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Subsidence and foundering of strata caused by the dissolution of Permian gypsum in the Ripon and Bedale areas, North Yorkshire

A.H. Cooper

SUMMARY: Underground dissolution of thick gypsum beds in the Edlington Formation and Roxby Formation of the Zechstein sequence in North Yorkshire, England, has resulted in a 3 km-wide and 100 km-long belt of ground susceptible to foundering. Within this belt a large subsidence depression at Snape Mires, near Bedale, was largely filled with lacustrine deposits in the later part of the Late Devensian and during the Flandrian. South of Snape Mires the Nosterfield–Ripon–Bishop Monkton area has suffered about 40 episodes of subsidence in the past 150 years, and the presence of several hundred other subsidence hollows indicates considerable activity from the later part of the Devensian onwards. The linear and grid-like arrangement of these subsidence hollows indicates collapse at intersections in a joint-controlled cave system. Linear subsidence features at Snape Mires are also joint-controlled. The transition from anhydrite at depth to secondary gypsum near surface marks the down-dip limit of the subsidence-prone belt. Cavities are propagated upwards by roof collapse of caverns in the gypsum, leading to the formation of breccia pipes. Choking of the pipes can reduce the surface expression of the underground collapse, but the larger cavities are liable to produce pipes that reach the surface even at the eastern boundary of the 3 km-wide belt described. Further subsidence in the Ripon area is predicted and some suggestions for remedial measures are given.

Evidence of the presence of soluble rocks within the Permian sequence is provided from time to time by dramatic subsidence resulting from their subsurface dissolution. The most graphic record of the oldest event is in Mayhall's *Annals of Yorkshire* (1878, Vol. 1, p. 187) where it is recorded that in 1796: 'On October 16th about six o'clock in the morning, the inhabitants of Ripon were greatly alarmed by a violent earthquake, which shook almost every house in the town; a mile from which, near Littlethorpe, about three roods of ground sunk nineteen fathoms, and a large ash tree growing on the spot entirely disappeared. For some time the gulph continued to increase, and an immense body of water issued from it, which filled the inhabitants with fear, for as there were no coal pits in the neighbourhood, it was evidently a great natural convulsion.' Between 1796 and 1881 eight more subsidences were recorded by various authors (Table 1). Suggestions that the subsidence hollows were the result of gypsum dissolution (Tute 1868, 1870; Kendall & Wroot 1924) were supported by Smith (1972).

During the recent 1:10,000-scale geological resurvey of the area the author recorded several hundred subsidence hollows affecting Late Devensian and Flandrian deposits. Many of the local landowners and farmers remember holes appearing on their land and their recollections have allowed the record of subsidences to be updated (Table 2, Fig. 2).

Geology

The Upper Permian and Lower Triassic rocks of this part of Yorkshire have been documented by Smith (1974a,b) and typify the marginal Zechstein sequence in England (Fig. 1). They dip gently eastwards and are briefly described below with emphasis on the soluble strata.

The Cadeby (Magnesian Limestone) Formation forms a marked escarpment that extends southwards from Bedale to Knaresborough and beyond, passing to the west of Ripon; it is up to 65 m thick, rests unconformably on Carboniferous strata and is composed mainly of porous dolomite and dolomitic limestone, details of which are given by Smith (1974a,b). The rock is an excellent aquifer that commonly yields artesian water down dip, and is hydrogeologically uniform throughout its outcrop (Aldrick 1978). The formation is generally well jointed and water-widened fissures are numerous. Caves, however, are uncommon and only nine have been recorded in North Yorkshire. Most of these caves are small and the largest is of tension fissure origin (Lowe 1978). During the mapping few stream sinks and only a few springs were observed. The most notable example of an underground river is provided by the Skell, which at times sinks near Fountains Abbey and rises again at Hell Wath, 2 km downstream and 40 m lower (Lowe 1978).

The Edlington Formation is exposed in only a few scattered places and most of the details of it

From HARWOOD, G.M. & SMITH, D.B. (eds), 1986, *The English Zechstein and Related Topics*, Geological Society Special Publication No. 22, pp. 127–139.

TABLE 1. Localities and dates of historically recorded subsidence hollows.

Date	Locality	Source of information
16/10/1796	[SE 3245 6891]	Harrison, 1892
18/10/1796	"	Kendal & Wroot, 1924
c. 1800	"	Cameron, 1881
c. 1830	[SE 3375 6566]?	Tute, 1868
c. 1828 - 1838	"	Tute, 1870
c. 1830	[SE 3186 7260]	Tute, 1868
-/6/1836	"	Tute, 1870
c. 1830	"	Fox-Strangways, unpublished notebook
19/6/1834	"	Harrison, 1892
12/7/1835	"	Kendall & Wroot, 1924
c. 1844	[SE 3254 7193]	Tute, 1868
c. 1850	"	Tute, 1870
c. 1848	"	Fox-Strangways, unpublished notebook
1857	Nunwick?	Fox-Strangways, unpublished notebook
c. 1861 - 2	[SE 3122 7328]	Tute, 1868
Spring 1860	"	Tute, 1870
Spring 1860	"	Fox-Strangways, unpublished notebook
21/5/1860	"	Harrison, 1892
21/5/1860	"	Kendall & Wroot, 1924
1871	[SE 3207 7229]	Cameron, 1881
14/5/1871	"	Harrison, 1892
14/5/1871	"	Kendall & Wroot, 1924
1873	[SE 3176 7842]	Cameron, 1881
1865 onwards	[SE 3254 7326]	Cameron, 1879
1877	[SE 3244 7317]	Cameron, 1879
1979	[SE 3170 7192]	Acrill Newspapers

have been obtained from boreholes. At outcrop the formation is generally represented by 7–20 m of mudstone, brecciated in places, with traces of gypsum and solution residues after gypsum and halite. At depths of up to 100 m, in a belt extending to 3 km from the outcrop, gypsum with evidence of patchy dissolution is present in the sequence; here the lower part of the formation comprises up to 40 m of massive secondary gypsum after anhydrite, equivalent to the Hayton (Anhydrite Formation) (Smith 1974a). The upper part is composed of up to 30 m of mudstone with nodular and bedded gypsum; subordinate dolomitic limestone beds—possibly equivalent to the Kirkham Abbey Formation of Smith (1974a)—are also present. At greater depths, where the circulation of water is restricted, the gypsum passes into anhydrite. At Ripon Parks (SE 307 753) the gypsiferous beds are exposed beside the River Ure where they comprise 7.1 m of massive alabastrine and porphyroblastic gypsum overlain by 6.5 m of interbedded gypsum and mudstone (Forbes 1958; James *et al.* 1981); the gypsum shows many signs of dissolution by groundwater, with numerous water-widened fissures, small caves and pipes present in the rock face, and is undergoing rapid erosion and dissolution by the River Ure at present (James *et al.* 1981).

