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Cover Photo:
Aerial view of the JWS sinkhole, Eddy Co., New Mexico, about six weeks after initial collapse. Photo compliments of the National Cave and Karst Research Institute.

THE ROLE OF SULFATE-RICH SPRINGS AND GROUNDWATER IN THE FORMATION OF SINKHOLES OVER GYPSUM IN EASTERN ENGLAND

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Abstract

Heavily karstified gypsum and dolomite aquifers occur in the Permian (Zechstein Group) of Eastern England. Here rapid active gypsum dissolution causes subsidence and abundant sinkholes affect an approximately 140-km by 3-km area from Darlington, through Ripon to Doncaster. The topography and easterly dip of the strata feed artesian water through the dolomite up into the overlying gypsum sequences. The shallow-circulating groundwater emerges as sulfate-rich springs with temperatures between 9-12 ^{o}C, many emanating from sinkholes that steam and do not freeze in the winter (such as Hell Kettles, Darlington). Water also circulates from the east through the overlying Triassic sandstone aquifer. Calcareous tufa deposits and tufa-cemented gravels also attest to the passage and escape of this groundwater.

The sizes of the sinkholes, their depth and that of the associated breccia pipes are controlled by the thickness of gypsum that can dissolve and by the bulking factors associated with the collapsed rocks. The presence of sulfate-rich water affects the local potability of the supply. Groundwater abstraction locally aggravates the subsidence problems, both by active dissolution and drawdown. Furthermore, the gypsum and dolomite karstification has local implications for the installation of ground-source heat pumps. The sulfate-rich springs show where active subsidence is expected; their presence along with records of subsidence can inform planning and development of areas requiring mitigation measures.

Introduction

Sulfate-rich springs are associated with the Permian Zechstein Group gypsum sequences of the Edlington and Roxby Formations in northeast England (Figure 1). These gypsiferous sequences are both underlain by dolomite or dolomitic limestone aquifers (Figure 2).

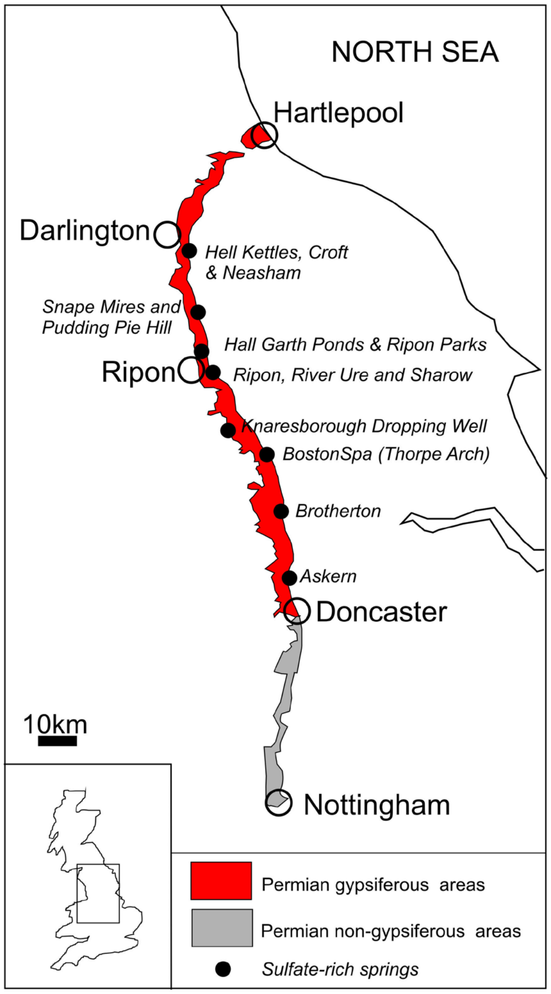

Figure 1. *Map of study area showing locations of main groups of sulfate-rich springs.*

