Permian and Triassic rocks of the Appleby district (part of Sheet 30, England and Wales)

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NOTES

All grid references given in brackets [] throughout the report are within the 100 km square NY.

Contents

Summary

This report describes the Permian and Triassic rocks of the 1:10 000 sheets NY 52 NW, NY 52 NE, NY 52 SE, NY 61 NE, NY 62 NW, NY 62 NE, NY 62 SW, and NY 62 SE. These rocks were the subject of a partial resurvey during the summers of 1998, 1999 and 2000, during the revision of the Appleby 1:50 000 geological sheet. The Carboniferous rocks of this area are described in a separate report.

The regional setting, lithostratigraphy and chronostratigraphy of the Permian and Triassic rocks are discussed in the opening sections of the report. These are followed by a detailed account of the distribution, lithologies, and sedimentological interpretations of the key lithostratigraphical units, namely the Penrith Sandstone Formation (including brockram facies), the Eden Shales Formation (including its important evaporite deposits), and the St Bees Sandstone Formation. The report concludes with a discussion of structure, evaporite-related subsidence and economic geology.

1   Introduction

This report describes the Permian and Triassic rocks of the 1:10 000 sheets NY 52 NW, NY 52 NE, NY 52 SE, NY 61 NE, NY 62 NW, NY 62 NE, NY 62 SW, and NY 62 SE (Figure 1). These rocks were the subject of a partial re-survey during the summers of 1998, 1999 and 2000, during the revision of the Appleby 1:50 000 geological sheet. The Carboniferous rocks of the area are described in a separate report. The terms 'Appleby district', 'Penrith district' and 'Brough district', as used in this report, refer to the areas covered by the Appleby, Penrith and Brough-under-Stainmore 1:50 000 geological sheets.

The Permian and Triassic rocks of the Vale of Eden are mostly concealed beneath a thick layer of glacial deposits. Our present knowledge of these sequences in the Appleby district stems largely from the detailed work carried out by the BGS in the Penrith and Brough-under-Stainmore dis-tricts to the north and east, and from a large number of confidential mineral exploration boreholes. Four boreholes were drilled during the BGS (then Institute of Geological Sciences) mapping of the Brough-under-Stainmore and Penrith 1:50 000 sheets (see Arthurton and Wadge, 1981; Burgess and Holliday, 1979), with the specific objective of elucidating the stratigraphy of the Upper Permian evapor-itic rocks. These boreholes (at Hilton, Langwathby, Loun-thwaite and Brough Sowerby; see Figure 2) have been of enormous importance to the local and regional understand-ing of Late Permian deposition in northern England. More recently, the Permian and Triassic rocks of west Cumbria, some 70 km west of the Appleby district, were studied in great detail during the Nirex-funded geological investiga-tions of the Sellafield area (e.g. Barnes et al., 1994; Jones and Ambrose, 1994; Akhurst et al., 1997).
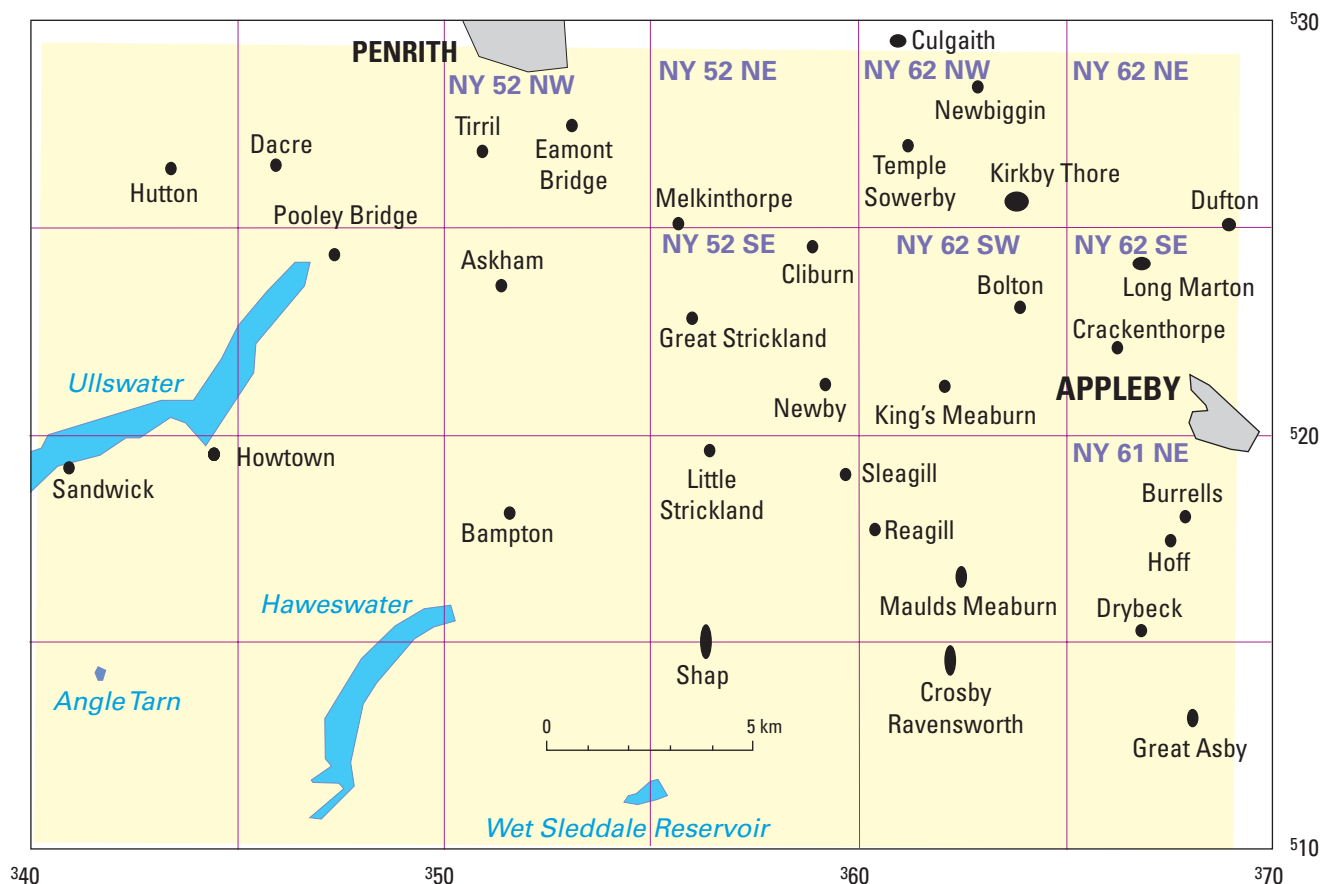
Figure 1   Locality map, showing area of Appleby 1:50 000 sheet (pale yellow), 1:10 000 sheet tiles, and main settlements.