The Brotherton (Magnesian Limestone) Formation forms a low escarpment sub-parallel to that of the Cadeby Formation. The best exposures are near Burton Leonard (SE 3318 6345) and Ripon Parks (SE 3131 7392). It consists of pale grey to white dolomitic limestone with a few vughs and is thinly to very thinly bedded and normally well jointed, breaking into small angular fragments. In boreholes it is 8–12 m thick and in many places has yielded artesian water. Very

TABLE 2. Localities, dates and sizes of subsidence hollows; compiled from the recollections of farmers and landowners in the Ripon–Bedale area.

Date	Locality	Diameter m	Depth m
post 1870	[SE 3156 7261]	30	-
pre 1910	[SE 3122 7190]	-	slight
1910 - recent	[SE 3114 7232]	c. 20	c. 5
1910 - recent	[SE 3121 7239]	c. 20	c. 5
1910 - recent	[SE 3115 7238]	c. 25	c. 6
1910 - recent	[SE 3120 7234]	c. 30	7
c. 1910	[SE 3192 7253]	c. 30	-
1930 - 1935	[SE 3227 7615]	14 - 19	c. 5
c. 1935	[SE 3146 7488]	c. 14	c. 3
c. 1935	[SE 3146 7490]	c. 14	c. 3
c. 1935	[SE 3122 7406]	c. 15	-
c. 1935	[SE 3135 7403]	-	slight
c. 1937	c. [SE 3175 7217]	-	slight
1930 - 1940	c. [SE 2830 8100]	10 - 14	1
1939	[SE 3184 7473]	35 x 25	8 - 10
1940 - recent	[SE 3149 7250]	20	1
1940 - recent	[SE 3140 7244]	1.5	0.5
1940 - recent	[SE 3147 7242]	10	0.5
1940 - recent	[SE 3145 7247]	20	1
1946	[SE 3160 7132]	10	deep
1950 - 1953	[SE 3116 7614]	10	2 - 3
pre 1960	c. [SE 339 728]	-	slight
pre 1960	[SE 3345 7312]	-	1
1960 - 1965	[SE 3248 7336]	5	-
1960 - present	[SE 3272 7311]	2 - 4	-
1960 - present	[SE 3194 7317]	8	2+
1960 - present	[SE 3027 7928]	-	slight
1965 - present	[SE 3134 7228]	2	c. 1
1968 - 1969	[SE 2999 8383]	1	1
1968 & 1970	[SE 3153 7242]	4	3
c. 1970	[SE 3187 7198]	2	1
c. 1975	[SE 3163 7419]	2	0.75
c. 1975	c. [SE 2919 8643]	8 - 10	2 - 3
1978	[SE 3207 7778]	2	2
1978	[SE 3238 7185]	2	0.5
c. 1978	[SE 3255 7192]	-	slight
1979	[SE 3164 7107]	-	slight
1979 & 1980	[SE 3170 7192]	14	4
1980	[SE 3187 7043]	c. 4	c. 2.5
1980	[SE 3210 7783]	15	0.5
1981	[SE 3118 7317]	10	slight
1/2/1982	[SE 3237 7182]	12	9.7

few signs of dissolution of the rock were observed in the field, and no caves have been recorded locally.

The Roxby Formation is of very similar character to the Edlington Formation and is likewise poorly exposed. It ranges in thickness from about 15 m at crop to about 30 m at depth where gypsum and anhydrite are present. Eastwards, at depth, the formation consists of up to 10 m of massive anhydrite overlain by anhydritic siltstone and mudstone. The anhydrite is the correlative of the Billingham (Anhydrite) Formation (Smith 1974a) and towards the crop passes into a similar thickness of gypsum. The gypsum thins out westwards where the formation comprises mudstone with solution residues and collapse breccias.

The Sherwood Sandstone Group forms a transition from the Roxby Formation into the overlying Sherwood Sandstone, about 300 m thick. The group has basal beds of red-brown, fine- to medium-grained sandstones with lenses of mudflake conglomerate and beds of mudstone and siltstone. Above are red-brown, channelled and cross-bedded, fine- to medium-grained sandstones.