The Edlington Formation containing up to 40 m of gypsum is underlain by the Cadeby Formation aquifer and overlain by the Brotherton Formation aquifer. This in turn is overlain by the Roxby Formation with another 10 m or so of gypsum that itself passes up into the major aquifer of the Sherwood Sandstone Group (Figure 3). The Permian sequence dips gently eastwards with a dip of a degree or so. It presents a wide dip slope of Cadeby Formation dolomite which acts as a rain-catchment area that collects water and channels it down dip to the east where it rises up in the lower ground through the gypsiferous sequence (Figure 2 and Cooper, 1986, 1988, 1998). The local rainfall averages around 594mm a year in the south and 648 mm in the north (for 10 – 38 year averages over 6 sites; Leeming, Topcliffe, Church Fenton, Linton on Ouse and Dishforth); the average temperature for Leeming over 38 years was 9.2°C with a minimum average of 4.7°C and a maximum average of 13.1°C (Tutiempo 2013). It typically varies from 1°C to 20°C and is rarely below -4°C or above 20°C (Weatherspark, 2013).

Numerous sulfate-rich springs occur at the foot of the dip slope and across the outcrop of the overlying strata (Figure 2). Many springs emerge under artesian pressure, some from within sinkholes that do not freeze in the winter due to the groundwater being at a temperature of 912°C.

The outcrop of these strata, where gypsum is present in the sequence and sulfate-rich springs occur, covers an area about 140 km long and 3 km wide extending from near Doncaster in the south through Askern, Boston Spa (Thorpe Arch), Knaresborough, Ripon, and east of Bedale to Darlington and the coast at Hartlepool (Cooper, 1986, 1998) (Figure 1). The area is prone to subsidence and sinkhole formation caused by the dissolution of the gypsum and the evolution of gypsum cave systems beneath the area. Some places are more susceptible than others and these tend to be where partly in-filled or buried valleys cut through the sequence allowing enhanced water flow.

In the north near Darlington, sulfate-rich groundwater escapes where the Tees Valley cuts the Permian sequence (Lamont-Black et al., 2002, 2005). The water forms the Spa springs at Croft and Hell Kettles a group of 3 sinkholes, one of which collapsed in the 12th century. Farther south, sulfurous water is recorded at Snape Mires near Bedale. Sulfate-rich groundwater is noted from here south to Ripon where the Permian sequence is cut through by the Ure Valley. Here tufa-depositing springs occur, forming tufa-cemented gravels (Cooper, 1986) and similar water emanates from the petrifying spring of the Dropping Well near Knaresborough. In the south of the area, sulfate-rich water is noted around Brotherton and subsidence ponds at Askern. The ponds at Askern, Hall Garth Ponds (Nunwick near Ripon) and Hell Kettles (near Darlington) all have or had artesian water emanating from them at a temperature sufficient to prevent them freezing easily in the winter.

The groundwater flow and active gypsum karstification leads to the formation of sinkholes that can be up to 20 m or more across and up to 20 m deep (Cooper, 1986, 1989,

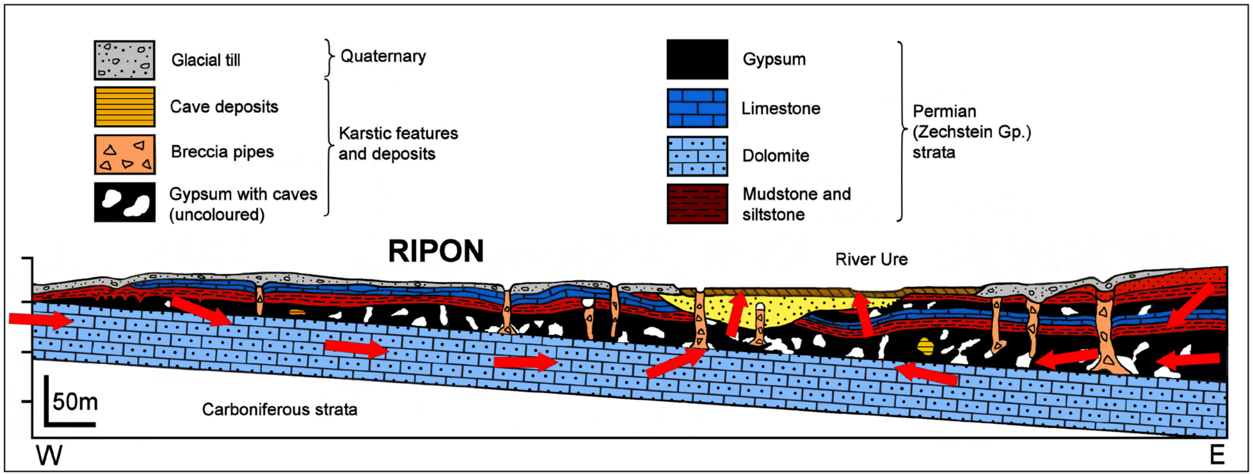

Figure 2. *Generalised cross-section through the easterly dipping Permian sequence showing water flow through the Permian dolomites and limestones into the Permian gypsum and then to the surface. The geological sequence is shown in Figure 3.*

