GYPSUM DISSOLUTION GEOHAZARDS AT RIPON, NORTH YORKSHIRE, UK

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Abstract: This guide is for a one-day field excursion to examine gypsum dissolution geohazards at Ripon in North Yorkshire. Gypsum is a highly soluble rock and under suitable groundwater flow conditions it can dissolve forming caves and karstic features including collapse and suffosion dolines. These have the capability of causing subsidence damage of the type that affects much of the Ripon area. The guide details the processes involved, the localities visited and some of the remedial measures undertaken.

Résumé: Ce guide concerne l'excursion d'une journée ayant pour but d'étudier les géo-aléas liés à la dissolution du gypse à Ripon dans la région du North Yorkshire. Le gypse est une roche hautement soluble et, dans des conditions adéquates d'écoulement de l'eau souterraine, pouvant se dissoudre et engendrer des grottes et formes karstiques telles qu'effondrements et dolines de suffosion. Celles-ci peuvent causer des dégâts de subsidence du type de ceux qui touchent la plupart des alentours de Ripon. Ce guide fournit des explications sur les phénomènes mis en jeu, les localités visitées et quelques-unes des mesures prises pour remédier à ces problèmes.

Keywords: subsidence, evaporites, aquifers, cavities, collapse, urban geosciences.

INTRODUCTION

Gypsum, hydrated Calcium Sulphate ($CaSO_4.2H_2O$), is attractive as satin spar, beautiful as carved alabaster, practical as plasterboard (wallboard), but the cause of a geological hazard capable of swallowing houses and collapsing dams. This field excursion will show some of the local geology related to gypsum and subsidence problems associated with the rock in the Ripon area of North Yorkshire. It will look at subsidence damage and dolines (sinkholes) caused by the dissolution of gypsum and the formation of gypsum karst.

GEOLOGY OF THE JOURNEY FROM NOTTINGHAM TO RIPON

On the trip north from Nottingham the geology we see will be dependent on traffic conditions and the route the bus takes. The generalised geological sequence that we cross on the journey and see at Ripon is shown below in Table 1, and the most likely route and underlying geology in Figure 1.

Table 1. Generalised geological sequence.

Chrono-stratigraphy	Lithostratigraphy	Lithology	Approximate thickness at outcrop
Flandrian	Alluvium and peat	Silt and fine sand overbank deposits on sand and gravel. Peat in low-lying areas.	0-20m
Devensian	Complex of named and informally designated glacial deposits	Moraines at Wetherby (York and Eskrick moraines combined) with glacial till and eskers to the north; glacial lake deposits both south and north of the moraines	0-45m
Triassic	Sherwood Sandstone Group	Red-brown sandstone, pebbly in the south	50-350m
Permian	Roxby Formation (Zechstein Group)	Up to 10m of gypsum overlain by 0-20m of red-brown mudstone with gypsum	0-30m
	Brotherton Formation (Zechstein Group)	Mainly thin-bedded dolomite and dolomitic limestone	0-30m
	Edlington Formation (Zechstein Group)	Up to 35m of gypsum overlain by 0-20m of red-brown mudstone with gypsum	0-55m
	Cadeby Formation (Zechstein Group)	Massive and bedded dolomite with reefs and algal stromatolites overlain by cross-bedded oolitic dolomite.	0-50m
	Yellow Sands Formation and basal breccia (Rotliegendes Group)	Lenticular areas of locally derived breccia overlain by aeolian yellow fine to medium grained sandstone.	0-10m
Carboniferous (Westphalian)	Pennine Upper Coal Measures Formation Pennine Middle Coal Measures Formation Pennine Lower Coal Measures Formation	Mixed sequence of mudstone and siltstone with numerous coals and numerous sandstone units.	Up to 1500m