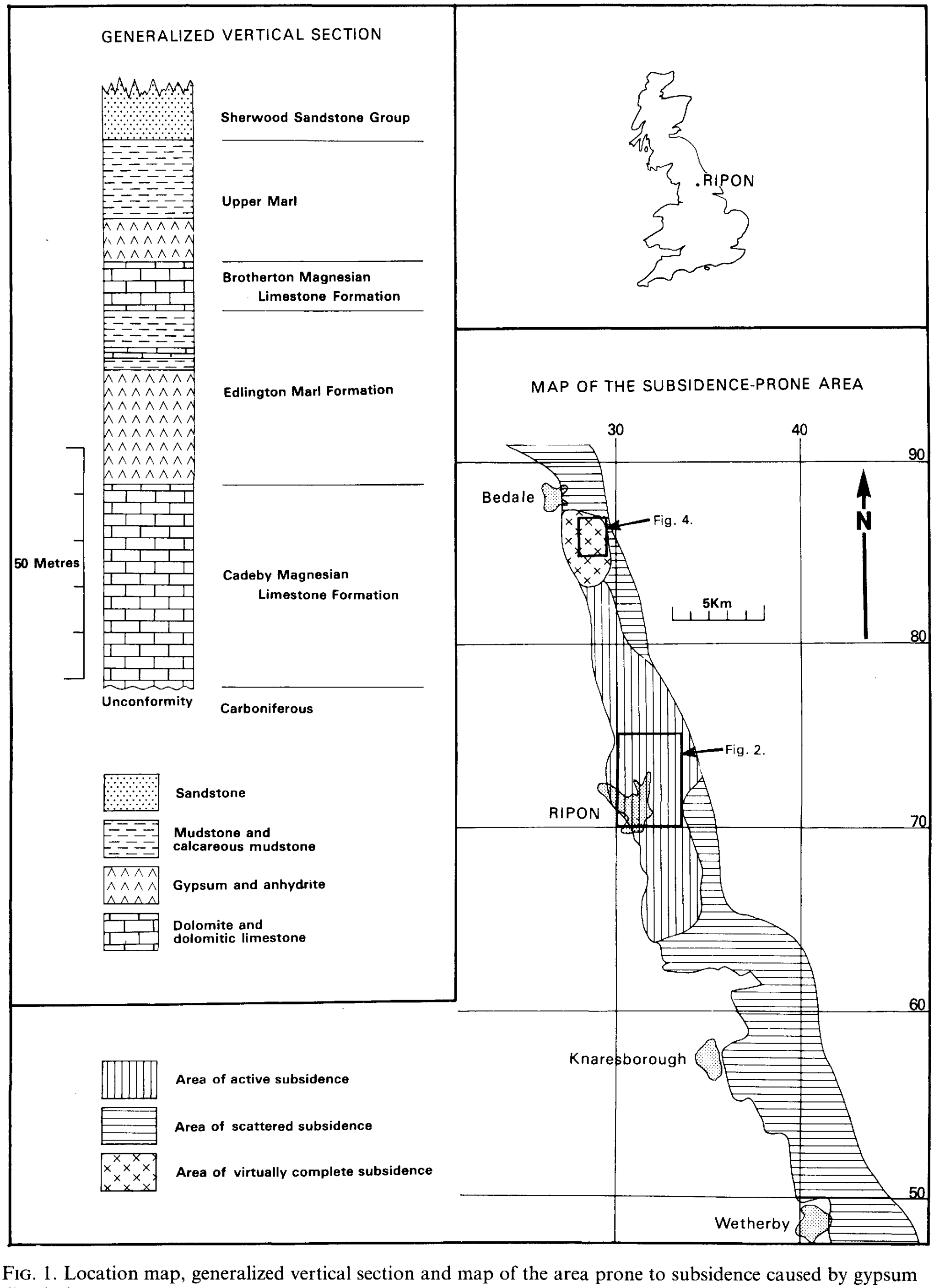

FIG. 1. Location map, generalized vertical section and map of the area prone to subsidence caused by gypsum dissolution.

Terminology

Subsidence features are found in many parts of the world where soluble rocks occur at or near surface. Extensive surface dissolution results in karst topography, but where substantial overburden is present subsidence hollows are the only visible effects of dissolution at depth. Terms used for these hollows include doline, sink, sinkhole, subsidence sinkhole, swallow, swallow hole, solution chimney, pipe cockpit, geological organ, polje and uvala. A review of the terminology is beyond the scope of this paper, and the terms 'subsidence hollow' and, for a large area, 'subsidence depression' are used here. The term 'breccia pipe' is used for the fill of the former cavity above a collapsed cavern.

The nature of the subsidence

The gypsum belt is about 3 km wide and extends from near Catterick to south of Doncaster (Smith 1972). Except for one record of subsidence at Burton Salmon, near Castleford (Edwards *et al.* 1940), most of the 40 recent subsidence hollows have formed in the area between Bishop Monkton, Ripon and Nosterfield. This active area also has hundreds of subsidence hollows that post-date the deposits of the Devensian glacial phase, suggesting a continuous history of subsidence during Flandrian time; most of these hollows are similar in size and shape to those formed recently, but in places they coalesce to form depressions up to several hundred metres across (Fig. 2). Near Dallamires Lane (SE 318 703), south of Ripon, a large area of peat 8 m below the adjacent fluvioglacial terrace occupies such a hollow. The origin of the large and small hollows is obvious where they have formed in flat fluvial or lacustrine deposits, but in areas mantled by glacial till it is difficult to distinguish old subsidence hollows from kettle holes. In areas of alluvium, only the recent hollows remain because of rapid filling by flood deposits. Within the subsidence belt there are also large drift-filled subsidence depressions, caused by the extensive dissolution of gypsum. These areas include Whitewater Common, south of Doncaster (Smith *et al.* 1973) and Snape Mires, near Bedale, which is discussed later. In a few places within the gypsum belt there is no surface evidence of subsidence and it must be assumed that any gypsum deposited there is still present or was dissolved before the last ice-age and the subsidence features obliterated.

The shape of a subsidence hollow depends upon whether there is solid competent rock or a substantial thickness of unconsolidated (usually glacial) deposits at the surface; the presence of competent rock results in the creation of steep-sided cylindrical shafts whereas conical depressions are formed in drift deposits.

A cylindrical hole about 14 m across and 15 m deep appeared in red Sherwood Sandstone near Ripon Railway Station (SE 3186 7260) in July 1834 (Tute 1868, 1870; Harrison 1892) and is still visible. A similar collapse occurred in 1860, breaching the Brotherton Formation at Ripon Parks (SE 3122 7328), and another affected the same formation at Hall Garth Ponds (SE 3184 7472) in 1939. At Hall Garth Ponds Mr J. Graham (pers. comm.) reported that "there was a loud noise and a large hole appeared and filled with water which bubbled and looked milky white. When the bubbling had ceased and the water cleared, trees were visible still rooted in the bottom of the hole". This hole is about 30 m in diameter. According to Mr N. Moore, a member of the local subaqua club, it is 7 m deep with rock (presumably all limestone) exposed in the sides; water flows from fissures in the rock and a tree is still rooted in the bottom.

Throughout much of the Ripon district thick superficial deposits, locally in excess of 20 m, blanket the bedrock. Subsidence hollows in these areas are nearly cylindrical when first formed but the sides rapidly slip to produce a conical depression. Corkscrew Pits (SE 320 731) are three such conical depressions. A small actively-subsiding hollow nearby (SE 3194 7317) has been repeatedly filled and is only about 1.5 m deep. The hollow has near-vertical sides, but if it were left unfilled they would become unstable.