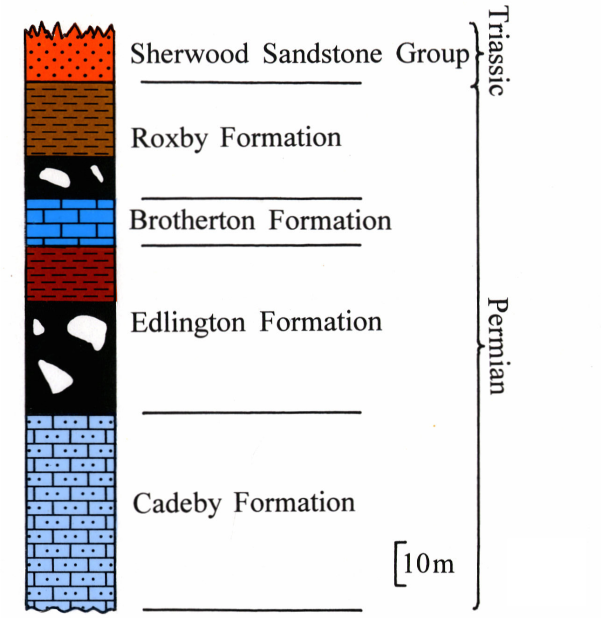

Figure 3. *Vertical section through the Permian Zechstein Group se quence in northern England; for lithological legend see Figure 2.*

1998). Planning for these problems and developing such areas requires special engineering mitigation measures (Paukstys et al., 1999; Cooper and Saunders, 2002; Cooper, 2008a, 2008b; Gutiérrez et al., 2008).

Sulfate-rich springs

Historical records of sulfate-rich springs

The historical records of springs and wells give us an insight into the locations and approximate characters of many mineral waters. Waters high in sulfur/sulfate were particularly sought for their medicinal purposes with long lists of cures attributed to them. We used these early records to help us locate sulfate-rich springs that we then sampled using modern techniques.

As early as the mid-17th century, doctors were investigating the nature of the mineral waters that they prescribed as cures for many ailments. Burrell (1896) records that examination by Dr French in 1654 of the Dropping Well water at Knaresborough found a pint weighed 10 grains more than a pint of common water. This equates to approximately 1140 mg/l of dissolved solids. In the 18th century Thomas Short described several “sulphur-waters” including the petrifying water of the Dropping Well at Knaresborough and the waters of “Croft Spaw” near Darlington and “Askern Spaw”, both of which he noted as having a white sediment deposit (Short, 1734).

From the 18th century onwards, the mineral springs of the country were more extensively documented for their medicinal properties and the ailments they were thought to cure. Consequently, many medicinal scripts were written on the efficacy of the waters. Dr Robert Willan (1757-1812: Booth, 1999) was one such practioner who published on the sulphur waters of Croft, near Darlington and at Harrogate (Willan, 1782, 1786). Winch (1817) quoting analyses done by Peacock in 1805 showed the Croft water to be high in calcium sulfate.

The waters of Askern north of Doncaster were similarly described for their medicinal benefits by Brewerton (1818) and Lankester (1842) both with analyses presented in grains per gallon showing the waters to be high in dissolved calcium sulfate. Edwin Lee (1854) wrote an extensive treatise on “The Watering Places of England – considered with reference to their Medicinal Topography” with mention of the springs at Dinsdale (near Neasham) and Croft near Darlington plus the springs at Askern; his work also presents analyses of the waters. Some of these very early analyses give what we would now consider very strange combinations of elements, but in general they show high concentrations of calcium sulfate and the weights of dry residue of the analyses can be considered fairly accurate. In the late 19th century, studies of the mineral waters became based more on their geological origins with papers by Bothamley (1894) on the mineral waters of Askern and by Burrell (1896) on the water of the Dropping Well at Knaresborough.