2   Regional setting

The Permian and Triassic rocks of the Vale of Eden are at the south-eastern extremity of a preserved outcrop that extends westwards and northwards into the Carlisle Basin, west Cumbria, southern Scotland and the eastern Irish Sea (Figure 2). The smaller basins that comprise this large depositional area were initiated in response to Early Permian rifting. The Vale of Eden Basin (Figure 2) is believed to have formed in an intermontane setting, in response to extensional faulting along the Pennine and Dent fault systems (Underhill et al., 1988; Holliday, 1993). The aeolian and fluvial Penrith Sandstone Formation and Brockram were deposited at this time. Late Permian regional subsidence accompanied the deposition of the dominantly lacustrine and continental sabkha Eden Shales Formation, and was succeeded in Early Triassic times by fluvial sedimentation of the St Bees Sandstone Formation.

Arthurton and Wadge (1981) used regional gravity data to model the geometry of the Vale of Eden Basin, and con-cluded that, in Early Permian (Penrith Sandstone Forma-tion) times at least, the depositional basin coincided roughly with the present day Vale of Eden. These same gravity data also appear to indicate that the Vale of Eden Basin was separated from the Carlisle Basin to the north-west (Figure 2) by an inter-basin high, where a relatively thin Permian and Triassic sequence is preserved.
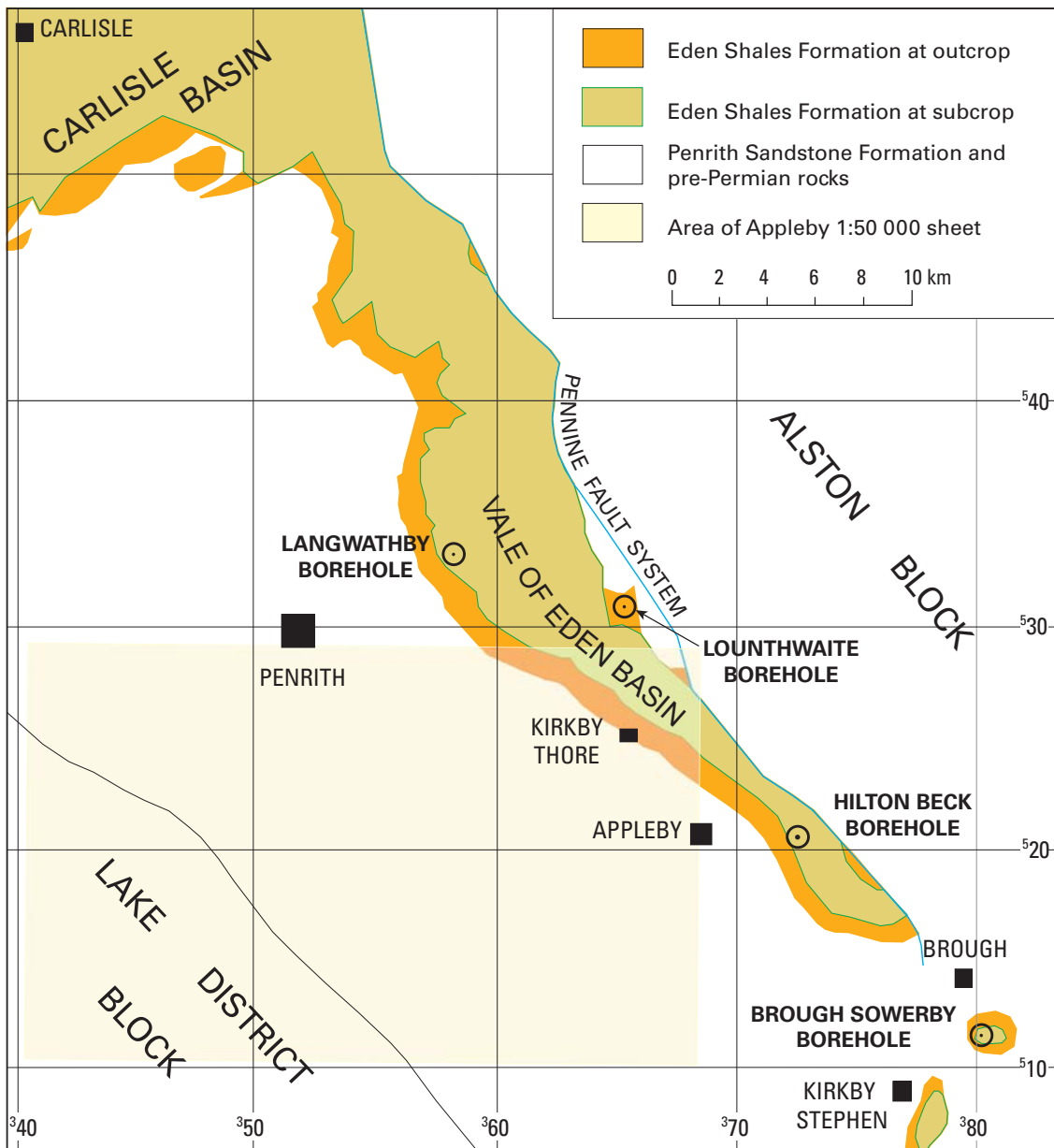
Figure 2   Crop of the Eden Shales Formation in the Vale of Eden (based on Holliday, 1993, fig. 1).

3 Lithostratigraphy

Barnes et al. (1994) published a revised lithostratigraphy for the Permian and Triassic of the Cumbrian coast. At group level this scheme is applicable to the Vale of Eden. It is summarised in Table 1 and presented graphically in Figure 3, showing the approximate thicknesses of the major lithostratigraphical units in the Appleby district.

Table 1 Permian and Triassic lithostratigraphy of Cumbria, north-west England.