The formation of a hollow in the drift-covered area (Figs 2 and 3) was illustrated on 3 August 1979 by the *Ripon Gazette* (Acrill Newspapers) which reported that on 28 July 1979 "A six-foot-deep circular pit appeared early on Saturday morning behind houses on Magdalen's Road" (SE 3170 7192). One resident described it as "like a minor earthquake". The Magdalen's Road subsidence hollow started as a slight downwarp and damaged two garages standing on the site. The garages were dismantled and soon afterwards the collapse occurred. The hollow was filled but subsided another metre in April and May 1980. The residents of the area were filling the hole during 1981, when slight slipping with associated tension gashes was evident on the western side. Left unfilled, slipping around the sides would have enlarged it, thus threatening the nearby houses; filling the hole is effectively controlling its size and preventing it from becoming a large conical depression.

On 1 February 1982 another hollow in a drift-covered area formed at Sharow (SE 3238 7182),

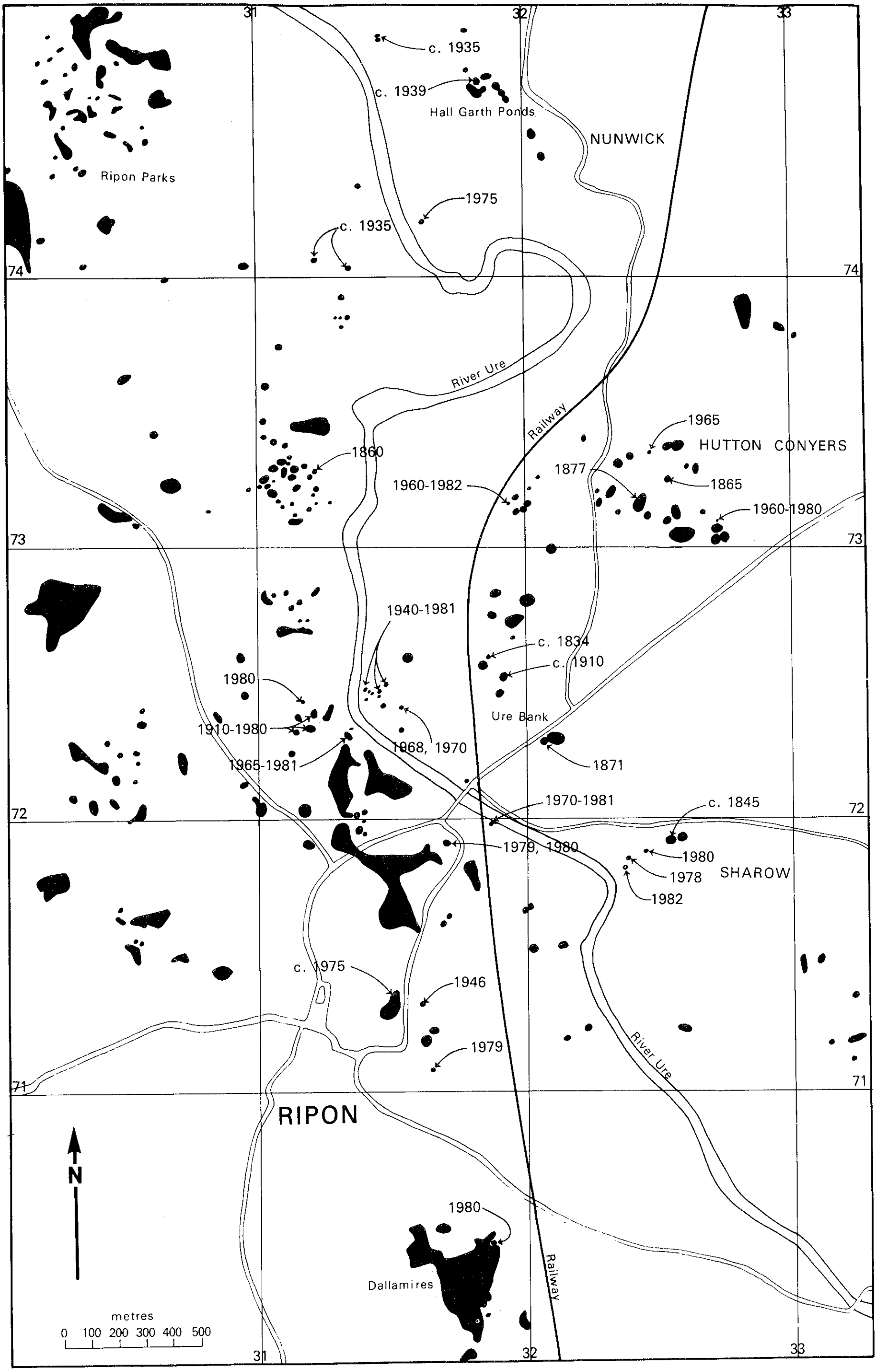

FIG. 2. Post-Devensian subsidence hollows in the Ripon area with dates of recent subsidence where known.

FIG. 3. (a) Subsidence hollow formed on 28 July 1979 behind houses on Magdalen's Road, Ripon (SE 3170 7192). Photo: Acrill Newspapers. (b) Subsidence hollow formed on 1 February 1982 at Sharow (SE 3238 7182). The hollow was 12 m in diameter and up to 9.7 m deep.

east of Ripon. The hollow was cylindrical, 12 m in diameter and up to 9.7 m deep (Figs 2 and 3). On 3 February 1982 it contained muddy water to within 0.8 m of the surface and incipient tension fissures had developed around the sides, which were actively caving in. This latest hollow appeared after a period of heavy rain, the field having been flooded a week or two earlier. When the flood abated a shallow puddle formed on the site of the subsidence hollow, but no other warning of impending collapse was observed.

Very few of the Ripon subsidence hollows are accurately dated, but by comparison with limestone karst areas (Newton 1977; Kemmerly 1980; Foose 1981) subsidence may be expected when there are changes in the water table level. Cameron (1879) recorded that small hollows or 'man holes' at Hutton Conyers, near Ripon, were formed mostly during very wet seasons.