We have used these historical records both to find the springs, but also to compare with our modern analyses. In some cases springs have disappeared due to groundwater abstraction or piping away in culverts, and these old references are the only records.

Because the sulfate-rich water is groundwater, commonly under artesian pressure, it can be warmer than surface temperatures and many of the ponds associated with the springs were noted for not freezing in the winter. This characteristic is also enhanced by the amount of dissolved chemicals in the water. The Mather Pit at Askern (Lankester, 1842), Hell Kettles at Croft, and Hall Garth Ponds near Ripon (AHC personal observation) all steamed in cold weather. The sulfate-and carbonate rich water is also favorable to the deposition of calcareous tufa, the best example of which is the Dropping Well tufa screen at Knaresborough (Burrell, 1896; Cooper and Burgess, 1993). Tufa-cemented deposits are widespread and associated with the sulfate-rich spring activity with cemented gravels at Ripon (Thompson et al., 1996; Cooper, 1998).

Modern sampling and analyses of sulfate-rich springs

Described from north to south, the main sulfate-rich springs are shown on Figure 1 and detailed in Table 1. The analyses were undertaken by three of the authors for their MSc studies (Miller, 2006; Greenwood, 2008; Brown, 2010).

Hell Kettles

At Hell Kettles there are three sinkholes, two combined into Double Kettle and one by itself a little to the south (Figure 4). Artesian sulfate-rich water overflows from the kettles, which are a Site of Special Scientific Interest for their uncommon flora. The highest concentrations of sulfate occur in the southern sinkhole, reaching 1225 mg/l (Table 1). The geological setting here is similar to that shown in Figure 2, being in the alluvial tract of the River Tees where it cuts down through the Permian sequence. Oxen le Fields Farm borehole is located about 400 m northeast of the kettles and yielded water less rich in sulfate than that seen at Hell Kettles.

Croft Sweet Well and Spa

Situated about 1.5 km south of Hell Kettles, the spring is near the base of the Cadeby Formation dip slope and formerly fed the spa hotel at Croft. The water is rich in sulfate (867 mg/l) and fairly high in carbonate.

Figure 4. *Hell Kettles near Croft, Darlington. Double Kettle on left, Croft Kettle on right; north is to the left and the field is 190m wide; oblique view on digital terrane model. Air Photography copyright UKP/Getmapping reproduced under licence No UKP2006/01.*

Neasham Low Springs

Located to the east of Hell Kettles, these springs emanate from the Triassic Sherwood Sandstone Group and negligible amounts of sulfate are present.

Snape, Snape Mires, and Gruntland springs near Bedale

Snape Mires is a large flat area of glacial-lake deposits with abundant subsidence features (Cooper, 1986; Powell et al., 1992). The area is a bedrock depression caused by subsidence due to gypsum dissolution. It is fed by water under artesian pressure from the Cadeby Formation dip slope to the west (pale blue on Figure 2) where at the dip slope base the prolific and sulfate-poor Mill House Spring emanates. In the low ground of the mire numerous springs well up and are associated with peat mounds, including one about 5 m high called Pudding Pie Hill which has very little sulfate in the water. Farther east, in the middle of the mire, the sulfate levels are high at The Gallops, falling again at Gruntland Springs, which emanate from the Triassic Sherwood Sandstone in the east.

Ripon, Hall Garth Ponds, near Nunwick

These ponds are very similar in character to Hell Kettles. They include a sinkhole that collapsed in 1939 (Cooper, 1986) and several other sinkholes that have been "landscaped" into larger ponds of different shape. The 1939 sinkhole has artesian water welling up within it and high sulfate levels also suggest spring activity in the adjacent ponds. The geological situation is similar to that shown in Figure 2, with the Brotherton Formation (dark blue on Figure 2) present in the east wall of the sinkhole.

Ripon springs and ponds at Ripon Parks

Ripon Parks includes a number of ponds occupying very large sinkholes and a number of springs that emanate from the gypsum of the Edlington Formation and the glacial deposits. Despite the springs emerging next to small gypsum outcrops, very little sulfate was present. Similarly, the ponds situated in collapsed glacial deposits also had low sulfate levels.

