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Geological hazards from salt mining, brine extraction and natural salt dissolution in the UK

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Abstract
Salt mining along with natural and human-induced salt dissolution affects the ground over Permian and Triassic strata in the United Kingdom. In England, subsidence caused by salt mining, brine extraction and natural dissolution is known to have occurred in parts of Cheshire (including Northwich, Nantwich, Middlewich), Stafford, Blackpool, Preesall, Droitwich, and Teeside/Middlesbrough; it also occurs around Carrickfergus in Northern Ireland. Subsidence ranges from rapid and catastrophic failure to gentle sagging of the ground; both forms being problematical for development, drainage and the installation of assets and infrastructure such as ground source heat pumps. This paper reviews the areas affected by salt subsidence and details the mitigation measures that have been used; the implications for planning in such areas are also considered.

Introduction

In the United Kingdom, rock salt is present in Triassic and Permian rocks, from which it has been exploited for several millennia (Northolt and Highley 1973; Sherlock 1921). Also called halite or sodium chloride (NaCl), rock salt is not only a valuable industrial commodity, but also a highly soluble material responsible for natural and man-made subsidence geohazards. The Triassic salt-bearing strata are widespread in the Cheshire basin area, but also common in parts of Lancashire, Worcestershire, Staffordshire and Northern Ireland (
Figure **1**). Permian saliferous rocks are mainly present in the northeast of England (Northolt and Highley 1973). This paper looks at the occurrence of salt deposits, the way they either dissolve naturally, or have been extracted by mining and man-made dissolution. It considers the subsidence problems that have arisen and continue to

occur and looks at ways of mitigating the problems by planning and construction/remediation techniques.

Like table salt, rock salt is highly soluble and dissolves very quickly in water to make brine. This process occurs naturally in the UK and as a consequence, salt is not seen anywhere at outcrop. Instead it is present in the subsurface, where the upper part of the sequence is dissolved, producing a buried dissolution surface (salt karst) overlain by collapsed and foundered strata. The natural dissolution processes and groundwater flow are evidenced by the presence of brine springs, many of which have been known and exploited since Roman times. Through the Middle Ages these springs were moderately exploited and gave rise to place names ending in 'wych' or 'wich' (Cooper 2002), but it was in Victorian times that large-scale extraction both by mining and brine extraction accelerated leading to some large and devastating instances of catastrophic subsidence (Calvert 1915). We are still dealing with this legacy and the effects of subsequent brine and rock salt extraction in many places especially in parts of Cheshire, Droitwich, Stafford and Preesall. Where shallow brine extraction has occurred it mimics the natural salt karstification processes and the results of natural and man-made events can be difficult to differentiate. In Northern Ireland the salt has been mined traditionally by pillar and stall mining. In certain cases severe subsidence has occurred due to water ingress into the mines causing dissolution of the pillars and catastrophic collapse.

Permian salt occurs at depth beneath coastal Yorkshire and Teesside. Here the salt deposits and the karstification processes are much deeper than in the Triassic salt and the salt deposits are bounded up-dip by a dissolution front and collapse monocline (Figure 2) (Cooper 2002). Salt has been won from these Permian rocks by dissolution mining and some historical to recent subsidence due to brine extraction has occurred along the banks of the River Tees and to the north-east of Middlesbrough (Tomlin 1982).

Modern pillar and stall salt mining is deeper than old Victorian mining and located in mudstone and salt sequences that are completely dry. Modern brine extraction is controlled and restricted to deep engineered cavities that are kept full of brine on completion, or used for other storage such as gas or waste; both methods of extraction have low or zero expectations of subsidence.

Distribution of salt deposits in the Triassic and Permian rocks of the UK

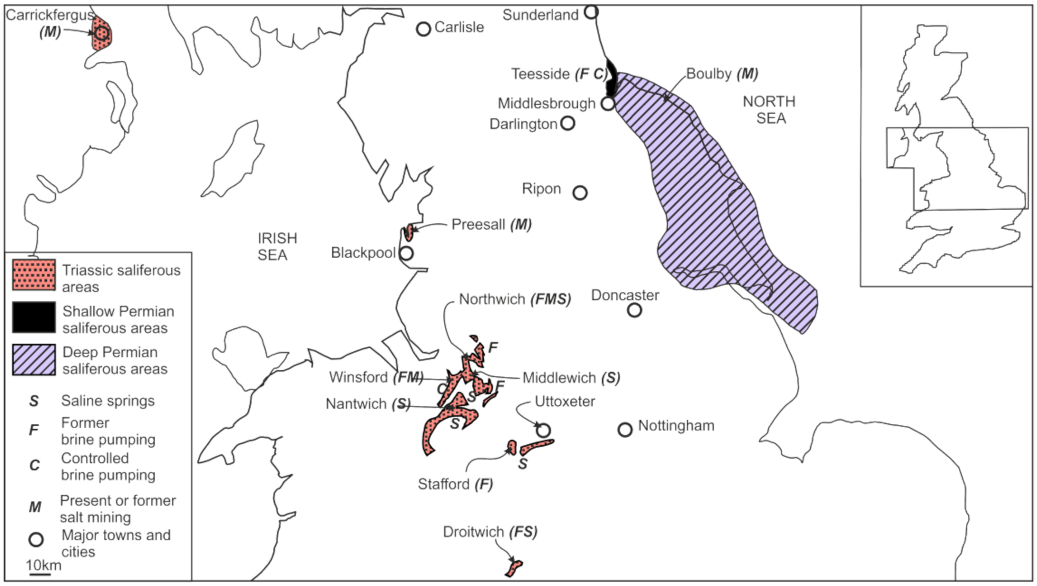

Figure 1. Distribution of salt deposits in the UK showing mined and brine pumping areas

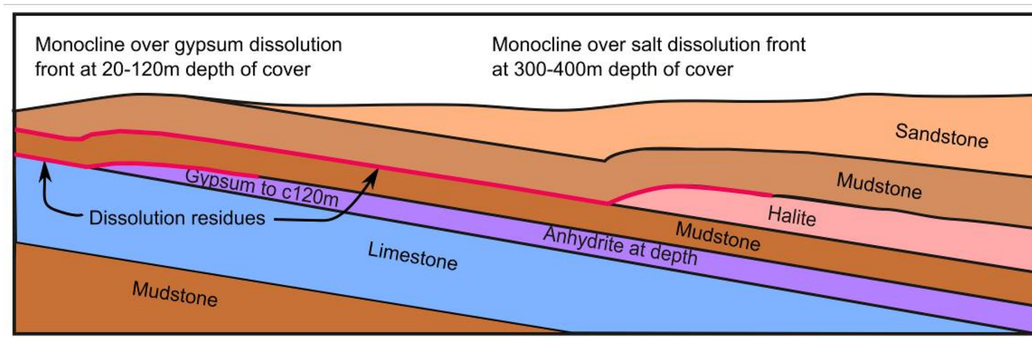

Figure 2. Characteristic structure and sub-surface morphology of Permian salt karst in north-east England

In England and Northern Ireland, Triassic salt deposits are present onshore Figure **1**) in Lancashire, Cheshire, Worcestershire, Staffordshire, Somerset, Dorset and Carrickfergus (Griffith and Wilson 1982; Jackson et al. 1995; Northolt and Highley 1973; Sherlock 1921; Whittaker 1972; Wilson 1990, 1993). The deposits formed in a semi-arid environment mainly within mainly fault-controlled land-locked basins linked to the major depositional centres of the North and Irish Seas. The sequence generally comprises thick sandstones and conglomerates overlain by red-brown siltstone and mudstone interbedded with halite and gypsum units. The Permian salt sequence was deposited as part of the Zechstein Group that formed in the extensive Zechstein Sea which extended eastwards from The United Kingdom to

Holland and Germany (Doornenbal and Stevenson 2010; Smith 1989; Taylor and Coulter 1975). Only the margin of the Zechstein Group occurs onshore in coastal parts of eastern England where the salt is interbedded with thick dolomite, mudstone and anhydrite formations.

