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Groundwater in Jurassic carbonates

Field Excursion to the Lincolnshire Limestone:

Karst development, source protection and landscape history

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Introduction[1]

The Lincolnshire Limestone is an important regional aquifer. Pumping stations at Bourne and other locations along the eastern edge of the Fens supply water to a large population in South Lincolnshire. Karst permeability development and rapid groundwater flow raise issues of groundwater source protection, one of themes of this excursion. A second theme concerns the influence of landscape development on the present hydrogeology. Glacial erosion during the Middle Pleistocene re-oriented river patterns and changed the aquifer's boundary conditions. Some elements of the modern groundwater flow pattern may be controlled by karstic permeability inherited from pre-glacial conditions, whereas other flow directions are a response to the aquifer's current boundary conditions. Extremely high permeability is an important feature in part of the confined zone of the present-day aquifer and the processes that may have produced this are a third theme of the excursion. The sites to be visited will demonstrate the rapid groundwater flow paths that have been proved by water tracing, whereas the topography and landscape history will be illustrated by views during a circular tour from the aquifer outcrop to the edge of the Fenland basin and back. Quarry exposures will be used to show the karstification of the limestone, both at outcrop and beneath a cover of mudrock.

Geology and Topography

The Middle Jurassic Lincolnshire Limestone attains 30 m thickness in the area between Colsterworth and Bourne and dips very gently eastwards. North of Lincoln (Fig.1) the limestone forms an abrupt escarpment (the 'Lincoln Edge'). To the south this cuesta landform broadens out to a dissected plateau that reaches 120 m above sea level along its western edge. The rocks beneath the aquifer are Lower Jurassic clays, ferruginous sandstones and shales. Above the limestone lies a sequence of shales and thin limestones, the Great Oolite Group. To the east of the upland formed by these rocks is the Fenland basin, a glacially-excavated lowland almost at sea level, floored by peat deposits and Quaternary gravels overlying Upper Jurassic clays. The Lincolnshire Limestone persists at depth beneath the Fens, thinning eastwards to a few metres thickness. Fig.2a is a NW-SE cross section published by the British Geological survey, which is simplified in Fig.2b to show the geographical division of the aquifer into three zones – an outcrop zone in the west and a confined zone in the east, separated by an unlabelled zone in which the aquifer is mostly covered by younger strata but is not hydrogeologically confined.

The modern drainage pattern is marked in the area to be visited by north-south, strike-aligned rivers. The valley of the Witham is at the west end of the sections in Fig.2, the River Witham flowing northwards as far as Lincoln where it turns abruptly east and passes through an important gap in the limestone cuesta (Fig.1). In the south the River Gwash passes through a smaller west-east gap at Stamford. Part way between these features, northeast of Grantham, is the Ancaster Gap not shown on Fig.1 but marked by a 'wasp-waist' narrowing of the limestone outcrop. This large valley cuts right through the cuesta but lacks any through-drainage. It is the source of the eastward-draining River Slea. Between the Ancaster Gap and the Gwash, the upland formed by Jurassic strata is drained by two parallel streams, the West and East Glen, which run from north to south. In our area the outcrop zone of the Lincolnshire Limestone aquifer lies mostly between the valleys of the West Glen and the Witham (Fig.1). It is traversed in its western part by the north-south A1 road and on its eastern side by the London-to-Edinburgh railway (Fig.2b). The valleys in this zone are mostly aligned west-to-east and form tributary networks to the deeper valley of the West Glen, but few of them house perennial streams. In summer the valley floors are generally dry, although in winter run-off from the glacial till that covers the interfluve areas gives rise to streams that frequently lose water into the limestone aquifer beneath the valley floors. Figure 5 is a map of bedrock and surficial geology that clearly displays the till sheet that covers the limestone plateau, with the valleys of the East and West Glen and their tributaries incised through it. The Lincolnshire Limestone aquifer is exposed in the floor and sides of the West Glen valley, but the East Glen runs on mudrocks of the Upper Estuarine Series and other younger strata. Further east, the same mudrocks are the aquitard that confines the groundwater in the Lincolnshire Limestone.

[1] Most of the hydrogeological subject matter of the excursion is based on unpublished research carried out by Ian Booker and Emma King at the University of East Anglia in the 1970s (Booker, ms 1982) and 1990s (King, 1994).

