boulmer. Its segments are offset sinistrally and some are up to 65 m wide. This subswarm was emplaced within the Swindon and Cragend-Chartners faults, a zone of east-north-east-trending structures that mark the southern margin of the Cheviot Block. Offsets on the St Oswald's Chapel Subswarm are broadly sinistral and the subswarm includes the Haltwhistle, Erring Burn, Bavington and Causey Park dykes, the last of which can be traced for some distance offshore from Druridge Bay. Near Hexham, this subswarm swings to a more north-easterly trend, converging on the High Green Subswarm. The High Green and St Oswald's Chapel dyke subswarms have similar palaeomagnetic signatures to the Alnwick Sill. Finally, near the southern limit of the Great Whin Sill exposures, the Hett Subswarm comprises several dykes to the south of Durham, including the Ludworth Dyke; palaeomagnetic evidence links this subswarm with the Great Whin Sill. On Holy Island (NU 123 416 to 149 419), the Holy Island Dyke is a complex mass which has several short sill-like sectors. Exposures of these exhibit gently dipping planar chilled upper surfaces. Parallel to these are zones of large vesicles in which the skin exhibits ropy flow-structures very similar to those described towards the top of the Farne Islands Sill at Harkess Rocks. A detailed magnetic survey suggests that the intrusion steps upwards through the stratigraphy both to the north and to the east ([P916083](#)). Examples such as this strengthen the thesis that the dykes are feeders to the Whin Sill-swarm.

## Petrology

The quartz-dolerite of the sills and dykes is composed of labradorite, subophitic augite and iron-titanium oxides with an intersertal, and commonly micropegmatitic, intergrowth of quartz and alkali feldspar. Minor constituents include hypersthene or pigeonite, hornblende, biotite, apatite and pyrite. Fresh olivine has been found only in the Little Whin Sill in the Rookhope Borehole and at Turn Wheel Linn, but pseudomorphs after this mineral have been found in at least some of the other sills and dykes. The chilled margins and many dykes contain some intersertal, pale brown, microlitic glass locally with skeletal ilmenite, but Ca-poor pyroxene is absent.

Grain size in the sills typically increases from the tachylitic or very fine-grained margins to medium grained in the centre. Where the sill is more than about 50 m thick, a pegmatitic zone may be developed about one third of the way down from the top, for example in upper Teesdale and in the Rookhope Borehole. Thus, this facies is rare in Northumberland where the sills are generally thinner than 50 m, though it is exhibited in Keepersfield Quarry (NY 896 727), where the sill is 36 m thick. Pegmatitic patches and veins are characterised by clusters of long, feathery augite crystals and intergrown quartz and alkali feldspar. Ca-poor pyroxenes are absent from the pegmatitic areas and iron-titanium oxides are rare, but biotite and hornblende are important minor constituents. Patches and veins of pink aplitic, fine-grained, quartzo-feldspathic aggregates with almost square phenocrysts of sodic plagioclase are also common in Northumberland, for example in Barrasford Quarry, at Cullernose Point and Dunstanburgh. Segregations such as these are typical final products



of differentiation seen in the upper parts of many thick sills. Veins and irregular masses of fine-grained basalt, presumably from later pulses of magma, have been recorded locally in both sills and dykes, for example at Swinburne Quarry (NY 947 765). The percentage of microphenocrysts increases towards the centre of the Great Whin Sill and differences in trace element geochemistry between the chilled margin and the sill interior imply that there was more than one pulse of magma.

The petrographical affinities are dominantly tholeiitic, but geochemically, the sills and dykes are transitional between alkaline and tholeiitic. The Great Whin Sill shows a very slight trend towards iron enrichment, in contrast to the Little Whin Sill which is geochemically homogeneous. It has been suggested from geochemical and mineralogical evidence that the Little Whin Sill may be an early differentiate from the Whin magma. However, the iron-rich nature of the Little Whin Sill and the presence of some resorbed calcic plagioclase crystals suggest that it had already undergone some differentiation prior to its emplacement.

Close to contacts, fault-planes, mineral veins or coal seams, dolerite and basalt may be altered to a pale cream or yellowish brown rock, referred to as 'white whin'. This is composed of quartz, illite, kaolinite, muscovite, rutile, anatase and carbonates and was formed by the interaction between dolerite and hydrothermal solutions, probably of juvenile origin. Where white whin occurs close to the sill contact, adjacent mudstones show a marked increase in  $\text{Na}_2\text{O}$  and the development of abundant albite, suggesting that sodametasmorphism has occurred.

In addition to the zones of white whin, a suite of late-stage hydrothermal minerals has commonly developed in joints and vesicles during the final stages of cooling. Quartz-calcite-chlorite veins are abundant locally throughout the Whin Sill-swarm, with smaller amounts of chlorite, bowlingite, sericite, stevensite, albite, anatase and titanite also present. Joint-surface veneers and late-stage veins contain abundant pectolite along with analcime, apophyllite, chabazite, prehnite, stilbite and rare datolite.