Salt karst and natural dissolution

Salt is a highly soluble mineral; up to 360g of salt will dissolve in a litre of water at 25^{O}C (Ford and Williams 1989) making a saturated solution with a specific gravity of 1.202 (FLUKA 2013). The dissolution rate of salt is extremely rapid, dissolving about 1000 times faster than gypsum at similar temperatures and pressures (Gutiérrez et al. 2008). The resulting brine is denser than normal groundwater and can, therefore, stay impounded below the ground surface (Howell and Jenkins 1976). However, where this dissolution interface coincides with the surface, or where there is sufficient hydraulic head, brine can flow to surface naturally as brine springs and it is around these that the historical salt industry has developed. Brine springs are well-documented in the Cheshire, Worcestershire and Staffordshire areas and their presence also led to the establishment of the Northern Ireland salt industry (Griffith and Wilson 1982).

In Cheshire the local place name ending in wich or wych derives from the medieval name for a salt spring. In Cheshire, brine springs occurred in many places including Northwich, Middlewich, Nantwich, Winsford. They were also present near Whitchurch (Shropshire) at Higher Wych and a place formerly called Dirtwich. Natural subsidence has occurred sporadically throughout the salt field, one of the earliest records being in 1533 at Combermere Abbey near Whitchurch (Sherlock 1921). Another was recorded at Bilkely in about 1659 near Cholmondeley Castle (Jackson 1669; Ormerod 1848). Numerous buildings at Wybunbury near Crewe were damaged by salt dissolution subsidence in the late 19th Century and the cause may have been natural since the nearest brine extraction was over 10 miles away (De Rance 1891). Many natural lakes such as Rostherne Mere near Knutsford were also formed by salt dissolution since the end of the Devensian ice-age and the Cheshire saltfield is dotted with meres many of which formed in this way (Waltham et al. 1997), though others are more probably of glacial origin.

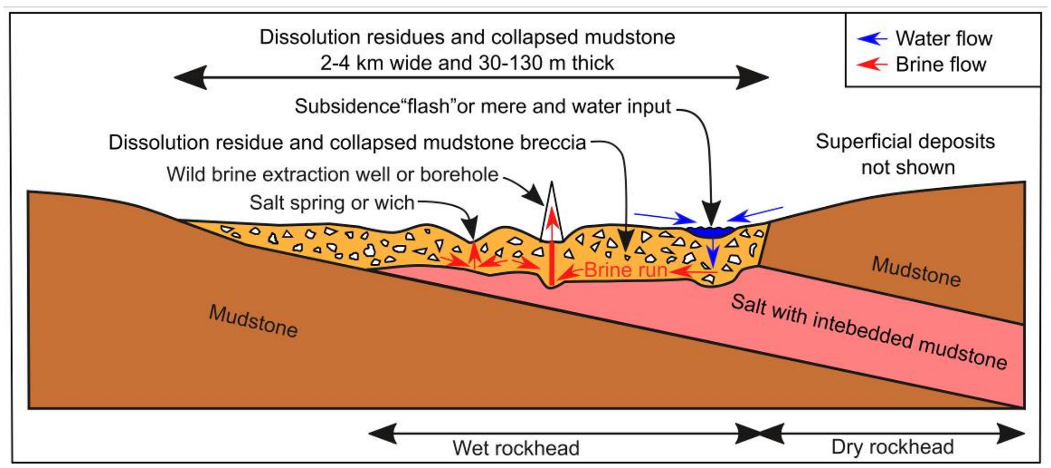

Figure 3. Cross-section through Triassic salt deposits showing wet and dry rockhead along with methods of salt extraction.

Where the Triassic saliferous rocks come near to outcrop in the UK, usually at depths of between 30 and 130 m, salt karst may develop (Earp and Taylor 1986; Wilson and Evans 1990) (Figure 3). This karst has been strongly influenced by groundwater flow variability and head induced during the last, and possibly earlier, glaciations. The last (Devensian) glaciation buried the northern and central parts of the United Kingdom beneath a thick wet-based ice-sheet producing elevated groundwater levels (Howell 1984; Howell and Jenkins 1976). This elevated groundwater head is thought to have depressed and/or flushed out the saline waters forcing the dissolution surface of the salt to cut deeper into the sequence. In the Cheshire basin the dissolution of the salt generated a rockhead depression into which the thick glacial sequence was deposited. When the ice-sheet melted, the groundwater regime changed again and further dissolution of the salt occurred as new regional groundwater patterns formed. Because these processes enhanced salt dissolution, the depth of salt dissolution is commonly very deep. This mechanism may also help to explain why the dissolution extends down to about 180 m in the Triassic salt of Cheshire, but to a much deeper 3-400 m in the Permian salt of northern England, where the cover of ice was probably much thicker. Here the edge of the preserved salt is marked by a dissolution front and collapse monocline (Figure 2). However, it must also be noted that the salt beds in the Permian probably would not come to outcrop because their facies is restricted to the deeper parts of the depositional basin (Cooper 2002; Smith 1989).

The way in which the salt karst has developed is also dependent on the nature of the lithological sequence in which the salt beds were deposited. In the Triassic deposits, most of the salt is interbedded with units of siltstone and mudstone, commonly with gypsum. Where the groundwater has circulated and removed the salt, only the interbedded insoluble rocks remain as a breccia, concealed by the commonly less brecciated, but foundered cover sequence. The traditional term for the salt surface where the dissolution has occurred is “wet rock head”. It is called this because in early exploitation by wells and boreholes it was from here that the original brine extraction took place. The area of wet rock head encompasses the brine-laden salt karst, but the depth of the karst surface generally lies some 30-130 m below the ground surface and may even reach a depth of 180 m in Cheshire (Howell 1984; Howell and Jenkins 1976). Foundered ground above this zone commonly has numerous collapse features. These range from enclosed hollows 20-200 m across to linear depressions up to several kilometres long. These natural depressions were called “brine runs” by the early brine miners and it was into these, and the brine springs that they sunk their extraction wells.

In contrast, the traditional name for the area where the salt has not dissolved because it is sealed and dry beneath a cover of strata is “dry rock head” (Earp and Taylor 1986; Evans et al. 1993; Wilson and Evans 1990) (Figure 3). The terms wet and dry rockhead have been used by the drilling industry in the context of salt exploration and appear in borehole logs in the British Geological Survey archives dating from 1948 (David Walker, Sheffield University pers. Comm. 18/01/2013); the terms were not used by Sherlock (1921) and thus appears to have originated between these two dates. Wet and dry rockhead must not be confused with the more common term of rockhead, which is the contact between superficial deposits or weathered rock and the underlying rock.

The Cheshire salt field has a long history of exploitation growing from its first pre-Roman development around the salt springs into a major industry (see below). The uncontrolled extraction of brine resulted in an artificial lowering of the brine/freshwater interface. This allied with groundwater abstraction from adjacent aquifers has disturbed the brine above the karst surface and introduced fresh water into some areas (Howell and Jenkins 1976). However, recent geochemical sampling (British Geological Survey 1999) has shown that brine from springs is entering the rivers in the Cheshire saltfield again. From river flow volumes, and the content of salt in the water it should be possible to calculate the amount of salt being removed annually from the Cheshire saltfield. However, not all the salt in the rivers is from the salt beds, since much of the British river chloride solute load is derived from the British maritime precipitation (Walling and Webb 1981) and anthropogenic sources such as road de-icing and sewage works (British Geological Survey 1999).

Mining and dissolution mining of salt

Natural "wild" brine extraction

Salt mining and brine extraction have played a major role in the modern development of the salt karst in the Cheshire, Worcestershire and Staffordshire areas. The original Roman and Medieval method of getting the salt was to tap into the natural brine springs. However, in the 16th to 18th Centuries increasing demand for salt required that wells were sunk into the brine springs tapping into the deeper more concentrated and more reliably available brine. From the late 16th Century reciprocating pumps were developed to draw up the brine (Woodiwiss 1992).