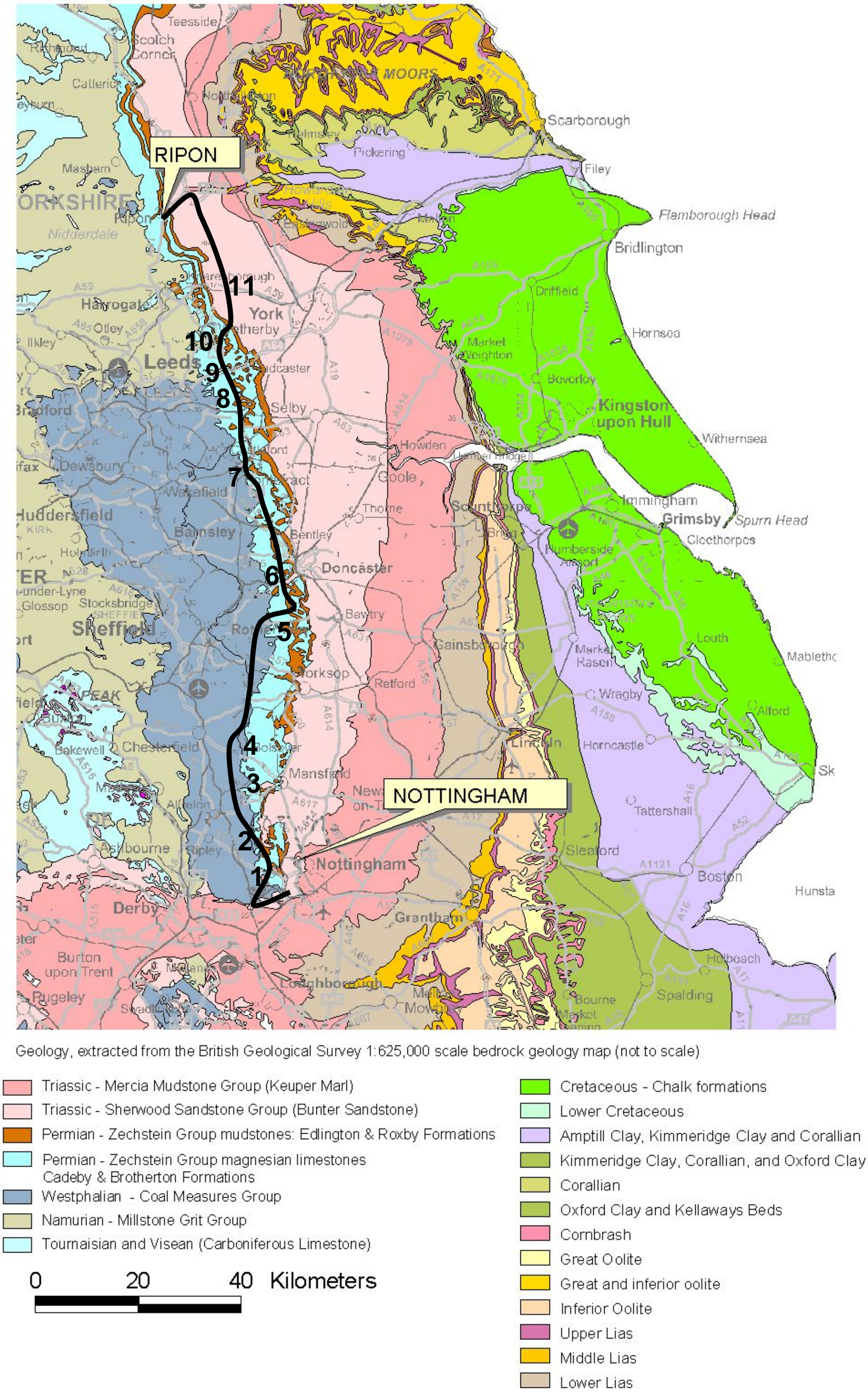

Figure 1. Extract from the 1:625,000 scale geological map for UK south (not to scale) showing the geology for the route from Nottingham to Ripon.

On the way to the M1 motorway we leave an area of Triassic Sherwood Sandstone Group rocks in the vicinity of the University and will probably head west across some poorly exposed Westphalian Coal Measures. At the motorway we will head north across thin poorly exposed Permian strata belonging to the Zechstein Group **(1 on map)** and comprising thin dolomitic limestone of the Cadeby Formation which locally has a dolomitic mudstone sequence at its base (this sequence was formerly called the Lower Magnesian Limestone and Lower Marl). After about 15km we pass onto the Westphalian, Pennine Coal Measures Group **(2)** and drive for about 45km with the Permian escarpment just to the east of the motorway.

Just to the north of Tibshelf Motorway Services, on top of the escarpment, there is Hardwick Hall **(3)** and 7km further on Bolsover Castle **(4)** can bee seen. A little past this, near the motorway, there are the remains of Markham Colliery and the surrounding spoil heaps. We head up the M1 and then pass north-eastwards on the M18; 7km after the M1/M18 junction the road crosses on to the Permian Zechstein Group rocks with cuttings in the Cadeby Formation **(5)**, the lowest magnesian limestone of the group visible at the roadside. After 5km we turn northwards on the A1 and traverse faulted Permian strata crossing back and forth from the Cadeby to the Edlington and Brotherton Formations **(6);** the Brotherton Formation is the upper of the two magnesian limestones at outcrop and was formerly called the Upper Magnesian Limestone. At the Doncaster A630 junction the A1 passes through a cutting in the Brotherton Formation that caps the hill here; north of this it crosses a narrow outcrop of the Edlington Formation then the gorge of the River Don, which is cut down into the Cadeby Formation. North of the river the road passes onto the Edlington then Brotherton formations again. North of here, the A1 like many major roads in the UK, partly follows what was originally a Roman road along the dry and less vegetated land that typifies the magnesian limestones. The A1 follows these strata most of the way to Wetherby where it steps on to the ridge of the Triassic Sherwood Sandstone Group blanketed with glacial deposits.

The recently completed A1M motorway passes through new cuttings in the Cadeby Formation to the west of Ferrybridge power station **(7).** This installation has large cooling towers and a flue gas desulphurisation plant that produces gypsum as a by-product of the reaction of sulphur in the flue gasses with limestone. This material is used nearby to manufacture plasterboard at Sherburn in Elmet where there used to be a gypsum mine in the Permian strata. (Nearby and just north-east of the Ferrybridge Power Station the <u>old</u> A1 passes though cuttings in the Brotherton Formation at its type locality the village of Brotherton). About 10km north of here and just after the M1/A1M junction the road dips into a deep valley at Aberford **(8)**, here algal stromatolite domes can be seen on the west side of the road (left); these are developed in the Wetherby Member of the Cadeby Formation (the lower member) followed by cross-bedded dolomites formed the Sprotbrough Member (the upper subdivision) seen on the east of the road as it climbs the hill towards the A64 road junction. From here the A1 runs along the top of the Cadeby Formation escarpment **(9)** with a wide dip slope to the east before dropping down to the River Wharfe near Wetherby.

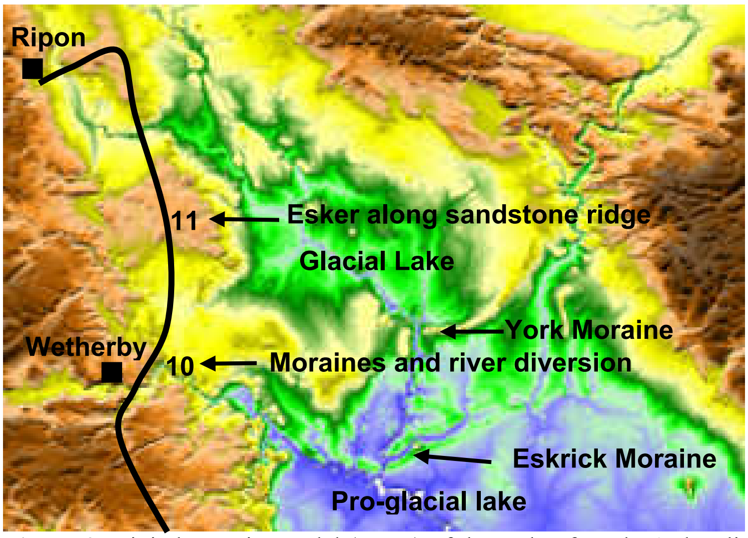

Figure 2. Digital Terrain Model (DTM) of the Vale of York. At locality 10 it shows the two moraines that come together at Wetherby and the diversion of the drainage from the west around the margin of the Devensian ice/moraine into the pro-glacial lake to the south. At locality 11 there is an esker running along the top of a ridge of Sherwood Sandstone. Digital Terrain data from Intermap Technologies, © BGS (NERC).

At Wetherby the landscape changes sharply as we cross the Devensian ice limit and pass through a cutting in the terminal moraines which here comprise the Eskrick and York moraines joined together **(10)**. At this point the River Wharfe enters a shallow and narrow gorge, which is its diversionary route around what was the edge of the Devensian ice. At Wetherby the glacial till is up to around 40m thick, but north of here most of the land is blanketed by about 20m of glacial till and glacial lake deposits. About 8km north of here on the A1M we pass the A59 York junction and to the east (right) of the road there is an elongate esker deposit of sand and gravel running through Allerton Mauleverer; the ornate observatory folly is located on this ridge **(11)**. About sixteen kilometres north of here we turn off for Ripon. The first stop is just to the north of Ripon on private land belonging to the Norton Conyers estate.