Ripon town Spa Field and road bridge springs

These springs are located in a low part of Ripon where there are numerous peat bogs and abundant active subsidence features (Cooper, 1986, 1989, 1998, 2008a; Cooper and Saunders, 2002). Recent site investigation has proved sulfate-rich water in a peat bog that occupies part of the former Spa Field near the former Spa Well.

Table 1. *Names, locations and main sulfate, calcium and bicarbonate compositions of springs in the study area. (Continued on following page.)*

Spring Name	NGR E	NGR N	pH	Temp	Conduc-tivity	Concentrations mg/l				Analyst or reference
				°C	mS/cm	Ca^{2+}	SO_4^{2}-	HCO_3-	TDS	
Hell Kettles, Croft, Darlington: Croft Kettle (CK2) at 5m	428151	510844	7.75	11.2	1.680	480.9	1225.3	256.9	2148.2	Miller 2006
Hell Kettles, Croft, Darlington: Double Kettle (DK1) at 4.2m	428091	510912	7.76	14.7	1.500	404.3	1097.8	232.0	1904.3	Miller 2006
Hell Kettles: Oxen le Fields Borehole	428340	511210	6.93	15.8	1.250	257.4	533.4	283.9	1185.3	Env. Agency (Miller 2006)
Neasham; Low Neasham Springs	431707	510709	7.2	12.7	N/A	135.0	12.0	317	N/A	Greenwood 2008
Croft: Sweet Well (Spa)	427879	509186	6.7	10.7	N/A	428.0	867.0	229.0	N/A	Greenwood 2008
Snape Mires; Pudding Pie Hill	427815	484458	7.6	13.5	0.161	58.7	32.4	N/A	416.4	Brown 2010
Snape Mires; The Gallops 1	428767	484395	7.34	12.0	0.320	548.9	952.5	N/A	1943.8	Brown 2010
Snape Mires; The Gallops 2	428794	484359	7.34	20.6	0.720	189.7	306.9	N/A	1305.2	Brown 2010
Snape Mires east; Gruntland Springs 1	428723	488409	7.26	10.0	0.320	211.4	228.3	71.2	698.2	Brown 2010
Snape Mires east; Gruntland Springs 2	428723	488409	7.26	10.0	0.315	247.9	338.1	83.4	948.4	Brown 2010
Snape Village; Mill House Spring 2	427408	484065	7.46	9.9	0.202	92.2	45.4	24.4	408.5	Brown 2010
Ripon, Hall Garth Ponds; 1939 sinkhole (N3) at 6.6m	431842	474707	8.03	10.2	1.700	490.7	1172.4	227.4	2001.0	Miller 2006
Ripon, Hall Garth Ponds; east pond (E3) at 0.8m	431895	474681	7.82	17.3	1.210	281.3	549.6	230.3	1146.6	Miller 2006
Ripon Parks, Queen Mary's Dubb at 4m	430662	474828	7.41	14.9	0.072	34.7	9.5	50.8	128.4	Brown 2010
Ripon Parks, Black Heath Pond at 1.4m	430435	474959	7.34	14.9	0.147	66.4	42.8	63.0	214.4	Brown 2010
Ripon Parks spring 4	430594	475472	8.27	11.6	0.220	122.9	55.7	91.5	368.4	Brown 2010