From the 18th Century onwards, boreholes with pumps were developed allowing the extraction of brine from greater depths. The technique was to tap into the natural underground brine runs that mainly existed at the interface of the rocksalt and the overlying deposits and collapsed materials. This method of brine extraction was uncontrolled and is referred to as "wild" brining. The method induced brine to flow towards the extraction boreholes aggravating any existing subsidence features or causing linear subsidence belts spreading along strike from the boreholes. This uncontrolled brine extraction enlarged the natural brine runs causing widespread subsidence for considerable distances from the extraction points. The large-scale abstraction of brine in this way enhanced the development of the natural salt karst into an unnatural form.

The technique of tapping into the natural brine at rockhead was continued well into the 20th Century with extraction in the Droitwich, north Cheshire and Stafford areas. Stafford ceased extraction in 1970 (Coxill 1995) due to legal pressure over subsidence and Droitwich ceased extraction soon after in 1972 (see Stafford and Droitwich sections). The last wild brine extraction in Cheshire by New Cheshire Salt Ltd stopped as late as 2005 amid concerns of subsidence affecting Northwich (Branston and Styles 2003) and as a result of an industry take over (Competition Commission 2005). The development of the linear subsidence "flashes" in Cheshire (Figure 4) was documented using air photographic interpretation (Howell 1986) and GIS/map/air photograph interpretation by (Cooper et al. 2011). They showed the extent of relatively modern brine extraction subsidence, discussed in detail below in the section about Cheshire.

Shallow salt mining and "bastard" brining

Two main methods were used to extract salt in the late 19th and early 20th Centuries: conventional mining and wild brine solution mining. Conventional mining was carried out in shallow "pillar and stall" mines with networks of tunnels commonly separated by narrow salt pillars. The salt was mined using very large extraction rates leaving very small pillars for support (Figure 5). Compared with modern mining the amount of salt left as pillars was minimal. Many of these mines were near to the wet rock head areas and flooding was a common hazard. To extract additional salt, many of the flooded salt mines were also pumped for brine, a technique referred to as "bastard" brining. This dissolved the pillars and produced catastrophic mine collapses with surface subsidence on such an enormous and unprecedented scale that it destroyed whole areas of towns, factories and infrastructure such as canals and roads. Around Northwich and Middlewich the resulting subsidence was particularly catastrophic and widespread. New lakes, locally called "flashes"(Figure 5), appeared almost daily with may extending for hundreds of metres, for example Moston Flash (Figure 4) near Elworth (Earp and Taylor 1986; Waltham 1989; Waltham et al. 1997). On July 21st 1907 a canal was disrupted and all the water lost (Calvert 1915). Even where collapse has not been so severe as to produce flashes, there are geomorphological features associated with subsidence (Lee and Sakalas 2001). Some of the early mines that have not collapsed have continued to be problematical until recent remediation (see mitigation section). The damage led to a major report on the subsidence (Dickinson 1873) and the establishment of the Brine Subsidence Compensation Board (discussed below).

Figure 4. View southwards (in 1996) over Moston Flash, a large lake lying between Crewe and Middlwich attributed to brine pumping about 2 km to the north (Waltham et al. 1997)

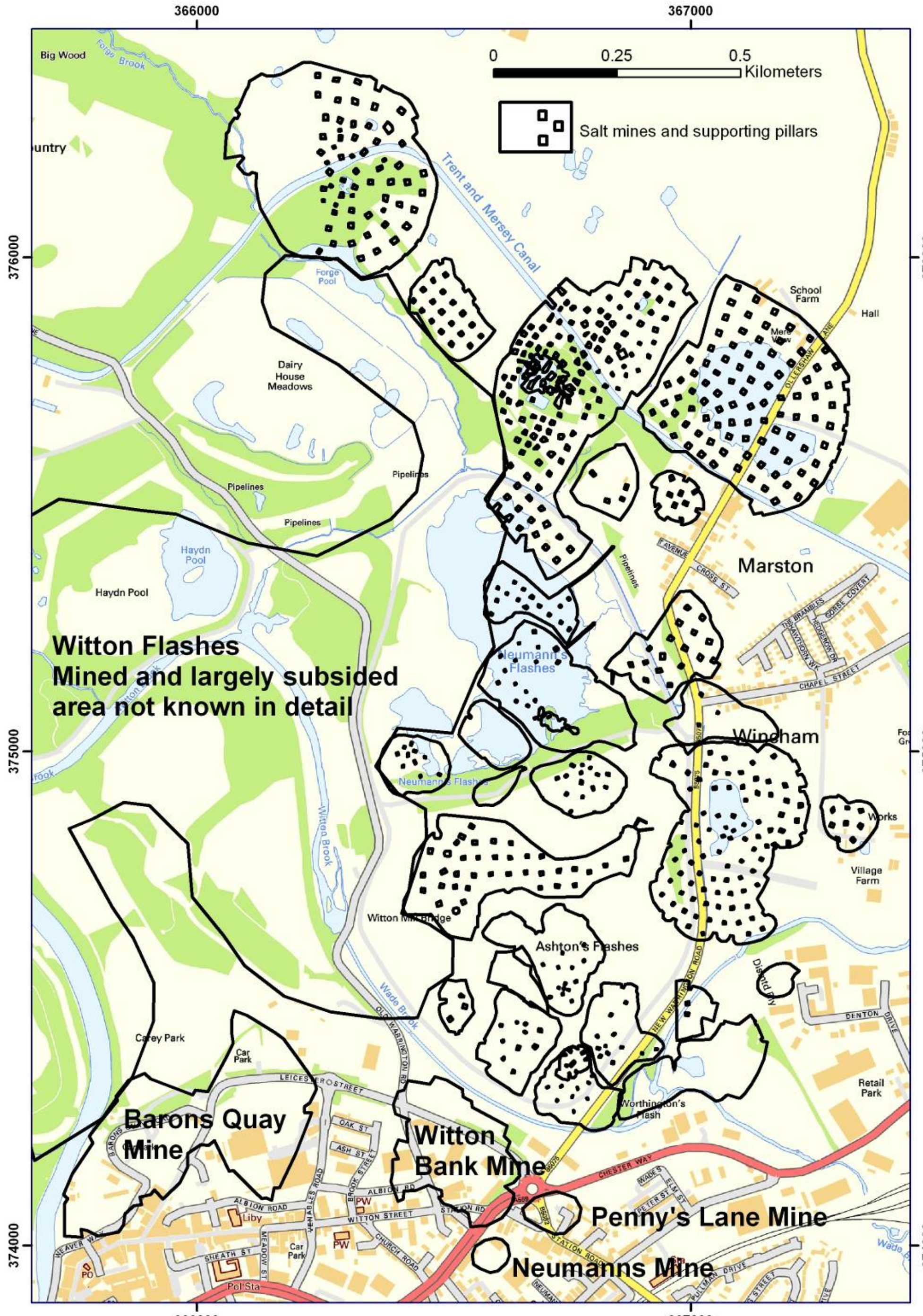

Figure 5. Major areas of undermining to the north of Northwich. The location of subsidence "flashes" (both water-filled, and reclaimed by infilling) are also shown. Contains Ordnance Survey data © Crown copyright and database right 2013.

No recent major salt mine collapses have been recorded in England. However, in Northern Ireland the collapse of the Carrickfergus mine in 1990 (Griffith 1991) and

Maidenmount mine in 2001 (Figure 11) highlight the susceptibility of such workings to water ingress. The collapse of these mines can cause overpressuring of the brine within the remaining caverns and the ejection of material from shafts and other weaknesses (Rigby 1905). Further afield, the loss of the complete Jefferson Island, USA salt mine in 1980 was due to one misplaced oil exploration borehole that drained Lake Peignear, caused a massive subsidence depression to form and ejected material from the mineshaft (Johnson 2005; Wikipedia 2013)These events are all similar to some of the Victorian mine disasters in Cheshire described by Calvert (1915) that created the Witton Flashes, Marston Big Hole and the Marston Flashes, to name but a few.