	Group lithostratigraphy (Barnes et al., 1994)	**Sellafield District** (Barnes et al., 1994; Akhurst et al., 1997)	**Appleby district** (this report)
Triassic	Sherwood Sandstone Group	Calder Sandstone Formation	(Calder Sandstone Formation?)
		St Bees Sandstone Formation	St Bees Sandstone Formation
Permian	Cumbrian Coast Group	St Bees Shale Formation	Eden Shales Formation
		St Bees Evaporite Formation	
	Appleby Group	Brockram	Penrith Sandstone Formation (including fluvial and debris flow breccia facies)

4 Chronostratigraphy

The Permian and Triassic rocks of the Appleby district are almost exclusively of continental sedimentary origin, and have yielded no biostratigraphically useful fossils. The only fossils recorded from the Early Permian of the Vale of Eden are vertebrate footprints, described from the Penrith Sandstone Formation in the Penrith district (Smith, 1884; Hickling, 1909). Macrofossil evidence from the Brough district (Burgess and Holliday, 1979, p. 69) indicates that the Belah Dolomite (from the upper part of the Eden Shales Formation, see below for details) is of EZ3, or Late Permian, age. Also in the Brough district, plant fossils from the Hilton Plant Beds (the lowest part of the Eden Shales Formation) indicate an age range of EZ1 to EZ3 (Burgess

and Holliday, 1979). Collectively, the evidence indicates that the Eden Shales Formation immediately to the east of the Appleby district is, in part, of Late Permian age, ranging from at least EZ1 to EZ3.

Consequential upon the age of the Eden Shales Formation are the interpretations that the underlying Penrith Sandstone Formation (including the Brockram) is of Early Permian age, and that the overlying St Bees Sandstone Formation is of Early Triassic age (Arthurton et al., 1978). However, in reality there is no biostratigraphical evidence to indicate the true position of the base of the Triassic in the Vale of Eden, and its inferred placement at the base of the St Bees Sandstone Formation is arbitrary (Arthurton et al., 1978).
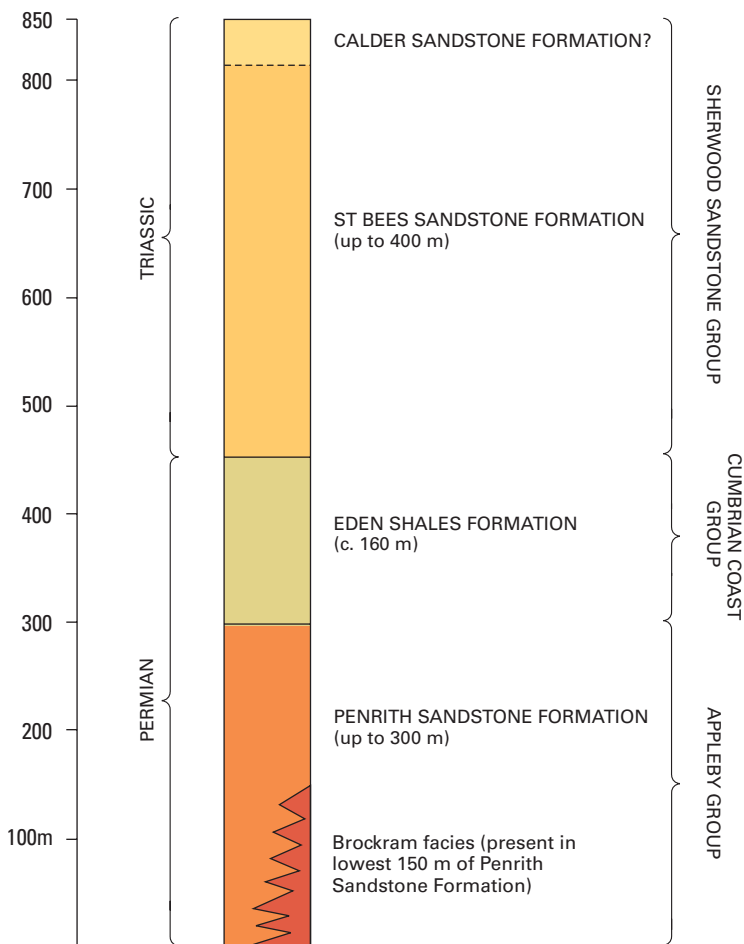
Figure 3   Generalised vertical section through the Permian and Triassic sequences.

5   Appleby Group

The Appleby Group (Table 1 and Figure 3), comprising the Penrith Sandstone Formation and the Brockram, crops out in a belt striking from Appleby [680 200] in the south-east to Eamont Bridge [520 280] in the north-west (Figure 1). The predominance of cross-bedding in the sandstones and the generally massive nature of the Brockram mean that true bedding is rarely recognisable. Consequently the thickness of the group is difficult to calculate, but may be as much as 400 m.

The sequence dips at an average of less than 10° to the north or north-east, and rests upon the underlying Carboniferous with an angular unconformity. The oldest Permian rocks overlap Carboniferous horizons ranging from the Stainmore Formation in the north-west (e.g. east of Melkinthorpe [56 24], see Figure 1) to Alston Formation siliciclastic rocks between the Scar Limestone and Five Yard Limestone members in the vicinity of Lookingflatt [684 172], south of Appleby. It is conceivable, but unproved, that the oldest Permian rocks overlie Westphalian rocks at depth in the more north-easterly (i.e. the deeper) parts of the Vale of Eden Basin.

5.1   BROCKRAM

Brockram is a term given to breccia facies present normally at the base of the Lower Permian sandstones of Cumbria (Figures 3 and 4). The term is believed to have originated as a local descriptive name for 'broken rock', quarried at Burrells [180 677] (Figure 1) and Kirkby Stephen (Waugh, 1967). The breccias are most common in the lower parts of the Penrith Sandstone Formation. They are laterally impersistent, polygenetic, and occur at several stratigraphical horizons; for these reasons the Brockram is regarded as a series of facies, and is not recognised as a formal lithostratigraphical unit.

Brockram is present only in the eastern part of the Appleby district (Figure 4). This restricted geographical distribution is consistent with the regional picture described by Arthurton et al. (1978) and Holliday (1993), in which the thickness of the basal Permian breccias diminishes north-westwards from a maximum in the Brough area [790 140] to nil in the Langwathby area [550 390]. This topic is discussed further below.