PERMIAN GYPSUM DISSOLUTION GEOHAZARDS

Gypsum dissolution and gypsum karst

Gypsum dissolves readily in flowing water, which next to rivers can be at a rate about 100 times faster than that seen for limestone dissolution. James *et al*. (1981) observed a 3m cube of gypsum being dissolved completely by the River Ure near Ripon in about 18 months; the associated gypsum face was then undercut by 6m in the subsequent 10 years. This alarming dissolution rate is for turbulent unsaturated water at surface. Underground dissolved sulphate in the water slows the dissolution, but it is still very rapid and caves in gypsum can readily form and expand. Such caves occur in the Vale of Eden, Cumbria and beneath Ripon, North Yorkshire (Ryder & Cooper, 1993, Waltham & Cooper, 1998). Some of the longest and most complex cave (maze cave) systems in the world are developed in the gypsum karst of the Ukraine (Klimchouk, 1992; Klimchouk *et al*, 1997) and it is thought that similar water-filled (phreatic) caves exist beneath Ripon. Under suitable groundwater flow conditions caves in gypsum can enlarge at a rapid rate resulting in large chambers. Collapse of these chambers produces breccia pipes that propagate through the overlying strata to break through at the surface and form subsidence hollows. Subsidence problems at Ripon (Figure 3) are due to this phenomenon (Cooper, 1986, 1989, 1995, 1996, 2002; Cooper & Calow, 1998).

Subsidence geohazards

The Permian sequence at Ripon contains approximately 35m of gypsum in the Edlington Formation (formerly called the Middle Marl) and 10m of gypsum higher up in the Roxby Formation (formerly the Upper Marl). These two gypsum sequences rest on two limestone aquifers, the Cadeby Formation (formerly Lower Magnesian Limestone) and the Brotherton Formation (formerly Upper Magnesian Limestone) respectively. The limestone dip slopes act as catchment areas and the water is fed down-dip into the gypsiferous sequences, before escaping into a major buried valley along the line of the Rive Ure (Figure 3, and Cooper & Burgess, 1993). Complex cave systems are developed in the gypsum and artesian sulphate-rich springs are locally present. Because of the thickness of gypsum present the caves are large and surface collapses up to 30m across and 20m deep have been recorded (Figures 3, 4, 7 and 8). The subsidence is not random, but occurs in a reticulate pattern related to the jointing in the underlying strata (Cooper, 1986). Around Ripon a significant subsidence occurs approximately every few years (Cooper, 1995 and Figure 4). The times of the subsidence events (Figure 4) show that some zones of subsidence are more active than others. Furthermore, areas bounding the Ure valley are more subsidence-prone due to the localised escape of cave water into the buried valley gravels (Figures 3 and 11). The subsidence has been mapped from its surface expression as sinkholes or dolines and by looking at building damage. Several building damage surveys have been carried out and the work is in progress to publish it. The technique used is based on the subsidence damage recording scheme introduced by the National Coal Board and has been successfully used near Zaragoza in Spain (Gutierrez & Cooper 2002). Information about building damage, sinkholes, springs, stream sinks and caves is for Ripon have being gathered by the British Geological Survey and stored in a Geographic Information System and associated databases (Cooper *et al.*, 2001). This database now has information for gypsum and salt karst features covering most of the country; it also contains information about limestone and chalk for about half of the country.

Gypsum caves and subsidence are not confined to Ripon; the subsidence-prone belt is about 3-4km wide and extends from just north of Doncaster to Hartlepool. Several areas along it suffer gypsum-related subsidence, though none as severe as Ripon. Subsidence affects the Darlington area, but in the urban district the problems are lessened by the presence of thick Quaternary deposits (Cooper, 1995; Lamont-Black et al., 2002, 2005).

Dissolution of gypsum in the UK, and internationally, has caused difficult civil engineering problems. In Spain the new town of Puilatos near Zaragoza had to be abandoned and demolished due to sinkhole developments over Miocene gypsum; roads and canals in the same area have also suffered collapse (Benito *et al.*, 1995). Similar subsidence conditions over Devonian gypsum are reported from northern Lithuania (Pauk©tys *et al*., 1997). The collapse of gypsum caves causes subsidence in the urban area of Paris (Toulemont, 1984). Gypsum dissolution subsidence also affects urban, peri-urban areas and their infrastructures in Germany, Italy, Poland, Ukraine, Russia and many more countries (Reuter & Tolmacev, 1990; Klimchouk *et al*., 1997 and papers therein).