Modern Salt Mining

Now that wild brine extraction has ceased in the UK, modern salt extraction is carried out in two ways – dry mining and controlled brine extraction. Most modern salt extraction takes place in deep, dry, pillar and stall mines at depths of 125- 200 m under Cheshire or as an adjunct to potash mining from beneath North Yorkshire (Cleveland Potash Ltd 2013; Woods 1979). In Cheshire the salt abstraction rate is between 68 and 75% and the typical void space left behind after extraction is 20 m wide x 8 m high, with 20 m square pillars left to support the over-burden (Salt Union Ltd 2013). The Salt Union Ltd mine at Winsford, for example, is completely dry and part of the disused workings are used as an underground document storage facility (Deepstore 2013) .

Modern controlled brine extraction, carried out at depths of more than 150-300 m, results in underground chambers that are left flooded and filled with saturated brine in order to minimise subsidence. Some of these chambers are used for waste disposal (Northolt and Highley 1973), but many more are now being utilised for onshore gas storage (Evans 2008). Cavities that have produced salt for industrial use are present in Cheshire, Lancashire (Preesall) and Teesside; salt cavities constructed specifically for gas storage have been made on the Yorkshire coast at Aldbrough (SSE Hornsea 2012).

Mining of Permian salt deposits

Teesside

In the north of England, salt is present in the Permian strata of the Zechstein Group. This evaporite and carbonate sequence extends from northern England eastwards beneath the North Sea to Germany and beyond. Only the marginal part of the Zechstein basin encroaches onshore in England where it includes thick units of anhydrite, halite and potash. The salt and potash deposits are currently mined by pillar and stall workings near the coast at Whitby. Here they are up to about 80 m thick and occur at depths of 1100-1250 m (Woods 1979) and up to 1500 m and 7 km out beneath the adjacent North Sea (Cleveland Potash Ltd 2013). The depth and location of the salt and potash workings means that any subsidence at the surface has very little effect.

Salt was first found accidentally in a boring for water at Middlesbrough sunk between 1859 and 1863 (Wilson 1888). Subsequent to this, on the north bank of the Tees in Middlesbrough itself and further north around Greatham, 19th and 20th Century brine wells were sunk and the Teesside salt and chemical industry developed (Marley 1890; Morris 1978; Sherlock 1921; Tomlin 1982). There are some records of subsidence, mainly related to the early wells and those drilled before and up to the 1950's (Morris 1978), but not the catastrophic subsidence seen around the same time in Cheshire (Cooper 2002). In the Teesside area the main brine field extends from Port Clarence northwards through Salthome to Greatham. In addition there is an area that has been exploited for salt to the west of Haverton Hill (British Geological Survey 1987).

At the coast the salt is present at a depth of about 500 m. Westwards and up-dip there is a dissolution front in the salt (British Geological Survey 1987) and the overlying strata have collapsed and formed into a west-facing subsidence monocline (Figure 2 and Cooper (1998).

In the Middlesbrough area the early methods of brine extraction used largely unlined or perforated boreholes and the water from the Sherwood Sandstone aquifer to drive the salt dissolution (Sherlock 1921; Wilson 1888). Sherlock (1921) describes the process:

"*In the Middlesbrough district the salt is worked by means of artesian wells sunk by the system adopted in America for petroleum-wells* Their boring is about 10 inches in diameter until the sandstone is reached, and is lined with steel tubes down to the sandstone to keep the Drift and marl from caving in. When the driving-tube is well embedded into the sandstone no more lining is necessary, and the sinking is continued until the bottom of the salt-bed is reached, after which a suction-pipe is inserted to within two or three feet of the bottom, and the brine extracted by means of a working-barrel and pump-bucket placed at an average depth of 200 feet from the surface. Water contained in the sandstone finds its way outside the suction-tubes to the bottom of the well, dissolves the salt and is lifted by means of the pump. The underground water-level in the district is about 15 to 20 feet below the surface, on the average, and this balances the column of brine to within 150 feet of the surface in the case of the shallow wells, but of course to lower depths in the case of deeper wells.*"
(*this is what we now call open hole drilling)

This process preferentially dissolved the top of the salt where the water exited the bottom of the borehole while the denser saturated brine was drawn off from the base of the suction tube. This method produced largely uncontrolled, wide, inverted cone-shaped cavities with a flattish upper surface and pointed lower end situated at the suction pipe (Morris 1978; Wilson 1888). As a consequence large unstable cavities were produced and parts of Middlesbrough north of the Tees and around the Saltholme area suffered subsidence (Figure 6). Further north at Greatham controlled brine extraction took place between 1894 and 1971 from salt at depths of between 300 and 400 m. The salt here is fairly shallow and the holes in close proximity to one another. Their presence has led to hydrogeological salt pollution issues affecting the overlying Sherwood Sandstone Group aquifer; consequently, the boreholes are now being remediated for the Environment Agency (Drillcorp 2013). East of the A178 road towards Seal Sands the post mid 1950's brine extraction has been from deeper and better engineered dissolution cavities that are expected to have good long-term stability, such that some are used for gas storage (Evans 2008). As early as 1888 Wilson expressed concerns about the uncontrolled method of brine extraction and the related subsidence. Morris (1978) suggests that small areas of instability may exist or have already subsided in the vicinity of some of the early brine boreholes located south of the River Tees, these are discussed under planning later in this paper.