The best exposures of the Brockram in the Appleby district are those in the Burrells-Hoff area [670 190 to 690 170] (Figure 1), though other exposures occur on the eastern flanks of Appleby Castle [6864 1994], in a small, disused quarry at Thistley Hill [6768 2044], in Gill Syke [694 170], Knock Bank [667 178], Barwise Hall [661 177] and Big Clinch [663 184]. The westernmost exposures of Brockram at the base of the Penrith Sandstone Formation in the district are at Lyvenet Bridge [613 227]. Thin beds of breccia, presumed to be Brockram, were reported by Dakyns et al. (1897) from the uppermost parts of the section

NORTH-WEST   SOUTH-EST

Acorn Bank   Kirkby Thore   Long Marton - Crackenthorpe   Brampton - Appleby

ST BEES SANDSTONE FORMATION

EDEN SHALES FORMATION
D-BED
BELAH DOLOMITE
C-BED
B-BED   HILTON PLANT BEDS
A-BED

PENRITH SANDSTONE FORMATION

BROCKRAM

STAINMORE FORMATION   GREAT LIMESTONE MEMBER   ALSTON FORMATION

I cm = 50 m vertical scale (1:5000)

Figure 4   Schematic section through the Permian and Triassic sequences of the Appleby district.

in Trough Gill [5862 2378], but were not found during the present resurvey. These breccias would occupy a stratigraphical position many tens of metres above the base of the Penrith Sandstone Formation. Brockram is largely unknown from the remainder of the district, though exposure of the Permian sequence is admittedly poor.

In the Burrells-Hoff area, the Brockram breccias form a continuous, 1.5 km long, scarp feature extending northwestwards from th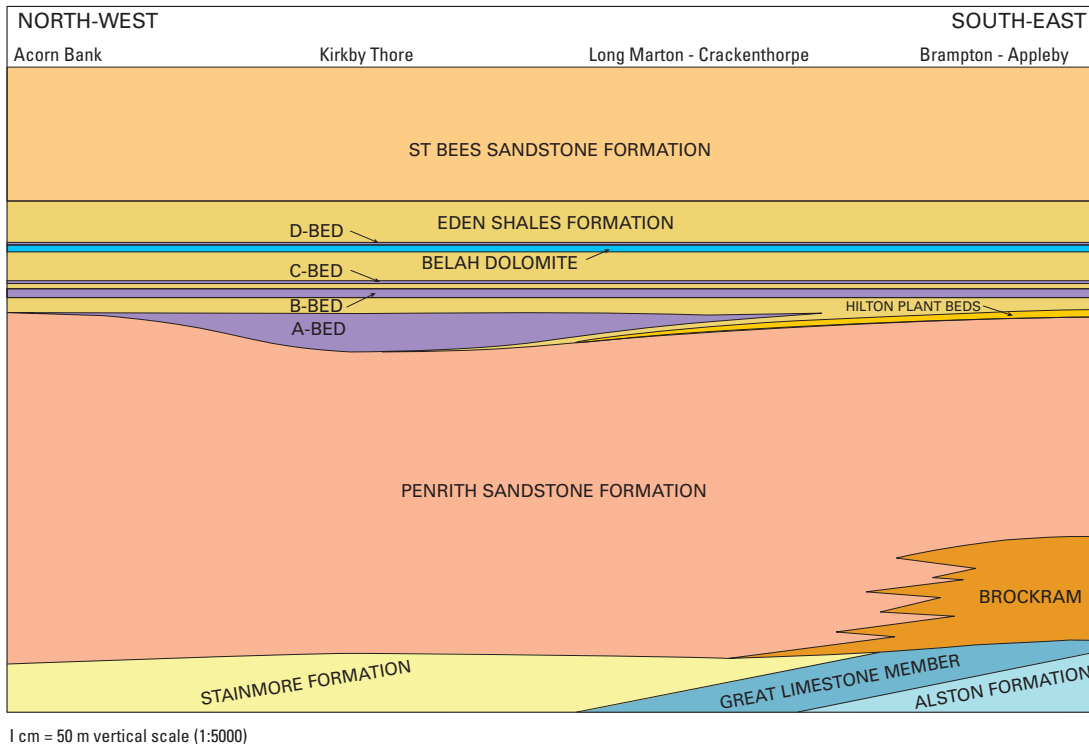e area [681 175] north-west of Lookingflatt to Bandley Bridge [671 188]. The best exposures are in a disused quarry [6768 1801] at Burrells, and in a crag feature which extends south-east from the quarry towards Lookingflatt. It is impossible to calculate the total thickness of breccias in the area because of the lack of exposure, but they are certainly present in the lowest 150 m or so of the Permian sequence between Hoff and Appleby.

Up to 10 m of irregularly bedded breccias and sandstones are exposed in the quarry face at Burrells [6768 1801]. Beds are mainly sheet-like, though lenticular units with erosive bases also occur. The breccias are polymictic, and both clast- and matrix-supported. The clasts are mostly angular or subangular, up to 80 cm in size, and are almost entirely of Carboniferous limestone and sandstone, commonly reddened. The matrix is of coarse sand grade, and contains rare, reddened 'millet seed' quartz grains derived from the Penrith Sandstone Formation. No exotic clasts were seen during the present survey, but the matrix is said to contain exotic grains of possible Early Palaeozoic origin (Mr Iain Burgess, personal communication, 1998). The rocks exposed in the crag feature [6790 1773] to the south-east of the quarry at Burrells are similar to those described above, but clast size is generally smaller, and the breccias are mostly clast-supported. Crude, upward coarsening sedimentary cycles here suggest fluvial depositional processes.

Very similar facies are exposed in a small, disused quarry [6768 2044] on the left bank of the River Eden at Thistley Hill, where approximately 8 m of breccias are exposed. The total thickness of breccias in the area is undoubtedly more, but cannot be calculated because of the lack of exposure.

The sedimentology of the Brockrams of Cumbria was the subject of a PhD thesis study by Macchi (1981). Macchi described a second brockram breccia facies of exclusively fluvial origin from farther east in the Vale of Eden Basin. This facies has been referred to as the 'Upper Brockram' by previous authors. It occurs in the higher parts of the Penrith Sandstone Formation, and consists of finer grained breccias that were deposited entirely by ephemeral streams or rivers under flash-flood conditions. These beds, or their correlatives, are not known to be exposed in the Appleby district, but they may be present at subcrop. It is probable that the 'breccias' described from Trough Gill [5862 2378] by Dakyns et al. (1897) were of this fluvial brockram facies.

5.1.1 Interpretation

Macchi (1981) concluded that the breccias that comprise the Brockram at the base of the Penrith Sandstone Formation were deposited on subaerial alluvial fan bodies in arid to semi-arid climatic conditions. The breccias are the products of two discrete depositional processes that occurred in subaerial alluvial fan settings, though Macchi acknowledged that a continuum exists between the two. The predominantly matrix-supported, sheet-like breccias that comprise most of the Brockram sequences are predominantly of fluvial origin, deposited by unconfined flow processes. In contrast, the more massive, clast-supported units are considered more likely to be the products of mass/debris flow processes.