The mechanisms controlling the subsidence

The solubilities of the rocks

Laboratory experiments on the dissolution rates of gypsum and limestone (Kemper *et al.* 1975; James & Lupton 1978; James & Kirkpatrick 1980); show that gypsum may be expected to dissolve in flowing water about 100 times faster than limestone. Limestone, in turn, is more soluble than dolomite. Chemicals present in the dissolving water also affect the solubility; waters rich in carbonic acid are aggressive to limestone (Sweeting 1966), and waters rich in $CaCO_3$ are capable of dissolving larger amounts of gypsum than pure water (Deer *et al.* 1962; Kempe 1972).

Field observations on gypsum and limestone dissolution support the experimental evidence. James *et al.* (1981) found that typical dissolution rates for gypsum by the River Ure at Ripon Parks were between 0.1 and 1.7 m per annum. By comparison Sweeting (1966) and Clayton (1981) considered dissolution in limestone of 0.01 m per annum to be a high value, achieved only by acid water drained from a peat bog.

Subsidence as a result of gypsum dissolution has been recorded in Texas (Olive 1957), Canada (Wigley *et al.* 1973), Germany (Hundt 1950; Herrmann 1964; Ströbel 1973), the Alps (Nicod 1977), Russia (Gorbunova 1977) and Newfoundland (Sweet 1977).

The gypsum-anhydrite transition

The western limit of the subsidence-affected area is the outcrop of the base of the Edlington Formation. The distribution of subsidence hollows indicates that the eastern limit, some 3 km away, approximates to the down-dip transition from gypsum to anhydrite in the Edlington and Roxby Formations. Within the subsidence belt this transition generally occurs at about 100 m, but if sufficient circulating water is available it is theoretically possible to extend to a depth of between 900 and 1200 m (Mossop & Shearman 1973).

The relationship between joints and subsidence

Observations of cave systems in limestone and gypsum indicate that their shape is largely controlled by bedding and joint orientations (Ford 1971; Kempe 1972; Waltham 1971; Jakucs 1977; Jackucs & Mezoso 1977). Furthermore, under phreatic conditions, roof dissolution can generate high caverns on sites where joints intersect (Waltham 1974). In the Ripon area the water flow in the gypsiferous beds is mainly phreatic and it is likely that the caverns that ultimately collapse to form subsidence hollows are located at the intersections of joints. Joint measurements in the Cadeby Formation and Sherwood Sandstone Group of the Ripon area (Fig. 4c) indicate that two major sets of joints cross at about 90°.

In much of the gypsum belt the subsidence hollows are apparently randomly scattered. However, hollows in the vicinity of Hutton Conyers, Ure Bank, Sharow and Ripon Golf Course have a linear or grid-like distribution (Fig. 2). The orientations of all the lines of three or more hollows are illustrated in Fig. 4(a), in which each segment is proportional to the total number of hollows on all the lines with that orientation. Because many of the hollows form a regular grid pattern (Fig. 4d,e,f) the rose diagram (Fig. 4a) shows four apparent trends. Many of the subsidence hollows are elongate or elliptical and a further rose diagram (Fig. 4b) shows the orientations of the long axes of 100 hollows near Ripon. The joint directions approximate to both the main lineations of hollows and the orientation of individual hollows (Fig. 4a–f), suggesting a close correlation between them. In Germany the location of subsidence hollows at the intersections of joints in gypsum was demonstrated by Ströbel (1973).

At Snape Mires (SE 285 860), east of Bedale, almost complete dissolution of the Permian gypsum, as proved by boreholes, has resulted in a large bedrock depression. This is about 8 sq km in area and bedrock levels are as much as 25 m below the drainage from the area. A fluvioglacial terrace which once covered the area has subsided and the depression is filled with laminated clay

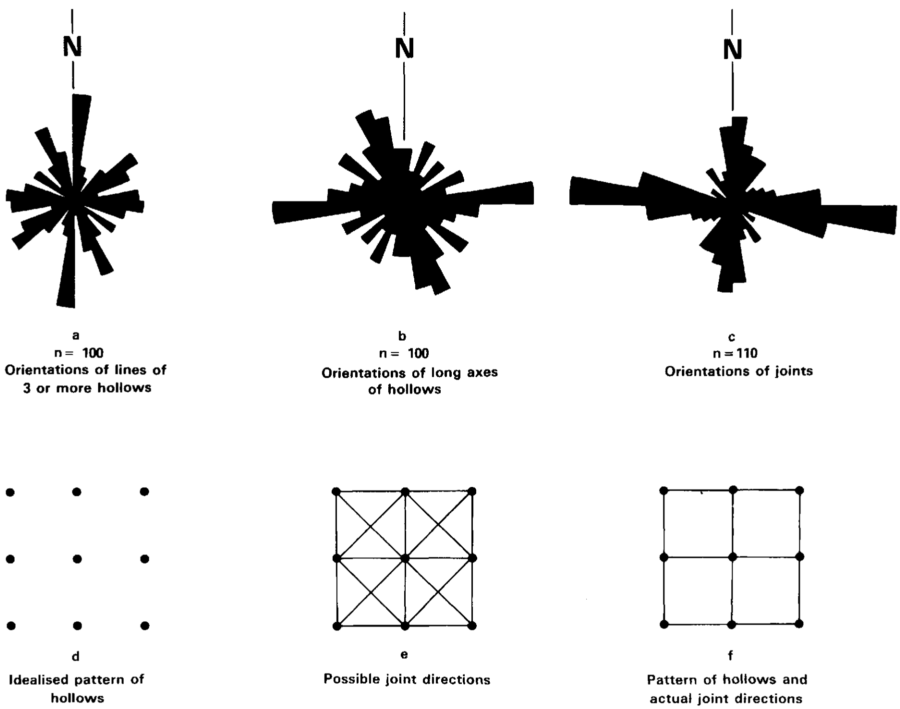

FIG. 4. Rose diagram and theoretical models showing the relationships between the orientations of lines of hollows, individual hollows and joints in the Ripon area.

deposited during the later part of the Late Devensian and during the Flandrian. Similar lacustrine deposits elsewhere in the Vale of York have a flat surface, but at Snape Mires they have a sharply uneven surface with a relief of up to 6 m. Between Rough Plantation (SE 2835 8525) and Flood Bridge (SE 2857 8752) the undulations take the form of N–S and E–W trending ridges and elongate hollows up to 1 km long (Fig. 5) and several turn through right angles. The probable sequence of events resulting in this morphology is shown in Fig. 5. The orientations of these subsidence ridges and hollows closely approximates to the joint directions found in the Permian rocks to the SW (Fig. 4c). It is likely, therefore, that the ridges represent the initial collapse of a joint-controlled cave system in the underlying gypsum (the pattern of which has been preserved by the drift infill) and the hollows coincide with areas where the remaining gypsum has subsequently been dissolved. The Snape Mires subsidence features are small drift-covered analogues of the joint-controlled subsidence troughs recorded from the gypsum plain in west Texas (Olive 1957).