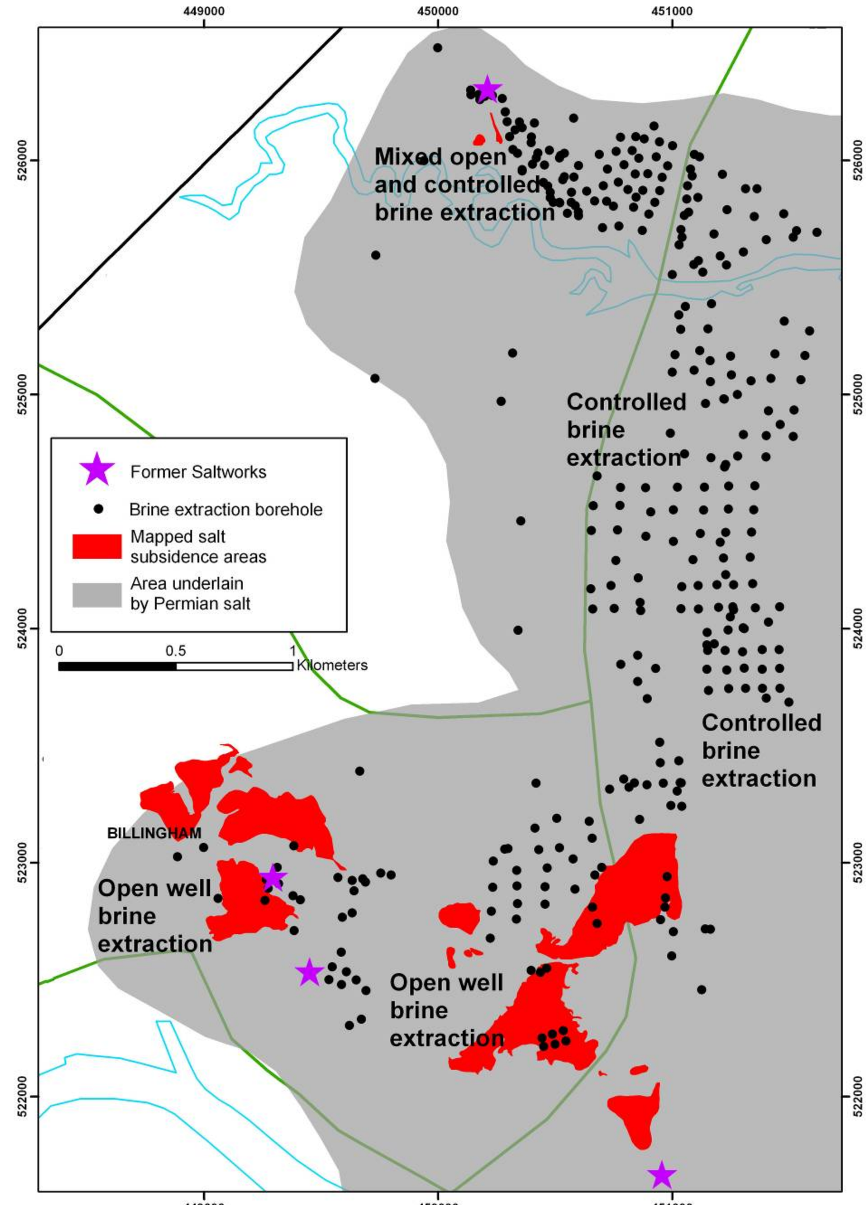

Figure 6. The Teesside brine extraction area showing subsidence areas and controlled brine extraction areas. Contains Ordnance Survey data © Crown copyright and database right 2013: water features in blue, roads in green, railways in black and National Grid with 1 km spacing.

Mining of the Triassic salt deposits:

Cheshire

Two salt formations are present in the Triassic Mercia Mudstone Group in Cheshire. These are the Wilkesley Halite Formation (up to 300 m thick) towards the top of the group and the Northwich Halite Formation (up to 200 m thick, with mudstone partings) in the middle of the group (Earp and Taylor 1986; Evans et al. 1993; Wilson 1993). The sequence between and below the salt formations is dominantly red-brown gypsiferous and dolomitic mudstone and siltstone. The natural salt karst has developed below the collapsed and foundered strata over wet rock head.

From Roman times the Cheshire saltfield has been exploited by shallow wild brine extraction then later by mining, bastard brine extraction and modern controlled brine extraction. The area to the north of Northwich (Figure 5) was particularly affected by pillar and stall mining and much of this has collapsed producing lakes or "flashes" (Calvert 1915). However areas of undermining remained that threatened some buildings and retail developments. Details of both the shallow mining and brine extraction methods with examples from Cheshire are given in the sections above about natural dissolution and mining methods illustrated by Figures 3, 4 and 5. Figure 7 shows the distribution of salt near surface and the subsidence flashes related to former saltworks in the central part of the Cheshire saltfield. The subsidence flashes form linear belts approximately radiating out from the former saltworks. Similar, but less extensive natural subsidence features can be seen in the east of the area. Despite the salt extraction having finished, natural dissolution and continued subsidence over man-made dissolution features affect the area including the railway (Figure 8). Details about mitigation in the Cheshire area and the stabilisation of saltmines around Northwich are given later in this paper.

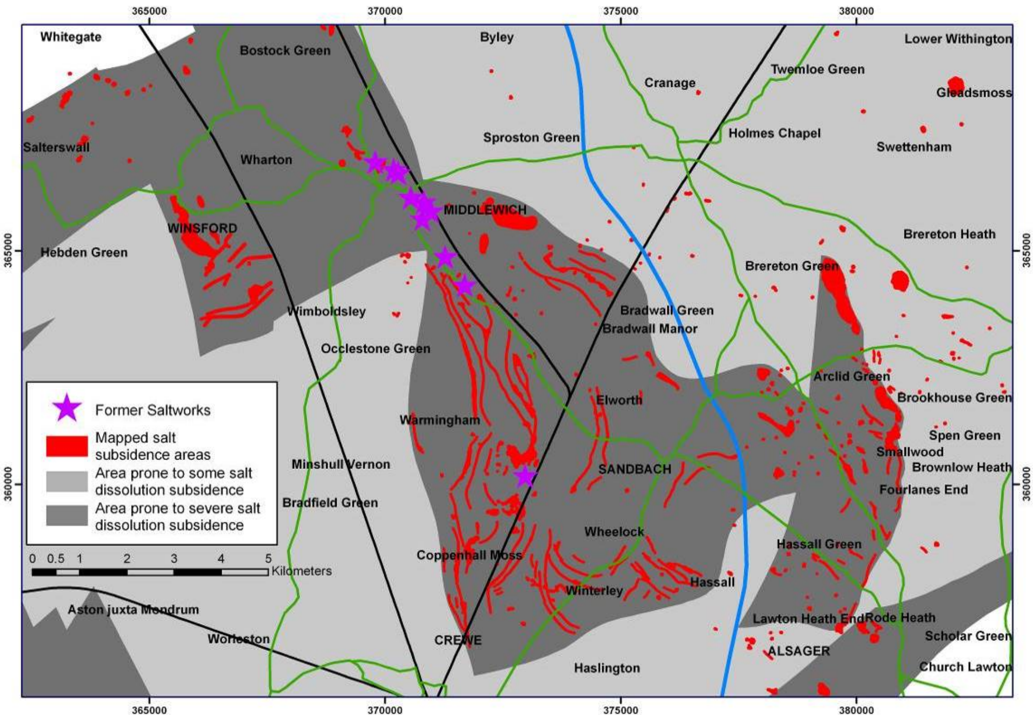

Figure 7. Map of the main Cheshire brine extraction area showing natural and man-made salt dissolution subsidence features with the locations of salt works. Contains Ordnance Survey data © Crown copyright and database right 2013.

Figure 8. Subsidence affecting the main railway line north of Crewe (photographed in 1996) near Elton Flashes Nature Reserve. Note the gantries on jackable foundations.

Blackpool and Preesall

The Lancashire coast beneath Blackpool and Preesall is underlain by the Triassic Mercia Mudstone Group, which includes several salt units. Two impersistent units, the Rossal Halite and the Mythop Halite, occur low in the sequence and a third more persistent unit, the Preesall Halite occurs high in the sequence (Wilson 1990; Wilson and Evans 1990). The Preesall Halite was formerly worked in salt mines at Preesall on the east side of the River Wyre. Here the east of the saltfield is marked by the Preesall Fault Zone. Adjacent to this the westerly dipping salt comes near to outcrop, but groundwater circulation has dissolved the salt to a depth of between 50 and 100 m resulting in a collapse breccia down to wet rock head (Wilson and Evans 1990). Though there are no confirmed saline springs in the area, their most likely position would be at the coast emerging beneath the sea. Sherlock (1921) notes the name of the village of Salwick near Kirkham just south of the district (however, because the coast is nearby, this name could equally relate to the production of sea salt). Probable subsidence areas, in which post-glacial peat deposits have formed, are also recorded in the district, especially around Mythop (Wilson and Evans 1990). These subsidence areas range from 30 to 150 m across and contain up to 10 m of peat formed over the last 12,000 years. They give an indication of the amount and rate of salt karstification that has taken place beneath the area. Commercial site investigation in the area of Blackpool south of the football ground suggest salt at rockhead beneath the superficial deposits with shallow brine and some local subsidence due to salt dissolution. However, few boreholes have been made public and the precise details of the geology of the area remain unknown.