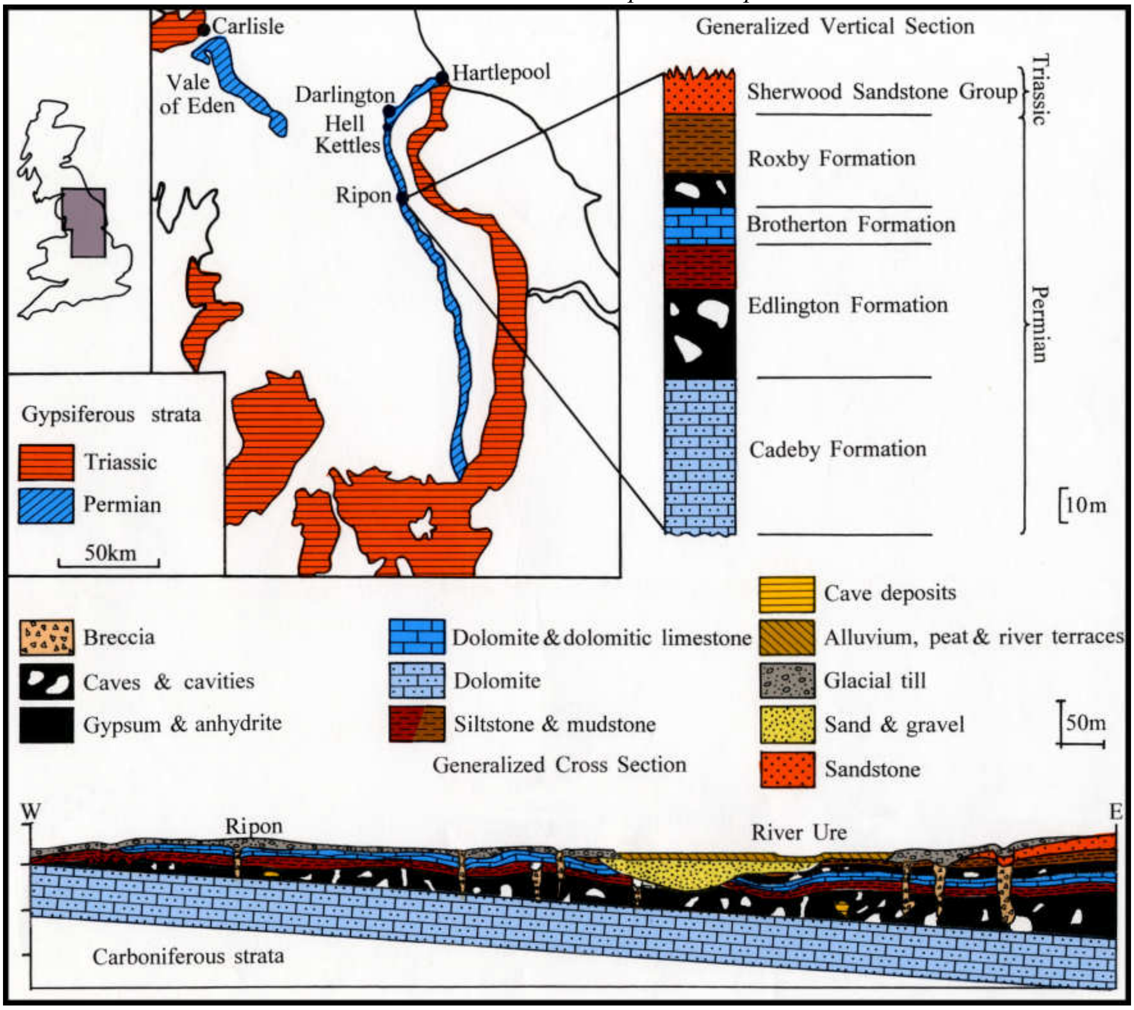

Figure 3. Regional geology of the Permian and Triassic gypsiferous sequences with a cross-section from west to east through the Ripon area showing the easterly dipping dolomite and gypsum sequence cut into by the glacial valley of the River Ure. The key on this figure is also the key to figures 7 and 8.

Problems related to water abstraction

Gypsum aquifers, despite their hard sulphate-rich water, are commonly used for water supplies. In some places the availability of the hard sulphate-rich water is considered a benefit, as it is already "Burtonised" and suitable for use in beer brewing as along with the hops it gives the beer some of its bitter taste – hence the name of English beer - "bitter". Several of the important brewing areas in the UK such as Burton on Trent and Tadcaster draw water from the gypsiferous sequences. Like all karst water systems gypsum karst can rapidly transmit pollutants (Lamont-Black et al., 2005). Gypsum karst aquifers are thus sensitive to both industrial and agricultural pollution and require careful exploitation and protection (Pauk©tys *et al*., 1997).

Water abstraction in gypsiferous terrains can aggravate the natural dissolution process by removing large volumes of sulphate-rich groundwater and drawing in aggressive recharge (Cooper, 1988). Calculations for a major water abstractor pumping from the Permian gypsum and limestone beds of Northern England showed some alarming results. The water contained approximately 1200 ppm of SO_4 mainly as dissolved $CaSO_4$ and the abstractor pumped 212 Ml of water per annum. This was equivalent to removing approximately 200m^3 of gypsum a year from the area. It is likely that much of the dissolution represented the enlargement of joints over a wide area. However, adjacent to the boreholes where rapid water flow occurs, severe dissolution could occur and result in subsidence around the wellsite. In addition water pumping can also cause changes in the groundwater level triggering subsidence in the cover rocks and superficial deposits (Benito *et al.*, 1995).

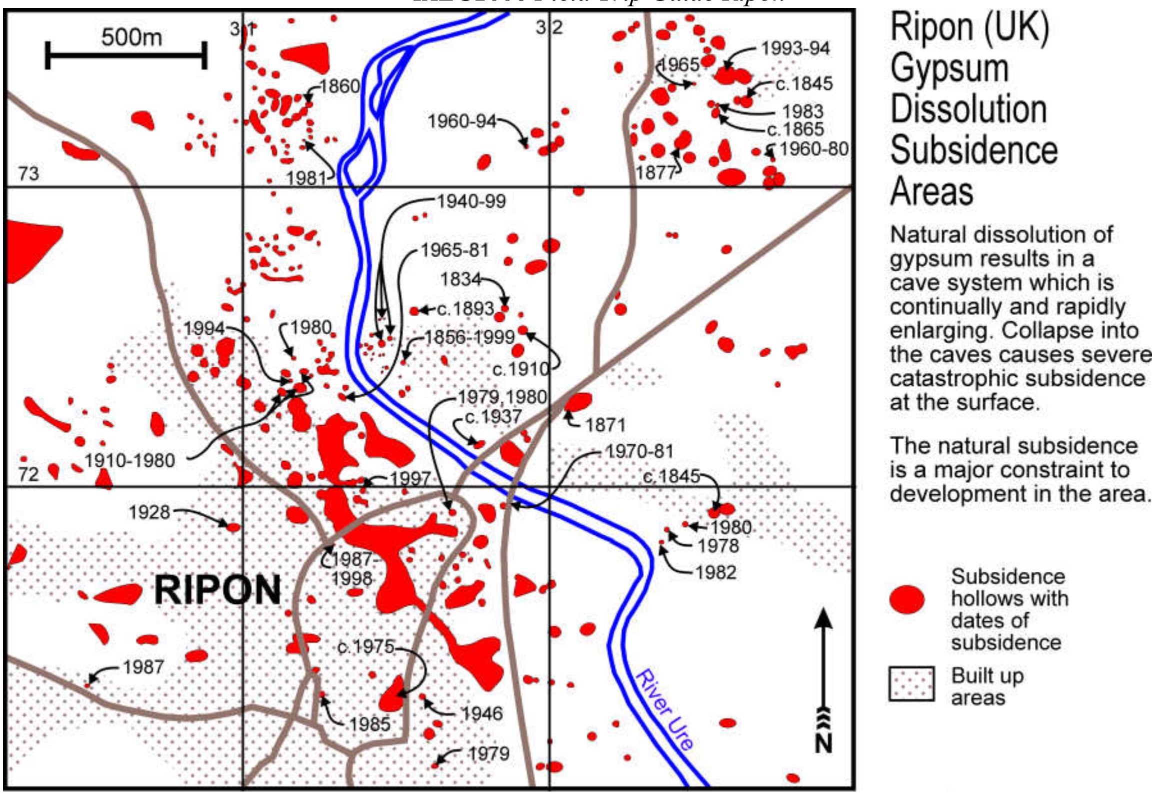

Figure 4. The distribution of subsidence hollows in the Ripon area with the dates of collapse where they are known.