Table 1. *Continued from previous page.*

Spring Name	NGR E	NGR N	pH	Temp	Con-ductivity	Concentrations mg/l				Analyst or reference
				^{o}C	mS/cm	Ca^{2+}	SO_4^{2}-	HCO_3-	TDS	
Ripon, Spa Field (Nr Spa Well at 431573 471607) at 1.6m	431505	471746					2015.0			Site investigation report
Ripon, Bridge foundations	431889	472039					1360.0			Thomson et al 1996
Ripon, Racecourse gravel pit (approx locality)	432950	469500					289.0			Thomson et al 1996
Ripon, Sharow spring	433041	470763	7.54	9.5	1.340	247.0	409.0	320.0		Simon Warwick pers. comm.
Knaresborough, Dropping Well spring	434766	456498	6.9	10.7	N/A	681.0	1360.0	298.0	N/A	Greenwood 2008
Knaresborough, Dropping Well tufa screen top	434773	456518	7.6	11.7	N/A	709.0	1420.0	264.0	N/A	Greenwood 2008
Brotherton; Burton Salmon - Lake outflow	448979	427269				178.7	65.8			P Murphy (1998, unpub.; high Cl.)
Brotherton: Byram - drainage ditch	448626	425162				256.1	358.3			P Murphy (1998 unpub.; high Cl.)
Askern; main lake inlet	456238	413583	7.1	13.8	N/A	610.0	1400.0	166.0	N/A	Greenwood 2008
Askern; main lake deep sinkhole (A1N) at 5m	456286	413505		17.5	N/A	561.0	1310.0	122.0	N/A	Greenwood 2008
Askern: Manor Bath (well)	456322	413525				433.0	947.0		2361.0	Bothamley, 1894 (page 351)
Askern; Lake borehole (location unconfirmed)						697.0	1172.0	306.0	N/A	Env. Agency (Greenwood. 2008)
Askern; Colliery borehole	455690	413640				585.0	1422.0	279.0	N/A	Env. Agency (Greenwood. 2008)
Askern; Manor Well at 0.9 m	456322	413525		9 to 17		594.0	1085.0			Brewerton 1818 (Greenwood, 2008)
Askern; Manor Well	456322	413525				573.0	1493.0			Lankester 1842 (Greenwood, 2008)
Askern; Charity Well	456197	413392				584.0	1251.0			Lankester 1842 (Greenwood, 2008)

Just to the east of this the new Ripon Bridge over the River Ure had sulfate-rich artesian water welling up in the foundation excavations and some of the local Quaternary deposits of sand and gravel were cemented with calcareous tufa, as are the gravels that occupy this part of the buried valley at Ripon (Cooper, 1986; Thompson et al., 1996). Nearby artesian springs were recorded in the bed of the river, and boreholes drilled for the bridge-site investigation had an artesian head about 1 m above river level. This water is fed from the higher ground to both the west and east as indicated in Figure 2, which is drawn through this area. Ripon has a spa hotel, but the water for this was piped in from Carboniferous strata several kilometers to the west.

Sharow Spring

Situated a little to the southeast of Ripon in a former glacial overflow channel, this spring has mixed water related to both gypsum dissolution in the Permian sequence below and water flowing through the Triassic Sherwood Sandstone to the east.

Ripon Racecourse

Water collected from the gravel pit ponds at Ripon Racecourse is high in sulfate and attests to spring activity from the underlying gypsum feeding sulfate-rich water into the gravel pit that is also fed by percolation from the nearby river. The location of the gravel pit is over the buried valley of the River Ure (Figure 2).

Knaresborough Dropping Well (petrifying)

The Dropping Well spring emerges from the Edlington Formation and its associated gypsum strata lying to the west of Knaresborough close to the contact with the underlying Cadeby Formation. The water is high in both sulfate and carbonate, the latter being actively deposited as a tufa ramp and screen below, in which artifacts are petrified as a tourist attraction (Figure 5). Several sinkholes are present in the fields that form the catchment to the spring. The spring above the tufa screen was sampled on 19th June 2008, it had rained heavily 6-7 hours previously and the flow was gauged at 5040 liters an hour.

Brotherton area springs

In the Brotherton area there are a number of sinkholes and several springs that feed into a small lake (Murphy, 2000): however, the water emanating from the lake has low sulfate levels (Table 1). Farther south, on similar Permian geology, a spring yields a moderate amount of sulfate, but also high levels of chloride, which may be anthropogenic or possibly related to chloride salts in the Permian sequence.

Askern springs and lake

Askern today has an ornamental lake next to the road in the middle of the village. The air photographs and the present sampling (Greenwood, 2008) show a number of sinkholes in the bed of the lake (Figure 6), but although sulfate levels were high in the lake they appeared to be related to water flow coming from a major inlet rather than artesian water coming up from the sinkholes. This might be because of groundwater pumping for mining and pollution control in the area. Historical maps show that in the past there were more ponds to the south of the present lake. These included the so-called Mather Pits that had very high sulfate levels and which did not freeze in the winter (Brewerton, 1818; Lankester, 1842; Bothamley, 1894).