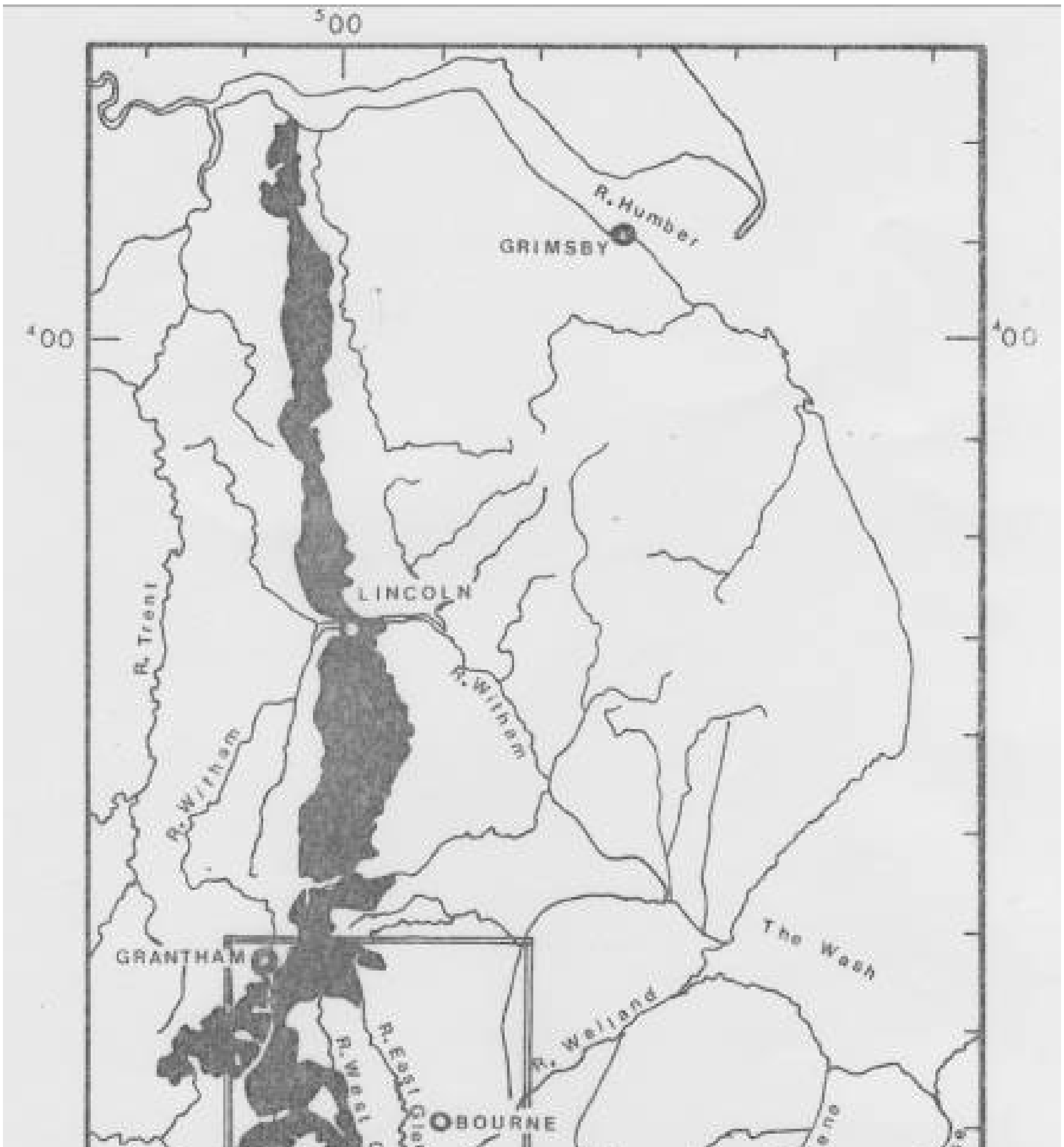


Figure 1 Lincolnshire Limestone outcrop and drainage patterns (Booker, ms 1982)