Gypsum dissolution as a hazard to civil engineering

The interaction of gypsum and water in engineering projects can cause severe problems and catastrophic ground and structural failures. In the foundations of hydraulic structures, such as dams and canals, seepage through gypsum can lead to rapidly accelerating leakage, dissolution and failure. In the USA, the presence of gypsiferous beds beneath dam sites has resulted in at least 14 examples of dams losing water or failing (James, 1992), and at least two dams in China have also been affected (Lu Yaoru & Cooper, 1997). In the UK, at Ratcliffe south-west of Nottingham, power station foundations have been affected by water leakage and dissolution of thin Triassic gypsum beds (Seedhouse & Sanders 1993).

Subsidence caused by gypsum dissolution produces difficult conditions for building construction and in many cases the collapses are so severe that little can be done to mitigate the problems. Good site investigation and hazard avoidance are the best approaches followed by construction that can cope with any expected subsidence. A phased approach to development is required with detailed site investigation and careful design. In Ripon there is special planning control and buildings are now constructed on reinforced raft foundations; additional protection could be afforded by extending foundations with supporting beams outside the main footprint of the property. In subsidence-prone karstic areas it is important to use flexible service pipe materials and to guard against water loss and infiltration that itself could trigger subsidence. In some places, service trenches have been lined with waterproof membranes to stop this happening.

Linear structures such as roads and bridges are very prone to subsidence damage. At Ripon, the new Ure Bridge is built with redundant strength and the capability for the structure to loose any one of its pillar supports without collapse (Figure 10, plus Cooper & Saunders, 2002). On the same stretch of road, the embankments are protected by two layers of strong geogrid material sandwiched in the embankment fill (Cooper & Saunders, 2002; Jones & Cooper, 2005). This sandwich of material is designed to span cavities up to about 15m across and sag rather than fail so that an indication of any problem becomes visible at the surface.

Geophysics as an aid to site investigation

Because of the severe problems outlined above, areas underlain by gypsum can pose difficult problems for developers and engineers. Breccia pipes and near surface cavities can be present, and physical investigations of their locations, by all but the closest spaced borehole survey, is difficult. Geophysics can help to delineate anomalies, which can then be avoided or investigated as part of the site development. Successful techniques include microgravity (Figure 9) (Patterson *et al.*, 1995) and various forms of resistivity and conductivity survey (Cooper, 1995) with 3D resistivity tomography being particularly effective. Ground probing radar (GPR) has also been used in areas where the surface material is not clayey (Benito *et al.*, 1995), but has not been used in Ripon. Geophysics is best used in conjunction with drilling; a phased approach of using geophysics to target "anomalies" and "normal" areas, followed by drilling has proved effective.

Planning for subsidence

The timing and precise location of the sudden, and sometimes catastrophic, subsidence caused by gypsum dissolution cannot yet be predicted. However, within England the gypsum subsidence belts have been defined and many of their controlling mechanisms described. Some areas are more at risk than others and deep buried valleys cutting through the gypsiferous beds are major controlling factors at Ripon, south of Darlington and Brotherton. Collapsed areas and existing breccia pipes remain potentially unstable and are best avoided for development. Areas adjacent to collapses are also suspect because of dissolution around the bases of the collapse pipes. From the distribution of the subsidence features and their sizes, the worst areas can be avoided and development in the less susceptible areas tailored to cope with the magnitude of the likely subsidence events.

In Ripon there is a formal planning policy with check-lists and signed documents to help control and protect development in the area (Thomson *et al*., 1996). To support this process the Ripon area has been divided into three development control zones: (A) no know gypsum present; (B) some gypsum present at depth; (C) gypsum present and susceptible to dissolution.

Within zone A no special planning constraints are imposed. In zone B, where the risk of subsidence is small, a ground stability report prepared by a competent person is usually required and the problem is considered in local planning.

The zone C area (which is most of Figure 4 except the very south-west corner) is subject to significant formal constraints and controls on development, which local planning has to take into account. In this zone, a ground stability report prepared by a competent professional person is normally required before planning applications for new buildings, or change of use of buildings, are determined. In most cases this report has to be based on a geotechnical desk study and a site appraisal, followed by a programme of ground investigation designed to provide information needed for detailed foundation design (unless this information, such as boreholes, exists from a previous study). Where planning consent is given it may be conditional on the implementation of approved foundation or other mitigation measures, designed to minimise the impact of any future subsidence activity. One key to the implementation of this approach is the use of a proforma checklist to be completed and signed by a competent professional person. For the UK a competent person is defined in the report as Geotechnical Specialist who is "A Chartered Engineer or Chartered Geologist, with a postgraduate qualification in geotechnical engineering or engineering geology, equivalent at least to an MSc, and with three years of post-Charter practice in geotechnics; or a Chartered Engineer or Chartered Geologist with five years of post-Charter practice in geotechnics". In addition to these qualifications it is also desirable that the practitioner has experience of the problems though this is not formally stated. This procedure has been adopted by Harrogate Borough Council, but is likely to be subject to minor changes with experience of its use. In general it is working well and removes the responsibility from the planners to the developers, but some sites where stability might be questioned have been developed.

Localities visited at Ripon, 11th September 2006

Note: stops 1, 2 and 3 are on private property and should not be visited without first obtaining permission from the landowners. Please also note that the order of the visit, or the sites to be visited, may change due to timing or weather conditions.

Locality 1. Gypsum cliff at the side of the River Ure, Norton Conyers Park [SE3075, 7528]. Here the Edlington Formation gypsum is exposed next to the River Ure. The gypsum in this formation is locally up to 35m thick and here the upper 10m or so of the gypsum and the overlying gypsiferous mudstone are exposed. The southern end of the section has suffered dissolution in the past and there is an area of foundered Brotherton Formation just downstream. This suggests considerable dissolutional activity prior to the last (Devensian) ice age as glacial till deposits cut across the top of the subsidence features. The recent history of the cliff's dissolution has seen it cut back by about 15metres in the last 25 years.