Regional evidence was interpreted as indicating that the geometry of the breccia bodies was strongly wedge-shaped in the direction of sediment transport. This direction, based upon a palaeocurrent analysis of cross-laminated sandstones within the sequence at Burrells quarry, was interpreted as indicating south-west to north-east palaeoflow. These interpretations explain the north-westward thinning of the Brockram in the Vale of Eden.

5.1.2 Provenance

The clast population of the Brockram in the Appleby district consists of 85% or more Carboniferous limestone, and 15% or less Carboniferous sandstone and chert, strongly suggesting a very local provenance. Lower Palaeozoic clasts, and dolerite clasts from the late Carboniferous Whin Sill were reported (Dunham, 1932; Versey, 1939) from fluvial breccias in the higher parts of the Penrith Sandstone Formation (the 'Upper Brockram'), east of the Appleby district.

5.2 PENRITH SANDSTONE FORMATION

The Penrith Sandstone Formation forms a west-north-west-striking outcrop, extending from Appleby in the south-east to Brougham in the north-west [530 280] (Figure 1). It is generally poorly exposed, particularly in the east of the district. The best exposures occur in the west where, partly because of secondary silica cementation, the sandstones are more indurated and form weak scarp features. The thickness of the formation is difficult to calculate with accuracy because of the lack of exposure and the absence of true bedding data. However, the maximum thickness may be as much as 400 m. In the Penrith area the formation is an important aquifer.

Typically, the sandstones of the Penrith Sandstone Formation are dull, brick-red coloured, medium- to coarse-grained, well sorted, and poorly cemented. 'Millet-seed' rounded grains — typical of, but not exclusive to, aeolian facies — are common. Large-scale cross-stratification occurs throughout, and foreset units are separated by flat or gently dipping erosion surfaces. Where secondary silicification has occurred the rock is hard, coherent, and splits readily along foreset surfaces to provide an excellent building stone. Generally, silicification is most common in the middle to upper parts of the formation in the Appleby district. However, the presence or absence of silicification is very variable locally, as noted by Waugh (1970) and Arthurton and Wadge (1981). Waugh (1970) interpreted the silicification process as penecontemporaneous with deposition, resulting from the production of silica dust from abrasion in the arid environment, and its dissolution in alkaline groundwaters.

Good exposures occur along the River Eden at Oglebird Plantation [6008 2708], north-west of Temple Sowerby [6062 2772], at Bongate Scar, Appleby [6884 1998], in disused quarries on Slate Hill [590 260] and Salter Hill [5842 2639] and in Whinfell Forest [570 270]. However, the best exposures are in the vicinity of the village of Cliburn [580 240]. Two, easily accessible sections have excellent exposures of the formation. The first, just north of Commonholme Bridge [576 248] is a quarried set of natural exposures. The second section, in Trough Gill [from 5874 2411 to 5862 2378], was described as 'the most

laterally extensive exposure in the Eden Valley' (Macchi, 1981).

Medium- to coarse-grained sandstones are exposed for a distance of some 280 m in the Trough Gill section [5874 2411 to 5862 2378]. Thin beds of breccia reported by Dakyns et al. (1897) from the uppermost parts of the Trough Gill section were not seen by Macchi (1981) or by the present author, and the exposures probably no longer exist. Approximately thirteen distinct dune bed forms are recognisable in the section (Macchi, 1981), separated by trough-shaped bounding surfaces. The morphology of the dune bed forms is interpreted as crescentic within a barchanoid ridge dune field, with dune axes trending west-north-west.

Macchi (1981) carried out a very detailed palaeocurrent analysis on the Penrith Sandstone Formation. He measured 277 foreset orientations from throughout the Vale of Eden, and calculated a mean vector of 281°, indicating a palaeowind direction from the east-south-east. This palaeocurrent analysis agrees closely with the earlier interpretations of Waugh (1970), and Arthurton and Wadge (1981).

6   Cumbrian Coast Group

The earliest attempts at classification of the Upper Permian rocks of the Vale of Eden (Goodchild, 1893; Dakyns et al., 1897) were severely hampered by the lack of exposure and the absence of borehole data. Before the 1930s the exposures in Hilton Beck (east of the Appleby district [710 200 to 730 210]) and stratigraphically restricted sections in gypsum and anhydrite workings were the only sources of information. Sherlock and Hollingworth (1938) and Hollingworth (1942) used boreholes to establish the succession, but miscorrelated the sequence established from the subsurface with that exposed in the Hilton Beck section. Meyer (1965) subsequently corrected the miscorrelation, and his classification remains largely unchanged to the present day.

Undoubtedly the most important advances in understanding the Upper Permian rocks of the Vale of Eden have been made as a result of the four boreholes drilled in the late 1960s and early 1970s during the resurvey of the Brough and Penrith 1:50 000 sheets (borehole locations shown on Figure 2). The boreholes and their interpretations are described by Arthurton (1971), Burgess and Holliday (1974; 1979), Arthurton et al. (1978), and Arthurton and Wadge (1981). Since then very few new data have entered the public domain, these publications remain of fundamental importance to our knowledge and understanding of the Upper Permian rocks of the Vale of Eden.

6.1   EDEN SHALES FORMATION

The main outcrop of the Eden Shales Formation (Figure 2) in the Appleby district strikes north-westwards from north of Appleby, through Kirkby Thore [630 250] to Culgaith [600 290]. The formation is also present in a small, fault block north of Close House [670 270 to 680 290], but is not exposed there.

The type section of the Eden Shales Formation is the fully cored and geophysically logged Hilton Beck Borehole (Burgess and Holliday, 1974) sited in Hilton Beck [7285 2056], 3.75 km east of the eastern limit of the Appleby district (Figure 2). The thickness of the Eden Shales Formation in the Hilton Beck Borehole is 184.73 m, and is the maximum proved development of the formation in the Vale of Eden. Despite its status as the type section of the Eden Shales Formation, important differences exist between the Hilton borehole sequence and that proved in the Appleby district, and these are summarised below. A generalised vertical section through the formation is presented in Figure 5.

The Eden Shales Formation comprises mudstone, siltstone, fine- to coarse-grained sandstone, breccia and conglomerate. The sequence exhibits considerable lateral and vertical lithological variation (Figures 4 and 5). The rocks are mostly red in colour, but brown, green and grey beds are also present, and locally form significant parts of the sequence. In addition, gypsum and anhydrite in the form of beds, scattered nodules, intergranular cements and displacive veins form a major part of the formation.