Stafford

The salt deposits under the town of Stafford lie in a synclinal structure faulted along its eastern side (Arup Geotechnics 1991). The salt occurs interbedded with mudstone in a sequence 50-65 m thick within the Mercia Mudstone Group (Coxill 1995). The near-surface deposits have dissolved to a depth of around 50 m (wet rock head) and the salt has largely dissolved adjacent to the eastern fault zone. The natural salt springs around Stafford are not well documented, but the town is surrounded by the villages with names ending in wich; these include Baswich, Milwich, Gratwich, Colwich and Shirleywich (along with the village of Salt), all suggesting the presence of brine springs. The springs at Shirleywich have a long history of exploitation from the 17th century to the late 18th century. The Shirleywich springs, and nearby ones at Weston, appear to be fed from salt deposits lying to the north-east in a belt running through Chartley Moss and other small lakes. These two springs produced some 3,750 tons in 1873 but production ceased at Shirleywich at the end of the century and at Weston-on-Trent in 1901 (Coxill 1995). Brine still flows to the surface in the Trent valley about 2.5 km south-east of Weston feeding the Pasturefields SAC/SSSI saltmarsh meadow (Natural England 1986; Stafford Borough 2012). Lying 5km to the NE of Shirleywich, Chartley had the strongest saline springs in Staffordshire in the mid 16th century (Sherlock 1921). Chartley Moss is a fresh-water pond and floating bog formed in a salt dissolution subsidence area. Localised collapse here causes minor seismic events that are felt on the surface of the bog, thus providing evidence of active salt dissolution and subsidence beneath the site (A. Brandon, pers comm. 2000).

Brine was discovered in a water borehole north of Stafford town on Stafford Common in 1881 and brine production started in 1893 with production of up to 95,000 tonnes a year in the early 1960s. Subsidence had been reported since 1948, but by 1964 it was becoming a serious problem (Coxill 1995). Lotus Ltd brought a High Court case against British Soda Ltd and in August 1970 they were ordered to cease production bringing an end to wild brine production here (and coincidentally soon after in the Droitwich area). Coxill (1995) estimated that 5 million tonnes (2.25 million cubic metres) of rock salt had been extracted as brine from beneath Stafford. Only something like 10% of the volume of salt removed by this brine extraction has been accounted for by recorded subsidence and further subsidence may still occur in the area. The main brine run trends NNE towards the extraction boreholes and about 2 square kilometres of land have been affected by subsidence. Since the 1940's about 20 properties have been demolished and 500 severely damaged (Arup Geotechnics 1991).

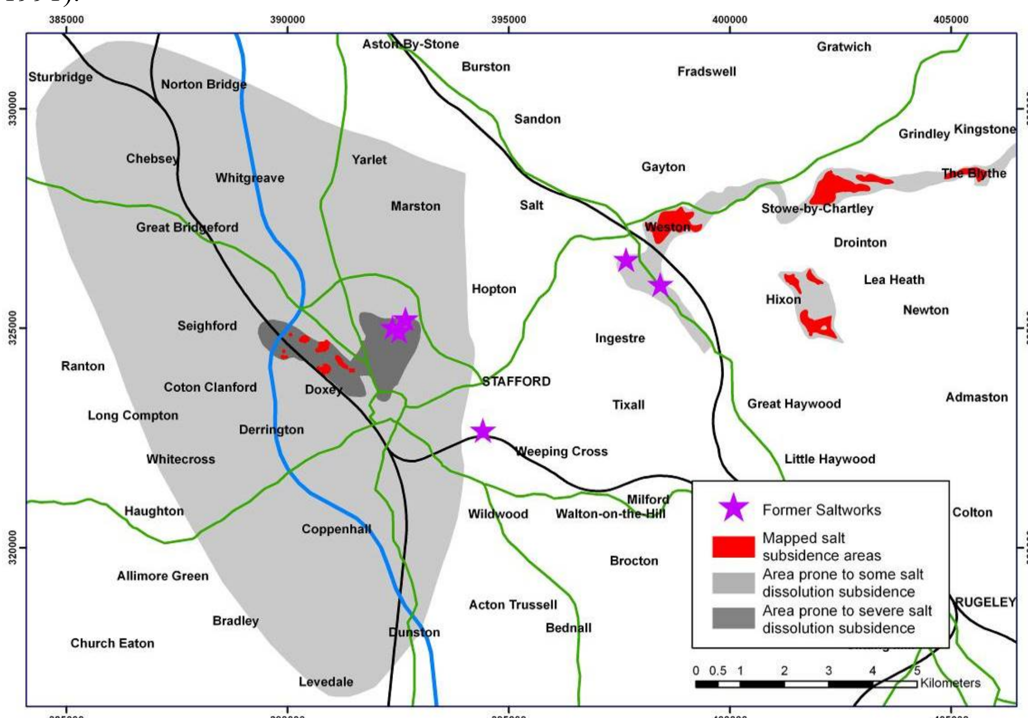

Figure 9. The Stafford salt subsidence area with known subsidence and former saltworks, brine extraction boreholes and brine springs as stars. Contains Ordnance Survey data © Crown copyright and database right 2013.

Droitwich

In Worcestershire the Triassic saliferous rocks are present in the Mercia Mudstone Group and include the upper and middle sequences of salt beds approximately equivalent to the Cheshire salt beds further north. There are about 90 m of saliferous strata including about 40% siltstone and mudstone. The Romans used the name Salinae for what we now call Droitwich, both names are indicative of the brine springs that rose there in the valley of the River Salwarpe. The three main salt producing springs of Netherwich, Middlewich and Upwich were noted by Rastell 1678 and some of their excavations described by (Woodiwiss 1992) and (Hurst 1997). In the 17th century shafts were sunk that increased the brine flow from the Droitwich springs. In the 18th century deeper pits encountered artesian brine that could not be controlled and largely ran to waste (Poole and Williams 1981). Some salt mining was undertaken in the district, but it encountered natural brine runs and the subsequent exploitation was by brine extraction from several pumps driven by steam engines in the town. Brine extraction in the town ceased in 1922 at which time it was causing serious subsidence, such as that seen in Droitwich High Street today (Wychavon District Council 2012).

In the early 19th Century salt was discovered some 6 km to the north-east of the town and mined at Stoke Prior where the shaft sequence was recorded by Murchison in 1839 (Wills 1976). In the 20th Century, large-scale brine extraction took place here from Stoke Prior saltworks. Brine extraction here ceased in 1972 as a consequence of the law case that saw the cessation of wild brine extraction in Stafford a few years earlier (Coxill 1995) and because of subsidence problems affecting housing (Pitts et al. 2012). Output in the latter years of operation were some 150,000 tonnes a year (Bloodworth *et al.* 1999). The brine abstraction caused the natural brine springs at the surface to dry up. It also caused a belt of subsidence along, and spreading out from, the course of the original sinuous brine run.

The natural brine run follows the wet rock head of the strata which dips to the south-east and it has a north-east trending course through Droitwich, Wychbold and the Upton Warren saline pools to the former salt works at Stoke Prior. The Upton Warren pools date back at least 42,000 years BP (Coope et al. 1961) with a salt marsh biota recorded from then until the present (Worcestershire Biological Records Centre 1999). Where the salt has dissolved, boreholes show that the zone of collapse over the wet rock head extends down to a depth of about 90 m forming a belt 1-2 km wide and 12 km long. The route of the original brine run was the area in which the most subsidence and building damage occurred in the 19th century. In the 1980's after the cessation of brine extraction, the brine levels began to rise. This caused (Poole and Williams 1981) to speculate that in the future brine would flow again from the sites of the original springs that were used by the Romans. The fact that brine now flows naturally to the surface here is proved by a geochemical survey (British Geological Survey 1999) which showed stream water Chloride concentrations of 3100 and 3400 mg/l on adjacent sites to the east of Droitwich.

There is some evidence that the ongoing flow of brine in the area is responsible for some subsidence and Wychavon District Council has consultants who conduct a regular surveying monitoring programme which measures changes in ground surface levels. The Council points out that the areas affected constantly change, but that with suitable mitigation development can proceed (Wychavon District Council 2006). Figure 10 shows the approximate zone affected by ongoing salt subsidence based on work by Poole and Williams (1981) modified in the light of further work.