## **Emplacement mechanism**

In the Midgeholme Coalfield, the Great Whin Sill is intruded into Coal Measures and in the Durham Coalfield, dykes of the Hett Subswarm emplaced within the Coal Measures do not pass up into Lower Permian strata. Near Appleby in the Vale of Eden, pebbles of dolerite are known from Lower Permian breccia ('brockram'). Thus, the intrusions were emplaced and exposed to erosion during the time interval represented by the unconformity between the upper Carboniferous (Duckmantian-Bolsoviaian) and lower Permian strata of the region. The age is reinforced by radiometric dates including a K-Ar whole-rock age of  $301 \pm 6$  Ma, a U-Pb baddeleyite ( $\text{ZrO}_2$ ) date of  $297.4 \pm 0.4$  Ma, both determined from the Great Whin Sill, and an Ar-Ar plagioclase date of  $294 \pm 2$  Ma from the Holy Island Dyke. The Ar-Ar age is younger than the U-Pb date and may support the view that the Farne Islands Sill and Holy Island Dyke Subswarm may have been emplaced later than the Great Whin Sill. Recent palaeomagnetic studies of all the sills and dykes revealed virtual geomagnetic poles that are consistent with the magmatism having occurred in earliest Permian times when the ancient geomagnetic field was reversed.

The dyke subswarms tend to occur at the margins of the main intrusions within the sill-swarm and it has long been suggested that the sills were fed by the dykes. Similarities in geochemistry and palaeomagnetic signature support this relationship, but a direct connection between them has not been proved in the field. Several examples of basaltic dykes cutting the Great Whin Sill have been cited as evidence that the dyke swarms may represent a slightly later event but, even so, the relationship of the dykes to the sills has been explained in a single emplacement model.

To explain the dykes and sills as the products of a single intrusive phase ([P916084](#)), it is envisaged that basaltic magma rose along the dykes at the outer margins of the sedimentary basins until it reached hydrostatic equilibrium. The magma then gravitated downwards into the lower, central parts of the basin succession where it accumulated to form an overall saucer-shape intrusion. On the opposite side of the basin, the magma then advanced up dip under the head of pressure, so that here the outer parts of the intrusion tend to be thin and steeper than bedding, pinching out as they approach the surface. This process should be reflected by magma-flow directions in the dykes and sills, determined from features such as fingers and tongues extending from contacts and from the large vesicles in the Farne Islands Sill and Holy Island Dyke. A study of the alignment of magnetic grains in the rock indicates a more complex pattern of magma flow than is suggested by the model, though the flow direction is predominantly north away from the Hett and Holy Island dykes, and southwards at the southern limit of the Farne Islands Sill at Harkess Rocks.

The large vesicles seen in the Farne Islands Sill and Holy Island Subswarm may have formed by repeated localised pressure falls caused by fluid-induced fracturing of the country rock as the tip of the intrusion advanced. Alternatively, they may have formed by rapid decompression during injection of the magma into the sedimentary pile close to the land surface of the time; substantial uplift and erosion in this region before emplacement is implied by this second mechanism. It has been estimated that the Great Whin Sill took about 60 years to crystallise completely, whilst the Little Whin Sill may have taken only one and a half to two years.

## **Permian, Triassic and Jurassic: deserts, rivers and shallow seas**

The major continental collision that drove the Variscan Orogeny during late Carboniferous and early Permian times created the Pangaeon supercontinent. Within this landmass, Britain lay in a tropical latitude, approximately 10° north of the equator, and drifted slowly northwards to subtropical latitudes of approximately 30° north by early Triassic times ([P916033](#)). The depositional environments included widespread deserts, tropical and evaporitic seas, fluvial outwash plains, ephemeral lakes and mudflats.

Erosion of the folded and uplifted Carboniferous strata had generated mature, gently rolling plains across which spread an early Permian desert. By late Permian times, continental extension had opened seaways, flooding low ground across large inland drainage basins. On the western edge of northern England, the Bakevellia Sea developed, covering approximately the area of the present-day Irish Sea and its marginal areas. To the east, the Zechstein Sea covered approximately the area of the present-day North Sea and extended as far to the east as Lithuania and Poland. Early Triassic times saw continental deposition restored over northern England. Large river systems transported sands from the south and aeolian dune fields developed. Further marine transgression in mid to late Triassic times, the result of expansion of the Tethys Ocean from southern Europe, then brought coastal conditions to northern England; open marine conditions followed in Jurassic times.

Today, Permian strata are preserved in northern England to the north-west of the Pennines, around Carlisle, in the Vale of Eden and in west Cumbria, and to the east of the Pennines, over much of County Durham. Permian strata also occur at the north-east end of the Isle of Man but are there entirely obscured by thick superficial deposits. Triassic strata have a similar though more restricted onshore outcrop. In northern England, Jurassic strata are only known from the vicinity of Carlisle; those that succeed the Triassic succession near Middlesbrough fall into another regional district — that of East Yorkshire and Lincolnshire. It is probable that Permian and Triassic rocks once partially covered the Carboniferous strata of the north Pennines, northern Cumbria and Northumberland, and that Jurassic rocks also had a much wider original distribution.

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