Following the practice of Sherlock and Hollingworth (1938) and most later authors, the four main evaporite beds

of the Eden Shales Formation (termed A bed, B bed, C bed and D bed) and the marine Belah Dolomite have been used to informally divide the formation, and as a means of correlation within and beyond the Vale of Eden.

Exposures of the Eden Shales Formation in the Appleby district are very few and very poor, due to the dissolution of evaporite minerals. Thickness variations and general lithological characteristics are known from commercially confidential boreholes drilled during exploration of the economically important gypsum and anhydrite deposits, centred on Kirkby Thore. However, many of the boreholes were drilled, rather than cored, until the target horizon was reached, and their lithological descriptions are very generalised. The descriptions of the various intervals of the Eden Shales Formation below are based mainly therefore upon the detailed interpretations of the Langwathby (Arthurton, 1971) and Hilton Beck (Burgess and Holliday, 1974) boreholes, and the account of Meyer (1965).

6.1.1 Hilton Plant Beds

The Hilton Plant Beds are the oldest part of the Eden Shales Formation, and in the Hilton area they rest directly upon the top of the Penrith Sandstone Formation. They comprise a local, laterally impersistent sequence that dies out abruptly westwards (Figures 4 and 5). The Hilton Plant Beds occur at the same horizon as the A bed, and may, at least in part, be contemporaneous in the area between Appleby and Acorn Bank [610 270] (Arthurton et al. 1978; Burgess and Holliday, 1979).

The sequence is exposed east of the Appleby district in Hilton Beck and is described from the Hilton Beck Borehole. Although not exposed within the district, the sequence is present at subcrop north of Appleby, where up to 7.49 m are present at the base of the Eden Shales Formation. In the Hilton Beck Borehole the Hilton Plant Beds are 18.01 m thick, and consist of laminated, calcareous or dolomitic fine-grained sandstones with abundant carbonaceous plant beds. The plant fossils (see Burgess and Holliday, 1979 for details) indicate an age range of EZ1 to EZ3.

6.1.2 A bed

This evaporitic unit has a remarkably restricted geographical distribution (Figure 4), and reaches a maximum thickness of 42.44 m south [637 273] of Black Leases. It is absent from the Hilton Beck Borehole, but in the eastern parts of the Appleby district it exceeds 35 m in thickness. It is absent from the area north-west of Acorn Bank, where the lowest rocks of the Eden Shales Formation are mudstones and siltstones, but is present farther north-west in the Langwathby borehole. The A bed is the main mining target of the gypsum-anhydrite mining industry centred on Kirkby Thore.

Where the A bed is greater than 30 m thick it generally rests directly on the Penrith Sandstone Formation. Where it is significantly less than its maximum thickness, it is commonly separated from the underlying Penrith Sandstone

Figure 5 Generalised vertical section through the Eden Shales Formation in the Appleby district.

Formation by up to 4 m of siltstones and dolomitic limestones. In the Langwathby Borehole, the supposed correlative of the A bed is 2.30 m thick (Arthurton, 1971) and consists mainly of nodular anhydrite in a laminated matrix of sandstone, siltstone and mudstone. Much of the anhydrite is replaced by nodular gypsum. The lower part of the bed consists of nodular anhydrite in a sandstone matrix, and the upper part of nodular anhydrite in a finer grained siltstone matrix, commonly rich in plant remains.

Meyer (1965) mentioned exposures of gypsum, dolostone and 'blue-grey shales' with plant material, belonging apparently to the A bed, on the banks of the river Eden [5994 2950] at Winderwath, near Culgaith. Meyer described approximately 9 m of mudstones with thin beds of gypsum and dolostone here. Boreholes sited within 400 m to the south-east of the locality show the A bed to be either absent, or represented as approximately 15 m of siltstones and mudstones with gypsum bands

Meyer (1965) also described a crude three-fold division of the A bed from borehole records in the Kirkby Thore area, summarised below.

'Thin layers of gypsum, anhydrite and dolomite with layers of argillaceous material'	18.29
'Contorted, discrete layers of gypsum or anhydrite separated by red or grey shale'	4.57
'Thin beds of spherical/lenticular gypsum/anhydrite separated by red-grey shale'	5.49 m

6.1.3 Sequence between top of A bed and base of B bed

This part of the sequence is not exposed in the Appleby district, and because the A bed is absent from the Hilton Beck Borehole, it is not known exactly to which part of the Hilton sequence it should be correlated. The most likely correlatives are 'pinkish brown to cream sandstones….with thin reddish brown silty mudstone partings' that occur below the B bed. The higher parts of the Hilton Beck sequence were said to contain abundant gypsum-anhydrite nodules, culminating in the B bed (Burgess and Holliday, 1974).

6.1.4 B bed

Both Hollingworth (1938) and Arthurton (1971) noted that the B bed is the most widely persistent evaporite horizon in the Permian of Cumbria, being recognisable from Cocklakes in the Carlisle Basin, as far south-east as the Hilton Beck Borehole. Within the Appleby district the bed reaches a maximum known thickness of 6.50 m. It has been mined extensively, and was formerly exposed in a series of small pits and quarries that extended from the vicinity of Stamp Hill Farm [650 262] north-westwards towards Hale Hill [643 274]. Some of these workings are described by Sherlock and Hollingworth (1938), but they are either no longer exposed, or now concealed beneath made ground.

The bed is described in detail from the Langwathby Borehole by Arthurton (1971) and from the Hilton Beck Borehole (Burgess and Holliday, 1974). At Langwathby the B bed is 4.88 m thick, and consists mainly of fine-grained anhydrite, with some gypsum. The lower and upper contacts here are sharply defined by grey, plant-bearing siltstones and mudstones. Complex anhydrite and gypsum replacement textures were described by Arthurton (1971). In the Hilton Beck Borehole the B bed is 3.05 m thick, and is lithologically very similar to that described from Langwathby, though it consists mainly of anhydrite.

The interval between the A and B beds was not described in detail from the Langwathby Borehole (Arthurton, 1971).

6.1.5 Sequence between top of B bed and base of C bed

This interval is not exposed in the Appleby district, but was described in detail from the Hilton Beck Borehole (Burgess and Holliday, 1974). There, it consists of a 6 m thick interval of reddish brown sandstones with thin siltstone partings. The lowest 2.75 m are interpreted as being mainly aeolian deposits, and the uppermost 3.25 m as mainly fluvial.