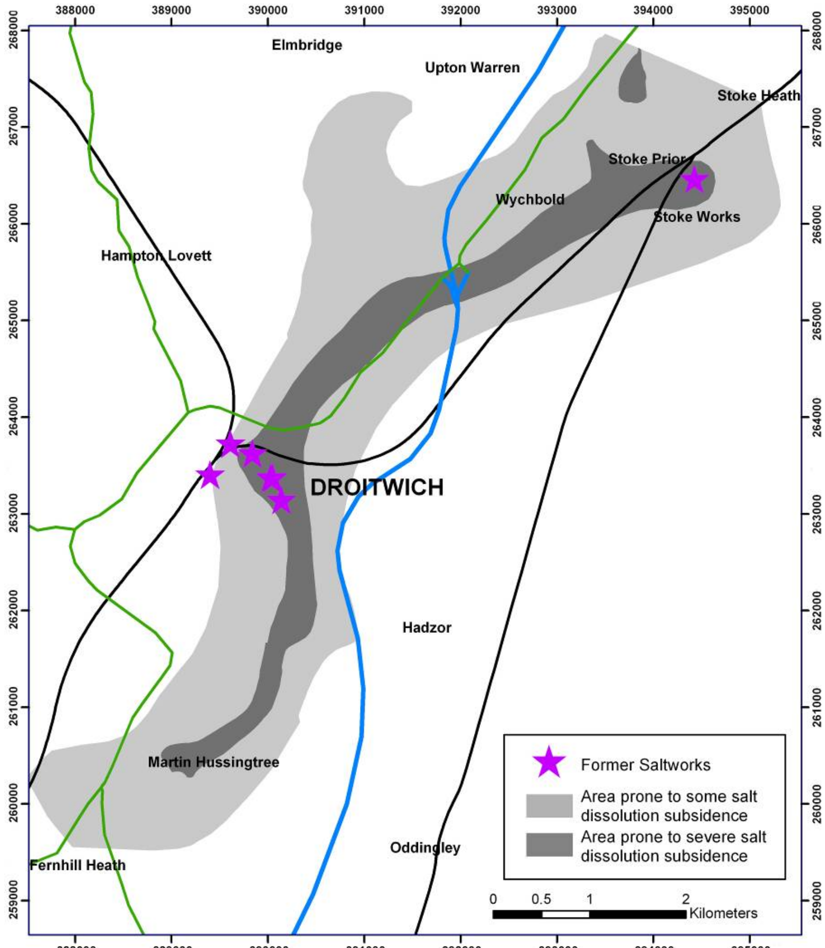

Figure 10. The approximate brine subsidence affected area around Droitwich and locations of saltworks/brine extraction sites. Contains Ordnance Survey data © Crown copyright and database right 2013.

Northern Ireland

Triassic saliferous rocks are present in the area around Carrickfergus and Larne, bordering on Belfast Loch in Northern Ireland. The Triassic sequence includes up to nearly 500 m thickness of salt, proved in the Larne Borehole, but in the Carrickfergus salt field only about 40-50 m has been proved. The salt deposits are largely protected from groundwater circulation by the overlying sequence and there is no record of wet rock head and extensive brecciation such as that found in Cheshire (Griffith and Wilson 1982). A salt spring was known at Eden, where salt mining subsequently developed, and slight brecciation of the sequence was recorded in a few boreholes, but was not extensive. The most spectacular dissolution feature recorded in the area was the collapse of the Tennant Salt Mine in 1990 (Griffith 1991), which also generated a vibration equivalent to a 2.5 record on the Richter Scale (Bell et al. 2005). This mine was a conventional pillar and stall mine, but subsequent owners removed substantial amounts of brine from the abandoned workings. This dissolved the pillars and produced a large crown hole with concentric failure planes and a depression about

130 m across. Maiden Mount Salt Mine in the same area was mined from 1877 to 1895 when it moved to brine extraction up until 1958 (Griffith and Wilson 1982), it collapsed in 2001 producing a large crater (Figure 11) that required expensive remediation. In Northern Ireland other mines including French Park and Carrickfergus International Mine are still considered at risk of collapse (Carrickfergus Building Services Committee 2010) and to avoid potential subsidence the Carrickfergus Development Plan excludes building over the former salt mines (Belfast Metropolitan Area 2013).

Figure 11. Maidenmount Salt Mine near Carrickfergus which collapsed on 19th August 2001 and was initially 50 metres wide and 15 metres deep, but continued expanding (BGS photograph P543378)

MITIGATINGSALT SUBSIDENCE PROBLEMS

Brine Subsidence Compensation Board

In Cheshire, the salt mining allied with "bastard" and "wild" brine extraction caused such severe subsidence that a Parliamentary investigation of the problems was commissioned (Dickinson 1873). Subsequently, an Act of Parliament was passed that placed a levy on all locally extracted salt. This levy, which funded building reconstruction and compensation payments, is still made by the "Cheshire Brine Subsidence Compensation Board", but at a lower rate to reflect the reduced risk from modern extraction (Collins 1971). This Act was modified by The Cheshire Brine

Pumping (Compensation for Subsidence) Act of 1952, which set up a single compensation district covering all areas of Cheshire where subsidence resulting from the pumping of brine was considered to be a possibility. The “Cheshire Brine Subsidence Compensation Board” was formed in order to discharge the responsibilities resulting from the passing of this Act.