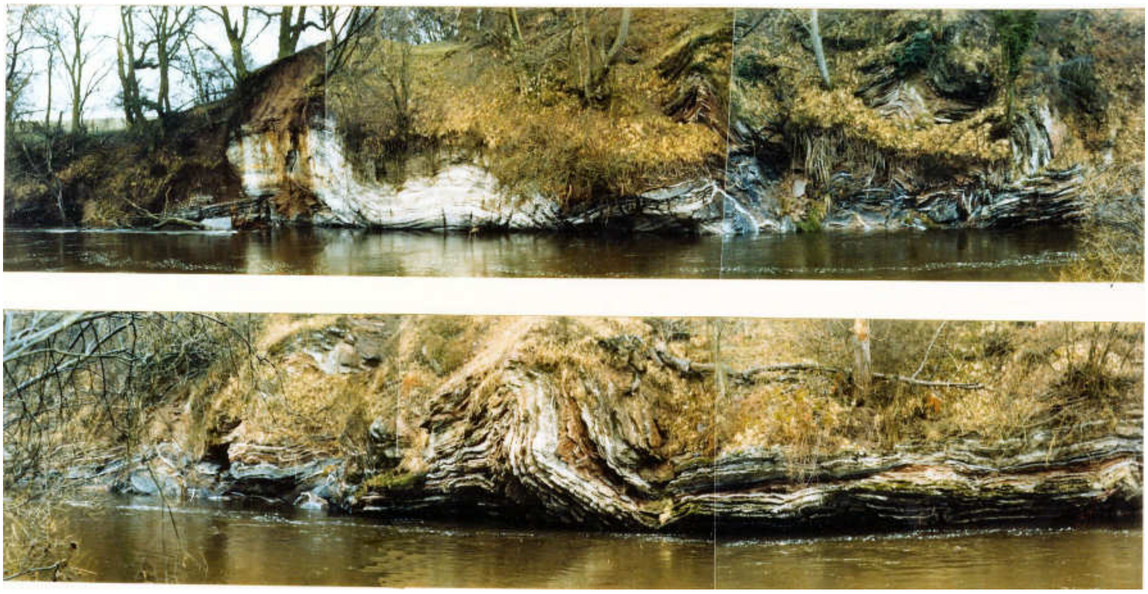

Figure 5. The gypsum cliff next to the River Ure at Ripon Parks, Norton Conyers. The cliff has changed considerably since this photograph was taken in April 1980. Firstly the massive gypsum became undercut by about 6m in 10 years. The cliff then collapsed and continued to be dissolved. Much of the southern end (top photo, left) has dissolved and collapsed revealing a collapsed area of fill materials from the overlying sequence. The recumbent fold (bottom photo, middle) has also become undercut and collapsed a couple of years ago. The dissolution of the cliff and the lithological details are given in James et al., 1981.

Figure 6. The gypsum cliff in 1990 just before it collapsed showing the complete flow of the River Ure going under the face.

Locality 2. Hall Garth Ponds [SE 3184 7473]. Several subsidence hollows are visible at Hall Garth Ponds. The pond with the steepest sides formed in 1939 is 35 by 25 metres and about 10m deep. The Brotherton Formation limestone (formerly Upper Magnesian Limestone) is exposed in the eastern side of the hollow (C and E in Figure 7). The main fishing ponds at this site used to comprise three intersecting circular ponds, but they have been considerably altered to make the ponds larger.

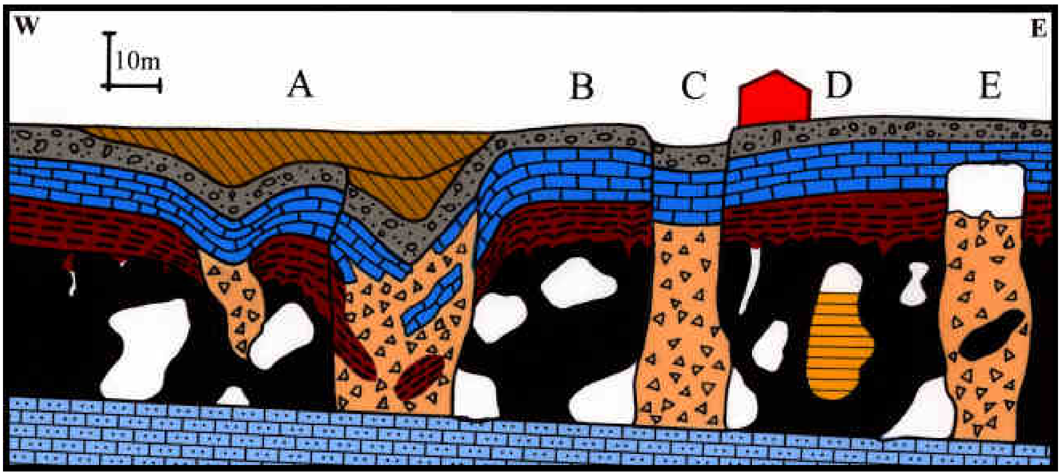

Figure 7. Cross-section through the middle part of the gypsum subsidence belt. See Figure 3 for legend.

Locality 3. Subsidence hollow behind the old Ripon Railway Station site [SE 3186 7260] (Figure 8). This subsidence hollow formed in July 1834. It is cylindrical in form (14m in diameter and 15m deep) with slightly overhanging sides. "Solid" red sandstone of the Sherwood Sandstone Group is exposed in the sides of the hollow and there is a thin covering of glacial till.