6.1.6 C bed

This horizon is not exposed in the Appleby district, but from borehole evidence it is known to vary in thickness here between 0.38 and 3.8 m. In the Hilton Beck Borehole (Burgess and Holliday, 1974) it consists of 1.53 m of 'red, green and grey laminated sandstones, siltstones, and mudstones with numerous gypsum-anhydrite nodules'. The C bed is 1.50 m thick in the Langwathby Borehole (Arthurton, 1971), and consists of layered anhydrite in the lower part and nodular anhydrite in the upper part.

6.1.7 Sequence between top of C bed and base of D bed, including Belah Dolomite

This part of the sequence is not exposed in the Appleby district. In the Hilton Beck Borehole (Burgess and Holliday,

1974) the sequence consists of mainly red-brown fine-grained sandstones, siltstones and silty mudstones, with mud-flake breccias and gypsum-anhydrite nodules common at many horizons. Similar lithologies are described from the Langwathby Borehole (Arthurton, 1971).

The Belah Dolomite occurs immediately below the D bed throughout the Vale of Eden, and is therefore an extremely useful marker horizon. In the Brough area (Burgess and Holliday, 1979) the Belah Dolomite yielded a shelly fauna of EZ3 age. Borehole evidence indicates that its thickness may be as much as 8.20 m in the Appleby district, where it consists mainly of dolostone, containing laminae of very carbonaceous mudstone, sandstone laminae, intraclast breccias, gypsum and anhydrite nodules, and veins of fibrous gypsum. Burgess and Holliday (1974) described an informal two-fold division of the Belah Dolomite in the Hilton Beck Borehole. There, the lowermost 1.27 m consists of buff dolomitic siltstones with micaceous siltstone laminae; there is rare carbonaceous and algal mat material. The uppermost 3.12 m consists of finely algal-laminated dolostone with abundant laminae of carbonaceous siltstone and black mudstone.

Arthurton (1971) described another evaporite horizon, the Langwathby Bed, from the interval between the C bed and the Belah Dolomite. This informal unit consists of 1.07 m of clastic-free, 'algal-mat gypsum anhydrite' within a 3 m evaporite-dominated interval. The Langwathby Bed is not present in the Hilton Beck Borehole, and has not been recognised in subsurface data from the Appleby district. However, the quality of most of the borehole logs in the Appleby district is poor, and the presence of the Langwathby Bed here cannot be categorically refuted.

6.1.8 D bed

The D bed is present throughout the Vale of Eden, and in the Appleby district it varies in thickness between 0.45 and 3.70 m. In boreholes within the district, the D bed is described as consisting mainly of massive and nodular anhydrite, with abundant secondary replacement gypsum and fibrous gypsum veins. Finely laminated 'algal-mat' dolostone and anhydrite are described from the lower part. Similar lithologies are described from the Hilton Beck Borehole (Burgess and Holliday, 1974), where 'intense penecontemporaneous deformation' affected the anhydrite and gypsum deposits. In the Langwathby Borehole (Arthurton, 1971) the D bed consists of 2.59 m of 'crudely layered' anhydrite.

6.1.9 Sequence above D bed

This sequence is up to 60 m thick, and comprises well laminated mudstones and siltstones, with sandstone increasing upwards. Anhydrite and gypsum nodules are present in the lower parts of the sequence. Burgess and Holliday (1974) believed that the finer grained lower part of this sequence is dominantly aeolian, and is succeeded by sandstones of increasingly fluvial character. The boundary between these rocks and the overlying St Bees Sandstone Formation is transitional, and is taken at the point where thick bedded, fluvial sandstones become dominant.

6.2   DEPOSITIONAL ENVIRONMENTS

Burgess and Holliday (1974) illustrated a variety of sedimentary structures from various horizons of the Hilton Borehole, including fluvial cross-lamination, desiccation features, mud-flake breccias, and adhesion ripples. Together with the presence of evaporites throughout the sequence, these features are interpreted (Burgess and Holliday, 1974; Holliday, 1993) as indicating a semi-arid to arid, continental alluvial plain or sabkha environment of deposition, in which the main evaporite beds were deposited in saline lakes, and in which aeolian depositional processes were periodically active. Burgess and Holliday (1974) believed that the main evaporite beds were deposited by infiltration of marine groundwaters into a coastal sabkha environment, and in so doing implied a relationship between the formation of evaporite beds and high stands of sea level. The Belah Dolomite is clearly the product of a marine incursion that can be related to a regional sea-level high stand.

Arthurton et al. (1978) explained the extremely limited geographical extent of the A bed by postulating that these evaporites accumulated in a restricted lacustrine environment within a pre-existing topographical hollow on the dune fields of the Penrith Sandstone Formation. It was suggested that the lake was fed from the south-east by a fluvial system, in which the sheet-flood sandstones of the Hilton Plant Beds were deposited. Arthurton and Wadge (1981) speculated that the topographical hollow might have been produced by selective deflation of unsilicified parts of the Penrith Sandstone dune fields.

Ahmed Benan and Kocurek (2000) described thick (up to 15 m) gypsum deposits that accumulated in interaeolian dune depressions, from the Jurassic of New Mexico, USA. The similarities between the relationships described from New Mexico and the Vale of Eden are striking, and add considerable weight to the earlier interpretations of Arthurton et al. (1978), and Arthurton and Wadge (1981).

An important palaeoenvironmental change occurred following deposition of the D bed. Burgess and Holliday (1974) interpreted siltstones and sandstones at this horizon to be of aeolian origin, deposited on an emergent land surface. These in turn are succeeded upwards by sandstones of increasingly fluvial character, culminating in the almost exclusively fluvial facies of the St Bees Sandstone Formation, that spread over much of Cumbria at this time.

6.3   REGIONAL CORRELATION

Holliday (1993) used geophysical log data to make regional correlations between the Eden Shales Formation of the Vale of Eden and the contemporaneous rocks of the Carlisle Basin, West Cumbria, the East Irish Sea Basin and the Southern North Sea Basin. He demonstrated close similarities between the Vale of Eden and Southern North Sea Basin sequences, and concluded that there must have been a persistent connection between these two depocentres from late EZ1 times onwards. Holliday concluded that the deposition of sabkha and saline lake evaporites in the Vale of Eden occurred by periodic westward extension of these facies from the Southern North Sea Basin, and suggested that the cross-Pennine connection between the two areas was the Stainmore Trough. The Belah Dolomite was deposited during the only truly marine conditions to have occurred in the Vale of Eden Basin.