Cavern collapse and breccia pipes

The volume of gypsum dissolved obviously affects the size and amount of the associated subsidence. The recent Ripon subsidences occur catastrophically, suggesting the sudden collapse of the roof of near-surface caverns. The gypsum beds, however, generally lie at depth and a cavity must propagate upwards by collapse, as a breccia pipe. A small exposure (SE 3129 7335) of brecciated Sherwood Sandstone in the Brotherton Formation outcrop near Ripon probably represents part of such a breccia pipe. Similar pipes above gypsum have been found in Texas (Eck & Redfield 1965) and the development of breccia pipes after the dissolution of evaporites was recorded for the Permian of Durham and Yorkshire (Smith 1972) and the Permo–Trias of Germany (Hundt 1950; Herrmann 1964; Prinz 1973).

Experience in mining areas shows that the collapse of a cavity generates an upward-propagating pipe, through overburden, for between four and 10 times the height of the cavity before breccia chokes the pipe (Piggott & Eynon 1978). Coal measures rocks have a high bulking factor (*op. cit.*), but Permo–Triassic mudstones and sandstones are soft and may be expected to compact more on brecciation, thus allowing their associated breccia pipes to penetrate greater thicknesses of strata. The size of the cavern also affects the propagation of the breccia pipes.

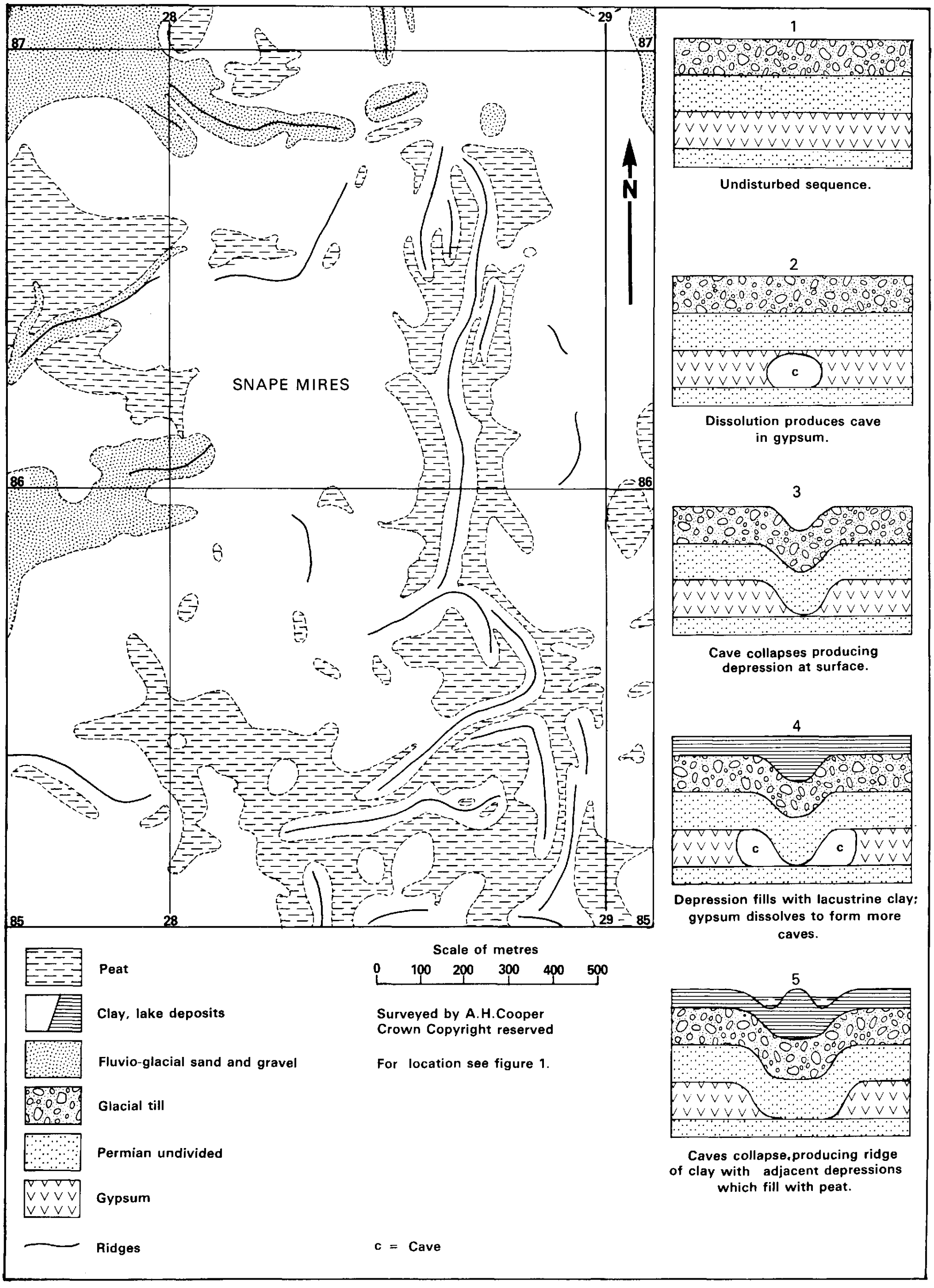

FIG. 5. The distribution and mode of formation of subsidence ridges in Snape Mires near Bedale, North Yorkshire. Geology based on provisional published maps of the British Geological Survey (NERC), crown copyright reserved.