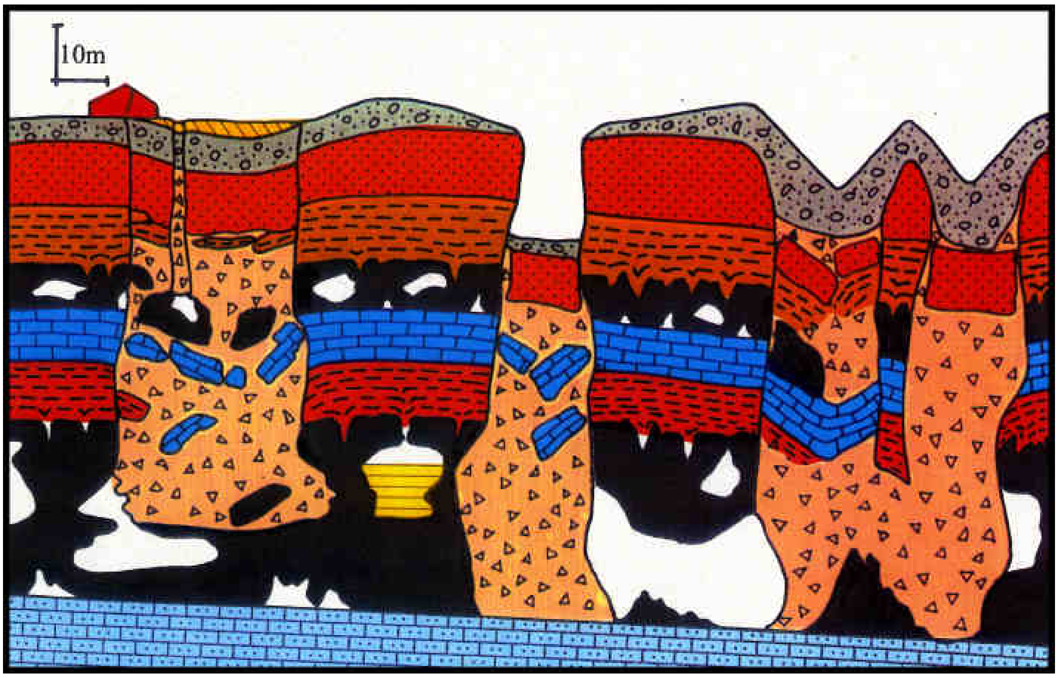

Figure 8. Cross-section through the eastern part of the gypsum subsidence belt, see Figure 3 for legend. The large subsidence in the middle of the section equates with the geological situation seen at locality 3.

Locality 4. Ripon Clock Tower [SE 3133 7182], the site of a small subsidence hollow that occurred in 1987, but is now filled in. This hole is adjacent to a large area of amalgamated subsidence hollows filled with peat and soft clay. The geological situation here equates with A on Figure 7.

Locality 5. Site of former "Broken Back Terrace" [SE 3138 7187] a row of terraced houses that had sagged in the middle and had to be demolished. They were built over a peat-filled subsidence depression.

Locality 6. Field with hill and subsidence depression [SE 3138 7197]. Bare soil on the sides of the subsidence hollow suggest that it is actively subsiding.

Locality 7. Former Tax Office. [SE 3155 7200]. No subsidence features are visible here, but a deep subsidence pipe was proved by microgravity geophysics and drilling on the west side of the site (Patterson *et al* ., 1995) (Figure below)

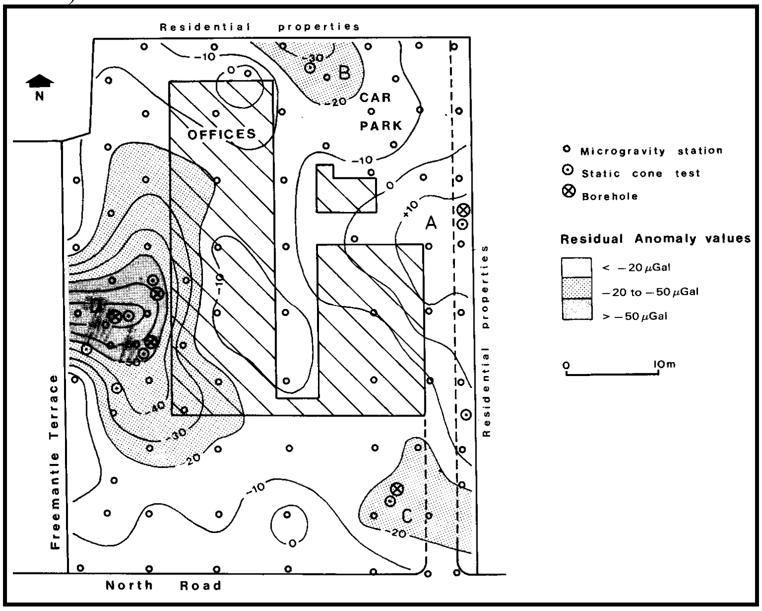

Figure 9. Plan of the former Ripon Tax Office site showing the microgravity results, cone penetrometer and borehole locations (from Patterson *et al.*. 1995).

Locality 8. Auction Mart site [SE 3163 7187]. Low area of subsidence with view to the Ripon Minster on glacio-fluvial terrace in the distance.

Locality 9. New road bridge over the River Ure [SE 3186 7195]. This bridge has been strengthened and has been designed to remain stable (but not usable) even if one of the piers fails. Electronic load monitoring is incorporated in the piers. The approach roads are strengthened with several layers of geogrid material; on less severe ground around Derby, on Triassic gypsum, the road is protected by reinforced concrete over stabilised cavity fill (Cooper & Saunders, 2002; Jones & Cooper 2005).