Furthermore, Holliday concluded that there is no evidence to support the idea that the Bakevillia Sea ever extended from the East Irish Sea Basin into the Vale of Eden, or therefore that the Eden Shales Formation evaporites are its marginal deposits. The Eden Shales Formation evaporites are not, therefore, continuous with the St Bees evaporites of west Cumbria and the East Irish Sea Basin.

7 Sherwood Sandstone Group

7.1 ST BEES SANDSTONE FORMATION

The St Bees Sandstone Formation is generally very poorly exposed in the Appleby district. The formation caps a prominent scarp feature between the villages of Culgaith [600 290] and Newbiggin [630 280]. Boreholes have proved a thickness of at least 180 m in the Appleby district, but the true maximum thickness could be as much as 400 m. The maximum thickness of the St Bees Sandstone Formation in west Cumbria is up to 600 m (Akhurst et al., 1997).

The contact between the underlying Eden Shales Formation and the base of the St Bees Sandstone Formation is not exposed. In boreholes it is clearly a gradational contact, but is taken at the base of the first thick-bedded fluvial sandstones above the thin-bedded sandstones and siltstones of the Eden Shales Formation.

Generally, the rocks of the St Bees Sandstone Formation are brick-red to yellow, fine- to coarse-grained sandstones, in medium to thick beds, and commonly cross-bedded. Thin siltstone partings occur throughout. The sandstones are generally well cemented, and the rock has been used widely as a building stone. In contrast to the Penrith Sandstone Formation, the St Bees Sandstone Formation is micaceous and feldspathic.

Though the sedimentology of the formation has not been studied in detail in the Appleby district, its general characteristics are believed to be very similar to those described for the same rocks in west Cumbria by Jones and Ambrose (1994). There, the formation is interpreted as having been deposited in a sandy, braided, low-sinuosity, north-north-west-flowing fluvial system, in which channel deposits were laterally and vertically superimposed to form an amalgamated sand-body complex.

Thin aeolian sandstones are present, but uncommon, and indicate reworking of earlier fluvial deposits.

7.2 CALDER SANDSTONE FORMATION

This formation (Barnes et al., 1994) comprises a predominantly aeolian (with lesser fluvial) sandstone sequence that overlies the St Bees Sandstone Formation in west Cumbria. Barnes et al. (1994) and Dr Douglas Holliday (personal communication, November 2000) speculated that the uppermost parts of the St Bees Sandstone Formation in the Vale of Eden might be part of the Calder Sandstone Formation. This tentative correlation is based upon the descriptions of the highest parts of the St Bees Sandstone Formation in the Penrith District (Arthurton and Wadge, 1981) as softer, more friable, and less well cemented than the lower parts.

By far the best exposures are in Dufton Gill [680 240 to 690 260], but further notable exposures occur in Milburn Beck [658 287, 639 290, and 634 291]. The stratigraphically highest parts of the St Bees Sandstone Formation in the Appleby district occur on the south-western (downthrow) side of the Pennine fault system east of Knock [680 260], and on the south-western (downthrow) side of the Lounthwaite Fault at Milburn. Exposure is very poor in both these areas, but the best sections (in a small, disused quarry [6497 2916] south-west of Milburn, and in another old quarry section [6841 2666] south-east of Knock) contain rocks that appear to be of fluvial origin. Ordinarily, these rocks would be interpreted as St Bees Sandstone Formation, but it is possible that they represent fluvial intervals within the Calder Sandstone Formation. Although the presence or absence of the Calder Sandstone Formation in the Appleby district cannot be categorically proved at the present time, it is more likely that the formation is absent.

8 Structure

The paucity of exposure in the area means that little can be deduced about structure from field evidence alone. However, the abandonment plans for Stamp Hill Mine and structural plans made available to the BGS during the course of the present project contain a wealth of information.

Dip throughout the area is generally ten degrees or less to the north or north-east, but increases in the east of the area to as much as thirty-five degrees.

The area is dissected by numerous, closely spaced, normal faults with a north-north-west trend, and with throws mostly of less than twenty metres. This fault trend is consistent with that in the Permian and Triassic basins of the East Irish Sea Basin and southern Scotland, where sequences are preserved in half-graben basins with approximately north–south orientated bounding faults. The age of the faulting in the Vale of Eden is not known.

9 Subsidence

Gypsum and anhydrite have been mined in the Appleby district for over a hundred years. A large number of collapses of underground workings are known to have occurred during this time; most of these are undocumented formally, but some are described in colloquial terms by Rogers (1994). However, the extent to which the underground collapses have caused subsidence at the surface is incompletely known, and the undulating topography of the surface covered by Quaternary deposits makes difficult the recognition and delineation of subsidence hollows.

Among the more obvious subsidence features are those in the vicinity of Acorn Bank Cottages [6192 2780], where a set of steep-sided pits, some 5 m deep and up to 15 m across, occurs in pasture land. It is not known with certainty whether these pits are related to underground workings at the now defunct Acorn Bank Mine, or whether they are natural subsidence hollows related to gypsum dissolution. Other areas of surface subsidence occur in the vicinity of Stamp Hill Mine, for example at [666 253].

Ryder and Cooper (1993) described a natural cave system in gypsum deposits being mined in the B bed at Houtsay Quarry, Newbiggin [624 276]. Sherlock and Hollingworth (1938) and Dakyns et al. (1897) also noted karst-like dissolution features at the nearby abandoned McGhie's Quarry [642 268] and Acorn Bank Mine [618 278]. The cave system described by Ryder and Cooper has since been consumed by mining. Although it was not really extensive, it raises the possibility that other concealed cave systems, and the potential hazards they present to surface stability, do occur within the district.

10   Economic geology

There is a long history of gypsum and anhydrite mining in the Appleby district. These minerals were formerly worked at a number of quarries and mines, the most important of which were Houtsay, Acorn Bank, Longriggs, Stamp Hill, Newbiggin and Birkshead. In recent years, the demand for mineral gypsum has declined due to the availability of desulphurisation gypsum from coal-fired power stations, and today only the Newbiggin and Birkshead mines remain active. The A bed is mined for gypsum at Birkshead, while B bed anhydrite is mined at Newbiggin.

There are no modern descriptions of the active mines, but Sherlock and Hollingworth (1938) published accounts of the Stamp Hill and Acorn Bank mines, and of the Thistle Plaster Quarry and Mine (formerly known also as McGhie's Quarry and Mine) on the site of the present day Birkshead Mine.

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