Observations on mines where soft mudstones form the overburden (S. Penn, pers. comm.) suggest that mud flow away from the bottom of a breccia pipe can enhance the effect and a cavity may propagate upwards through overburden for more than 20 times its original height. If a propagation figure of 20:1 is applied to the Ripon–Bedale gypsum belt, it means that even at the eastern limit of the gypsum, collapse of cavities in excess of 5 m high may be expected to breach the surface. It would appear, therefore, that choking of breccia pipes is not the factor limiting the down-dip margin of this subsidence belt.

Water flow and the amount of subsidence

Water flow is a major factor controlling gypsum dissolution and subsidence. High water flow in the past has resulted in almost complete dissolution of the gypsum, as at Snape Mires. Nil water flow results in sulphate-saturation of the water in the rock and no dissolution occurs. A flow between the two extremes results in an active area.

Around Ripon, the most actively subsiding area at present, the volume of 35 subsidence hollows formed in the past 150 years is about 27,000 m^3. These hollows are scattered over an area of about 5 sq km, giving an average annual subsidence volume of about 36 m^3 per sq km. The actual rate of gypsum removal by groundwater must be greater than this, because of the choking of subsidence pipes. Many water wells in the area have very high concentrations of sulphates and the presence of such waters, in the valley gravels east of Ripon, points to a considerable down-dip movement of water. Calculations by Dr J. Aldrick (pers. comm.), based on assumptions of the infiltration and water flow, show that the possible amount of gypsum dissolved per square kilometre could be of the order of 120 m^3 per annum. In view of the assumptions used to make this calculation, a volume of collapse at surface of 36 m^3 per sq km per annum does not appear to be unreasonable and may indicate a smaller flow of water than was assumed.

In the Snape Mires area the presence of the large foundered area, filled with glacial and post-glacial lacustrine deposits indicates severe dissolution of gypsum during the later part of the Late Devensian and during the Flandrian. An approximate calculation shows that over an area of about 8 sq km a thickness of up to 25 m of gypsum has been dissolved in less than 13,000 yr $\pm$ 600 BP. This equates with an annual dissolution rate of at least 1,600 m^3 of gypsum per sq km. The area has abundant, commonly calcareous, springs and artesian water has been found in the Cadeby and Brotherton Formations. Even assuming generous water infiltration rates and a large catchment area for the groundwater, it is unlikely under present-day conditions that more than 1,000 m^3 of gypsum could be removed in a year. This fact, the lack of widespread active subsidence, and the presence of late and post-glacial deposits in the subsidence depression, suggest that most of the dissolution occurred when more water was available, possibly beneath or adjacent to the melting Devensian icesheet. Subsidence over gypsum in recently deglaciated valleys has been recorded in the Alps (Nicod 1977), and Sweeting (1974) attributed enlargement of Pennine cave systems to dissolution by the abundant water flow during the deglaciation.

Prediction of subsidence and remedial work

The long-term future of the actively subsiding areas is further subsidence and it is currently impossible to predict which places are likely to be unstable. However, in areas where the subsidence hollows have a regular grid-like or linear arrangement controlled by joints, it is likely that ground on lines between hollows is most at risk. The more numerous and closer the hollows, the greater likelihood there is of another hollow developing along that line. Land adjoining a subsidence hollow is also at risk because many of the hollows occur in groups of two or three.

If a subsidence hollow forms, the best course of action is to fill it with inert fill; this will prevent the sides from slipping and migrating outwards, thus stopping the hollow from becoming a large conical depression. Further subsidence of the fill in hollows, however, has occurred in several places. Filling the subsidence with toxic refuse should be avoided because pollution of local springs may occur. Disposal of surface water into hollows is also unwise as it may trigger off further subsidence. The effects of water abstraction from the gypsiferous formations is not known, but removal of large quantities of water high in sulphates may influence the subsurface dissolution of gypsum and so increase the likelihood of subsidence.

For very expensive structures, detailed site investigation is the only certain way to determine the stability of the ground. Such an investigation should involve drilling boreholes down to the Cadeby Formation (20–130 m) to determine the state of the gypsum beds, the presence or absence of cavities and the hydrogeological conditions in the adjacent strata. Down-hole and surface geophysical surveys may also be useful in defining the state of the gypsum. If cavities are found they may be filled and water flow through the gypsum thus stopped to prevent further dissolution; these measures are very expensive. For normal buildings, construction on rafts, subject to the advice of a qualified structural engineer, is probably the safest and most economical method.

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References

ALDRICK, R.J. 1978. The hydrogeology of the Magnesian Limestones in Yorkshire between the River Wharfe and the River Aire. *Q. Jl eng. Geol. Lond.* **11,** 193–201.

CAMERON, A.G. 1879. Ripon swallow-holes. *Geol. Mag.* **6,** 575.

—— 1881. Subsidences over the Permian boundary between Hartlepool and Ripon. *Proc. Yorks. geol. polytech. Soc.* **7,** 342–51.

CLAYTON, K. 1981. Explanatory description of the landforms of the Malham area. *Field Studies,* **5,** 389–423.

DEER, W.A., HOWIE, R.A. & ZUSSMAN, J. 1962. Gypsum. In: *Rock Forming Minerals,* Vol. 5, 201–18. Longmans, London.

ECK, W. & REDFIELD, R.C. 1965. Engineering geology problems at Sanford Dam, Borger, Texas. *Eng. Geol. Sacramento,* **2,** 15–25.

EDWARDS, W., WRAY, D.A. & MITCHELL, G.H. 1940. Geology of the country around Wakefield. *Mem. geol. Surv. G.B.* London.

FOOSE, R.M. 1981. Sinkholes follow the pattern. *Geotimes,* **26,** 20–4.

FORBES, B.G. 1958. Folded Permian gypsum of Ripon Parks, Yorkshire. *Proc. Yorks. geol. Soc.* **31,** 351–7.

FORD, D.C. 1971. Geologic structure and a new explanation of limestone cavern genesis. *Trans. Br. Cave Res. Ass.* **13,** 81–94.

FORD, T.D. (ed.) 1977. *Proc. 7th int. Speliological Congress, Sheffield 1977.* British Cave Research Association, Sheffield.

GORBUNOVA, K.A. 1977. Morphology of gypsum karst. In: FORD, T.D. (ed.), (*q.v.*), 221–2.

HARRISON, W. (ed.) 1892. *Ripon Millenary. A record of the festival, also a history of the city arranged under its wakemen and mayors from the year 1400.* W. Harrison, Ripon.