Figure 5. *The Dropping Well (petrifying spring) at Knaresborough.*

Figure 6. *Askern Lake showing the sinkholes within it as deeper water in the middle, southeast and southwest; west (left) edge of lake is 195 m long. Air Photography copyright UKP/Getmapping reproduced under license No UKP2006/01.*

Interpretation

There is a close relationship between the presence of sinkholes that affect the Permian gypsiferous sequence and the locations of sulfate-rich springs. The driving mechanism is water flow from the catchment largely dominated by the Cadeby Formation dolomite sequence that underlies the gypsum formations and which has a large dipslope to the west of the main gypsiferous units. Water passing through this dolomite sequence is rich in magnesium and calcium carbonates. This type of common-ion-water mixing is aggressive to gypsum, causing rapid dissolution resulting in numerous sinkholes (Klimchouk, 1996). The common-ion effect also dedolomitizes the dolomite at its contact with the gypsum (Bischoff et al., 1994) and changes it to a weak calcitic mesh that can also break down and cause subsidence. This process also helps to release calcium carbonate that is redeposited as tufa and tufa cements. The water analyses of the springs show different mixtures of sulfate and carbonate waters that appear to be controlled by the positions of the springs with respect to the Cadeby Formation dip slope, the low ground with the gypsum, and the higher ground formed by the overlying Triassic sandstone.

Artesian water is present wherever valleys cut through the Permian sequence. It is in these locations in the lower ground that the most aggressive dissolution is occurring and where the most active subsidence is happening. Consequently, where the valleys of the rivers Tees, Ure, Nidd, Wharfe, and Aire cut through the Permian escarpment, there are concentrations of sulfate-rich springs and sinkholes.

The distribution of the sinkholes is controlled by several factors. The western limit is the feather-edge boundary of the gypsum onto the underlying Cadeby Formation dolomite (Figure 2). The eastern limit is the down-dip transition from gypsum to anhydrite. This transition is largely controlled by the reduction in groundwater flow due to the sulfate-cemented nature of the aquifer units adjacent to the gypsum/anhydrite sequence. This gypsum to anhydrite transition occurs at a depth of about 100-120 m, giving the subsidence-prone belt a width of about 3 km (Cooper, 1986, 1988). Up to 40 m thickness of gypsum is present in the Edlington Formation and another 10 m or so above it in the Roxby Formation (Figure 3). The thickness of gypsum present means that if a significant part of it dissolves the resultant cavities and breccia pipes cannot generate enough breccia to bulk up and fill them, resulting in very large subsidence features at the surface (Cooper, 1986).

The study has shown that sulfate-rich springs are much more widespread than previously recognized. It also shows that sulfate concentrations similar to those recorded by Cooper (1986) commonly occur. The geology along the Permian escarpment and gypsiferous rocks is similar along the length of the outcrop. The superficial geology situation, with buried valleys cutting the sequence, is also repeated in several places (Figure 2). Cooper (1986, 1988) suggested models for the amount of gypsum dissolution in the Ripon area based on groundwater with a sulfate level of 1200 mg/l, as found in a local borehole in Ripon. The calculation presented by Cooper (1986) suggested an annual amount of around 120 cubic meters of gypsum being dissolved every square kilometer. The sulfate-rich spring information we present suggests that if similar infiltration rates occur along the Permian escarpment, then similar annual amounts of gypsum are being dissolved along most of the gypsum belt.

The presence of sulfate-rich springs also helps to indicate areas where there is very poor groundwater quality due to the high presence of sulfates. They also indicate areas where groundwater abstraction should be discouraged for purposes such as irrigation, both because of the acceleration of dissolution such as that described by Cooper (1988), but also because of the problems of subsidence caused by rapid fluctuations of the piezometric level. Within the gypsum-subsidence-prone area some farm irrigation boreholes have been implicated as the possible causes of subsidence in the immediate vicinity to them. Currently there is an acceleration in the desire to install ground-source heat pumps. The presence of sulfate-rich water and the likelihood of enhanced dissolution mean that within the gypsum belt only closed-loop systems should be considered (Cooper et al., 2011).

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