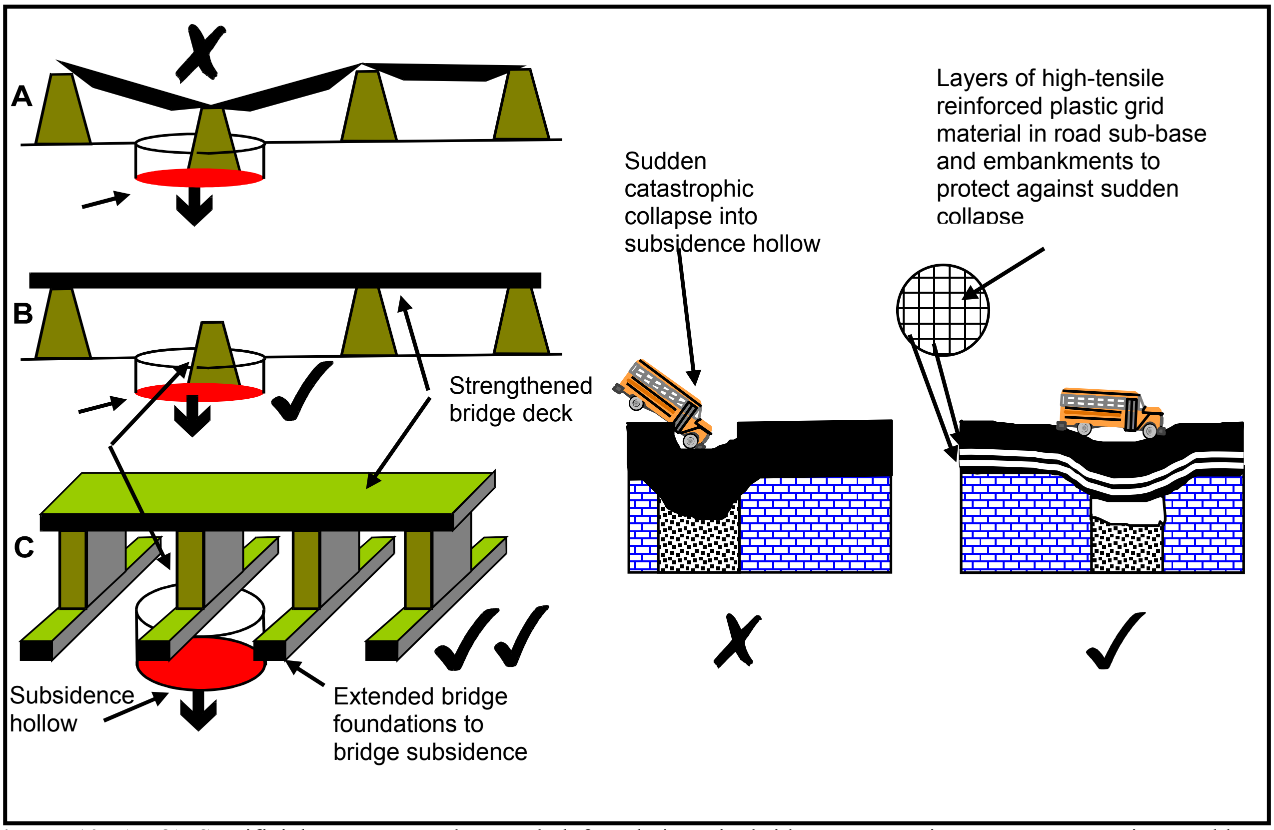

Figure 10. (Left) Sacrificial supports and extended foundations in bridge construction to protect against sudden subsidence failure. **(Right)** The use of geogrid material in road construction to protect against sudden collapse.

Locality 10. Magdalen's Road subsidence hollow [SE 3179 7181]. This large peat-filled subsidence hollow lies at the side of the deep buried valley that follows the present river valley. (Figures 3 and 4).

Locality 11. Magdalen's Chapel [SE 3173 7178]. The chapel has been buttressed and the adjacent cottages to the south-west have suffered subsidence at their eastern end where they abut a subsidence hollow.

Locality 12. Subsidence-damaged terraced houses [SE 3165 7176]

Locality 13. Subsidence-damaged terraced houses [SE 3156 7165] with a new pair of houses (reported to have been built on piles) at the eastern end. The previous houses were severely damaged.

Locality 14. Warehouse leaning towards subsidence depression [SE 3147 7175]

Locality 15. Subsidence hollow, damaged garages and threatened houses on Ure Bank Terrace [SE 3153 7242]. This hollow started its present phase of subsidence on 15th February 1995. Initially it was about 6m across, now it is 10m across and 5.5m deep. The latest and largest collapse was on 23rd-24th April 1997; It has been filled and collapsed 6 times since 1995. The hole has a long history of subsidence and was noted to have previously moved in 1968 and 1970 (Cooper, 1986). There are still legal problems over the liability for the hole and the responsibility for keeping it filled and moderately stable. A report commissioned by the Council (Cooper, unpublished) suggested filling the hole with granular material that would funnel into any cavities. This would help to support the sides (and the road) and also make any movement obvious. Taking advice from consulting engineers, the hole was filled in late 1999 with 37.5mm, type B, filter drain material which is readily available (Cooper, 2005). The material has continued to funnel into the hole and there is now a conical depression; the hole is in need of refilling, but no one wishes to take the responsibility.

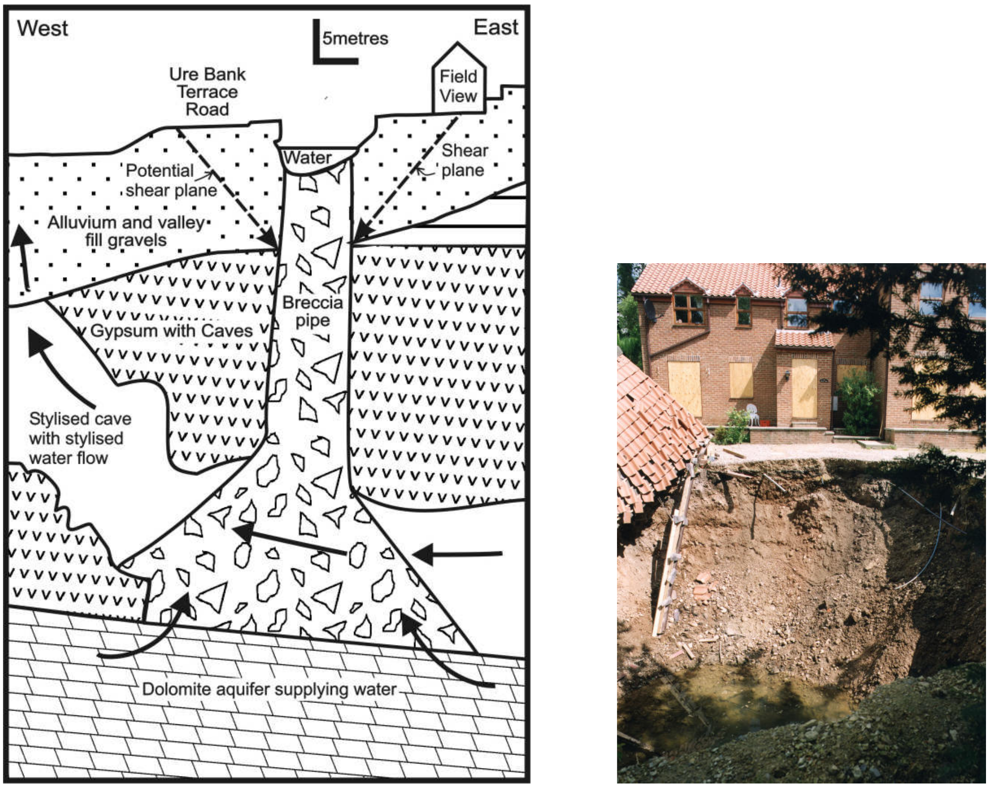

Figure 11. Schematic cross section and photograph of the Ure Bank Terrace collapse in early May 1997.

Figure 12. The Ure Bank Terrace collapse in late April 1997 viewed from the upstairs window of the house.

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