HERRMANN, A. 1964. Gips-und Anhydritvorkommen in Nordwestdeutschland. *Silikat Jl,* **3,** 442–66.

HUNDT, R. 1950. *Erdfalltektonik.* W. Knapp, Halle (Saale).

JAKUCS, L. 1977. *Morphogenetics of Karst Regions.* Hilger, Bristol.

—— & MEZOSO, G. 1977. Genetic problems of the huge gypsum caves of the Ukraine. In: FORD, T.D. (ed.) (*q.v.*), 248–51.

JAMES, A.N. & LUPTON, A.R.R. 1978. Gypsum and anhydrite in foundations of hydraulic structures. *Geotechnique. London,* **28,** 249–72.

—— & KIRKPATRICK, I.M. 1980. Design of foundations of dams containing soluble rocks and soils. *Q. Jl eng. Geol. Lond.* **13,** 189–98.

——, COOPER, A.H. & HOLLIDAY, D.W. 1981. Solution of the gypsum cliff (Permian, Middle Marl) by the River Ure at Ripon Parks, North Yorkshire. *Proc. Yorks. geol. Soc.* **43,** 433–50.

KEMMERLY, P.R. 1980. A time-distribution study of doline collapse: framework for prediction. *Environ. Geol.* **3,** 123–30.

KEMPE, S. 1972. Cave genesis in gypsum with particular reference to underwater conditions. *Cave Sci. No. 49,* 1–6.

KEMPER, W.D., OLSEN, J. & DE MOOY, C.J. 1975. Dissolution rate of gypsum in flowing water. *Proc. Soil Sci. Soc. Am.* **39,** 458–63.

KENDALL, P.F. & WROOT, H.E. 1924. *Geology of Yorkshire.* Vienna.

LOWE, D.J. 1978. Farnham Cave, a rift cave in the Magnesian Limestone. *Trans. Br. Cave Res. Ass.* **5,** 23–8.

MAYHALL, J. 1878. *The annals of Yorkshire from the earliest period to the present time,* Vol. I. Johnson, Leeds.

MOSSOP, G.D. & SHEARMAN, D.J. 1973. Origins of secondary gypsum. *Trans. Instn. Min. Metall.* **82,** 147–54.

NEWTON, J.G. 1977. Induced sinkholes—a continuing problem along Alabama highways. *Publ. int. Ass. hydrol. Sci., Wallingford, No. 121,* 453–63.

NICOD, J. 1977. Deux karst du gypse remarquables des Alps occidentales. In: FORD, T.D. (ed.) (*q.v.*), 321–5.

OLIVE, W.W. 1957. Solution-subsidence troughs, Castile Formation of Gypsum Plain, Texas and New Mexico. *Bull. geol. Soc. Am.* **68,** 351–8.

PIGGOTT, R.J. & EYNON, P. 1978. Ground movements arising from the presence of shallow abandoned mine workings. In: GEDDES, J.G. (ed.) *Large ground movements and structures,* 749–80. Proceedings of the Conference held at The University of Wales Institute of Science and Technology, Cardiff 1977. Pentech Press, London.

PRINZ, H. 1973. Zur Entstehung von Einbruchsschloten und Korrisionkesseln über tiefem Salinarkarst. In: *Proceedings of a symposium on sink-holes and subsidence,* Hannover, [T2-D] 1–6. Deutsche Gesellschaft für Erd- und Grundbau. Essen.

SMITH, D.B. 1972. Foundered strata, collapse breccias and subsidence features of the English Zechstein. In:

RICHTER-BERNBURG, G. (ed.) *Geology of Saline Deposits*. Proc. Hannover Symp. (Earth Sciences 7), 255–69. Unesco, Paris.

—— 1974a. Permian. In: RAYNER, D.H. & HEMINGWAY, J.E. (eds) *The Geology and Mineral Resources of Yorkshire*, 115–44. Yorkshire Geological Society, Leeds.

—— 1974b. The stratigraphy and sedimentology of Permian rocks at outcrop in North Yorkshire. *J. Earth Sci. Leeds Geol. Ass.* **8,** 365–86.

SMITH, E.G., RHYS, G.H. & GOOSSENS, R.F. 1973. Geology of the country around East Retford, Worksop and Gainsborough. *Mem. geol. Surv. G.B.* London.

STRÖBEL, W. 1973. Der Grundgips im Raum Stuttgart als Modell für Gipsauslaugung und Bildung von Erdfällen. In: *Proceedings of a symposium on sinkholes and subsidence*, Hannover, [T1-G] 1–8. Deutsche Gessellschaft für Erd- und Grundbau. Essen.

SWEET, G.A. 1977. Hydrogeology of gypsum karst in Newfoundland. In: FORD, T.D. (ed.) (*q.v.*), 390–1.

SWEETING, M.M. 1966. The weathering of limestones, with particular reference to the Carboniferous Limestone of northern England. In: DURY, G.H. (ed.) *Essays in Geomorphology*, 177–210. Heinemann, London.

—— 1974. Karst geomorphology in north-west England. In: WALTHAM, A.C. (ed.) *The Limestones and Caves of North-west England*, 46–78. David & Charles, Newton Abbot.

TUTE, REV. J.S. 1868. On certain natural pits in the neighbourhood of Ripon. *Geol. Mag.* **5,** 178–9.

—— 1870. On certain natural pits in the neighbourhood of Ripon. *Proc. Yorks. geol. polytech. Soc.* **5,** 2–7.

WALTHAM, A.C. 1971. Controlling factors in the development of caves. *Trans. Br. Cave Res. Ass.* **13,** 73–80.

—— 1974. The geomorphology of the caves of North-West England. In: WALTHAM, A.C. (ed.) *The Limestones and Caves of North-west England*, 79–105. David & Charles, Newton Abbot.

WIGLEY, T.M.L., DRAKE, J.J., QUINLAN, J.F. & FORD, D.C. 1973. Geomorphology and geochemistry of a gypsum karst near Canal Flats, British Columbia. *Can. J. Earth Sci.* **10,** 113–29.

A. H. COOPER, British Geological Survey, Windsor Court, Windsor Terrace, Newcastle upon Tyne NE2 4HE.