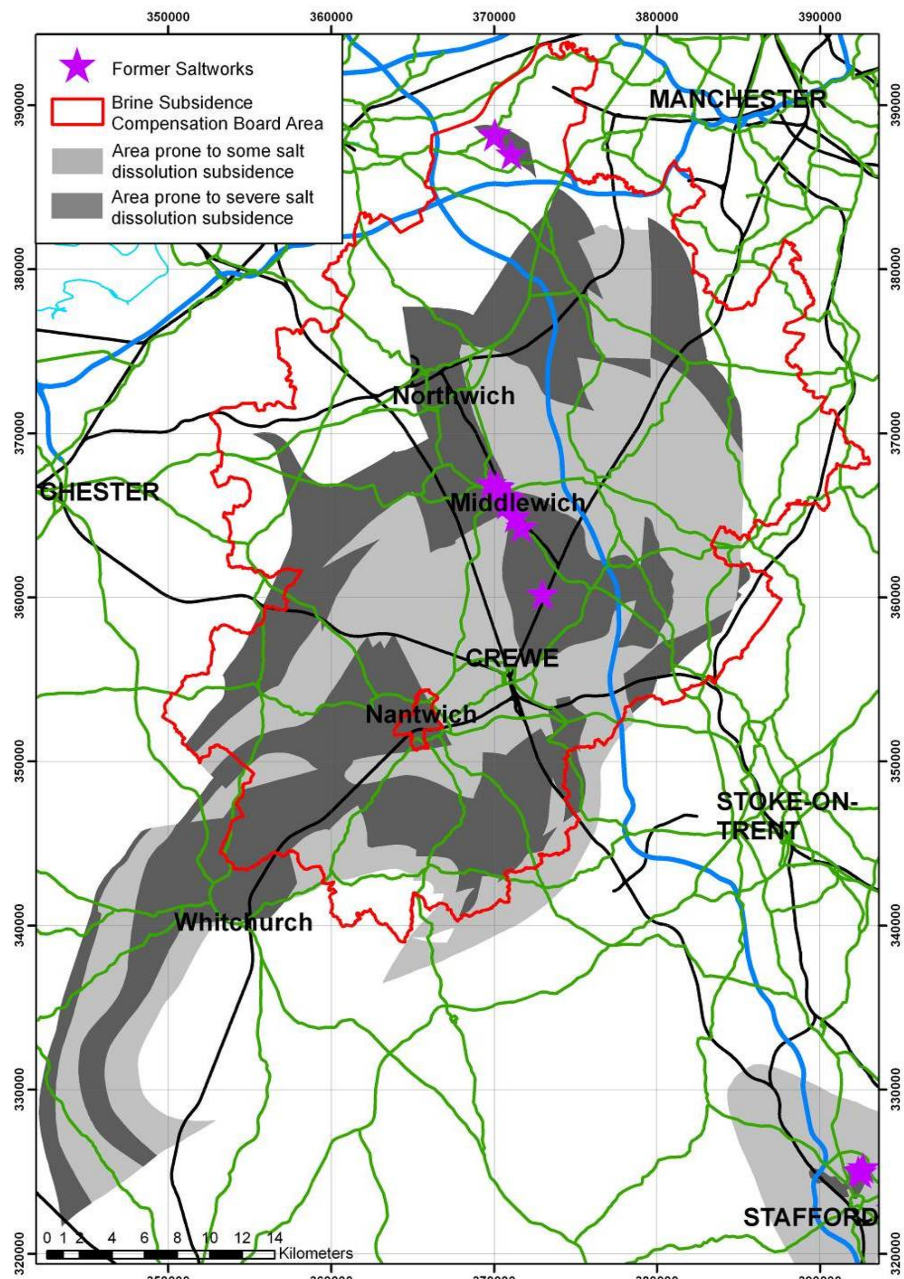

Figure 12. The Cheshire saltfield and the area included in the Brine Subsidence Compensation Board remit. Contains Ordnance Survey data © Crown copyright and database right 2013.

The main duties of the Brine Subsidence Compensation Board are to make compensation for specified categories of damage to land and buildings caused by subsidence due to brine pumping, and to give advice to the Planning Authorities and

Building Control in connection with development on land which may be affected by historic brine pumping (Cheshire Brine Subsidence Compensation Board 2013). The remit of the Board includes the issuing of statutory notices, liaison with the public, maintenance of file records, responding to planning enquiries, progressing of subsidence damage claims, maintenance of a claims register, monitoring of ground movements and preparation of search reports for property transactions. With regard to Planning and Building Control consultations, the Board is responsible for prescribing the Consultation Area under Section 38(1) of the 1952 Act and consultations are submitted by the Local Authorities to the Board as part of the planning process. The Board has no liability for damage resulting from the collapse of current or abandoned salt mine workings or associated shafts.

Since May 1st 2006 the duties of the Board have been discharged via consultants who run the board and the day to day enquiries for Cheshire Brine Search Reports via the Coal Authority mining search facility http://www.cheshirebrine.com/.

Salt mine stabilisation

The historical salt mines in the Northwich area have continued to cause problems for development of the town and have threatened some modern constructions. Instability of the old mine workings was aggravated by wild brine pumping, but even after this ceased in 2005 there was still concern about the stability of the mines. In 2002 £32 million pounds was pledged by the government agency of English Partnerships to stabilise the salt mines of Barons Quay, Witton Bank, Neumanns and Penny's Lane (Figure 5). Where possible these mines were ultrasonically scanned to establish their condition and dimensions. They were modelled using this information and historical mine plans. The mines were stabilised using a grout of saturated brine, pulverised fuel ash (PFA) and cement (Brooks et al. 2007). A void volume of 780,500 m^3 at depths of 90 m was successfully filled and 32 ha of ground stabilised. The exercise was a logistical challenge bringing in cement and PFA by rail to Winnington and pumping it down a pipeline that included a 470 m horizontally bored section beneath a river and Site of Biological Interest to the grouting (Arup 2013; W S Atkins Consultants Ltd 2001).The stability of other unfilled salt mines in the area, including those at Wincham, and north of Northwich (Pringle et al. 2012) may be problematical and will require either their avoidance or investigation and remediation by grout filling to make the land suitable for development.

Monitoring and investigation

In certain areas underlain by salt where dissolution has caused subsidence, monitoring by geodetic levelling is undertaken to record the amount and distribution of the movement. Development in Droitwich (Wychavon District Council) is constrained by such levelling. Here it helps to define an active central brine run (Zone A) and a passive marginal brine run area (Zone B), there is also a Zone C where ground movements are suspected, but little evidence is available. Within these zones development may require additional monitoring or levelling. Development is constrained to certain construction types and reinforced structures as designated by the council and their consultants.

Microgravity geophysics has proved to be useful tool for monitoring cavity growth and subsidence due to salt dissolution. Branston and Styles (2003) imaged a subsiding area to the east of Penny’s Lane Mine (Figure 5) and showed that it was not related to undermining. They linked the subsidence to salt dissolution at shallow depths due to wild brine extraction that was being undertaken from a factory located to the east. This was drawing in brine from a considerable distance away. They showed that the microgravity signature indicated less density over time and the development of brecciated rock associated with brine dissolution and subsidence. Long-term monitoring of the Trent-Mersey Canal where it crosses former salt workings showed microgravity and topographical changes related to upward-migrating cavities and subsiding areas (Pringle et al. 2012). Other geophysics such as ground probing radar and electrical resistivity tomography also have the potential to image cavities and collapsing ground in similar circumstances. However, electrical methods may be limited in depth penetration if there is shallow conducting brine in the area.

Construction on ground susceptible to salt dissolution subsidence requires the avoidance of actively subsiding areas and similar mitigation measures to those adopted for coal mining regions. Large structures may be particularly susceptible to unwanted movement and it is important to understand the local geology, faulting and collapse mechanisms such as those described by Wilson (2003) for Manchester Airport.

Planning for soluble rock geohazards

Current planning procedures ensure that the modern exploitation of salt deposits lies largely outside of urban areas so that risks are considerably reduced. The salt is now mined either in deep dry mines, or by controlled brine extraction from depth. However, there is still a legacy of problems related to the salt deposits. These include old salt mines that have not collapsed, and compressible or unstable collapsed ground over former salt mines. In addition, natural salt dissolution at the rockhead interface, between the salt deposits and the overlying superficial deposits, can cause ground engineering problems and corrosive saline groundwater. With the ending of most near-surface mining and brine extraction, the hydrological system has, or is in the process of, re-balancing itself. It may be expected that natural groundwater flows will be re-established through the disrupted saltfields and further subsidence problems may occur. The accurate mapping of the rock salt and associated deposits and saltmines, plus an understanding of salt dissolution and collapse characteristics, can help development and planning in these subsidence-sensitive areas. These problems can then be reduced by careful planning and construction or remediation of former mines.

Examples of such planning include Droitwich where zonation with specific monitoring and building controls is undertaken. In Teeside, the local planning guidelines for development in former salt dissolution extraction areas (Morris 1978) place a zone, that is considered to be susceptible to subsidence, of between 150 m and 300 m radius around every former brine extraction borehole in the area. The size of this buffer zone appears to relate to the depth and amount of salt extracted from each hole. In these areas, it is recommended that avoidance or special precautions should be taken for certain types of construction. In Northern Ireland development is not permitted over or adjacent to former salt mines (Belfast Metropolitan Area 2013).

In Cheshire collapse of some former mines are causing subsidence and their remediation is being undertaken. In most of the salt karst areas, there is a legacy of difficult ground conditions produced by natural and man-made causes and restrictions on the places where future mining and brine extraction can be undertaken (Collins 1971). Information to help with large-scale planning is available from the British Geological Survey GeoSure dataset and the karst database (Cooper 2008; Cooper et al. 2011; Farrant and Cooper 2008)

Once dissolution has occurred, there is the possibility of metastable cavities being present in the subsurface. Infiltration and disposal of surface water to the ground can trigger subsidence. Consequently, areas of salt karst are not recommended for the installation of sustainable drainage systems (SUDS) (Dearden et al. 2013) or for the installation of open loop ground source heat pumps (Cooper et al. 2011). In common with building over subsidence-prone ground, the use of strengthened foundations and novel materials such as geogrid and lightweight embankment materials should be considered. Practices used for development over gypsum karst prone to subsidence are also suitable for salt karst areas (Cooper and Calow 1998; Cooper et al. 2011; Cooper and Saunders 2002).

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