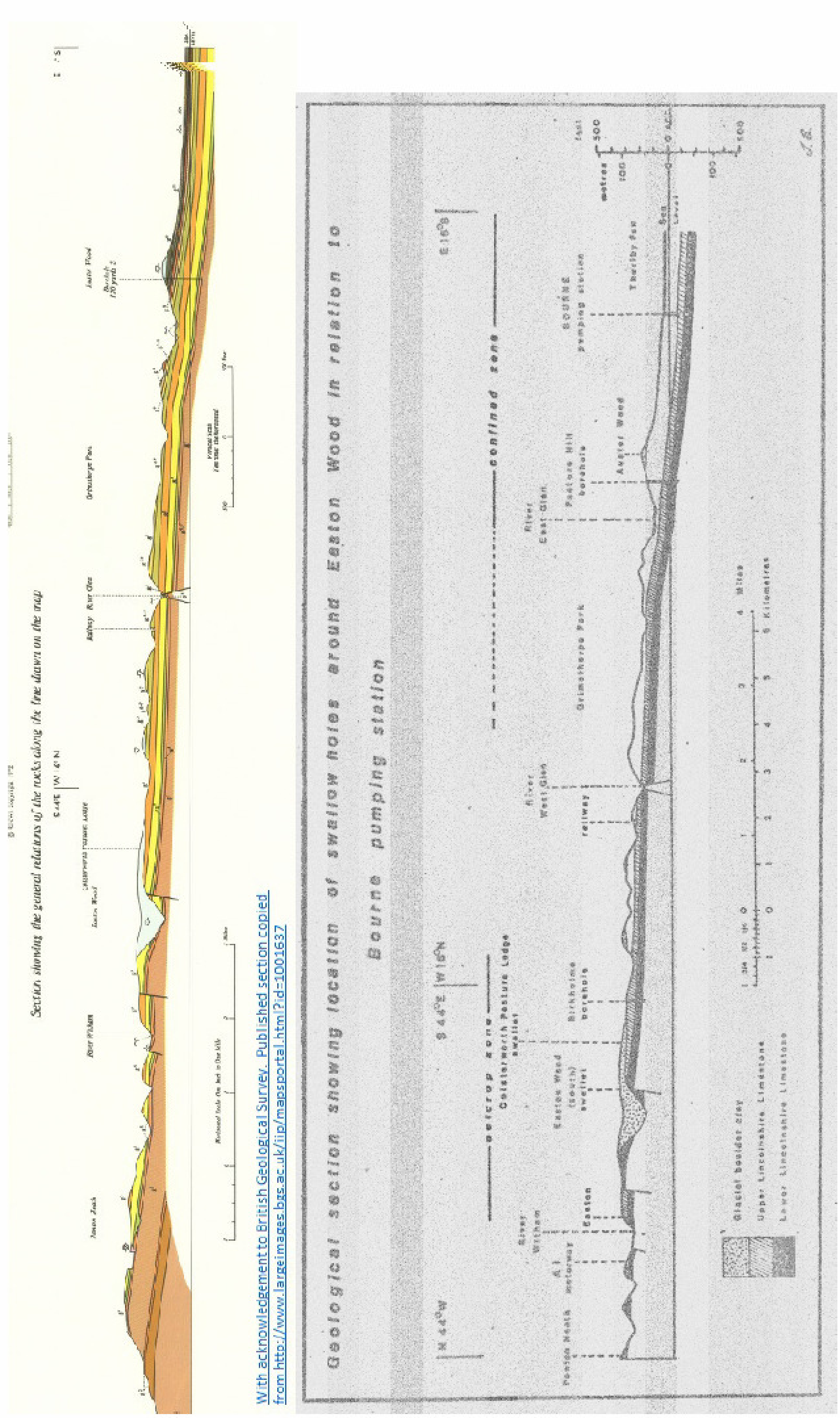


Figure 2: Cross-section of the Lincolnshire Limestone plateau (see Figure 3 for NW-SE alignment of section).
Above: published section (British Geological Survey).
Below: simplified version redrawn by Ian Booker (ms 1982

The outcrop zone is marked by around 60 groups of dolines and swallow-holes that were mapped and described by Hindley (1965) (Fig.3). Remapping from aerial photographs by Booker located 257 closed depressions in 100 km^2 of limestone outcrop. Some engulf streams, the largest having a catchment area of 400 ha and peak discharge 0.3 $m^3.s^{-1}$ (Easton Wood Swallet, Stop 1). Others are used to dispose of field drainage (e.g. Rodbecks swallow-hole, Fig.4). The largest closed depression is 6 m deep and 30 m diameter. In a few there are blind shafts, usually formed in collapsed sediment in the depression floor. Even where bedrock is temporarily exposed these shafts close down to narrow fissures at a few metres depth. No enterable caves are known in the area. In addition to the features already noted, the River West Glen loses water into swallow holes in its bed at a point close to Burton Coggles (named on Fig.3, marked ‘BC’ on Figs.5 & 10).

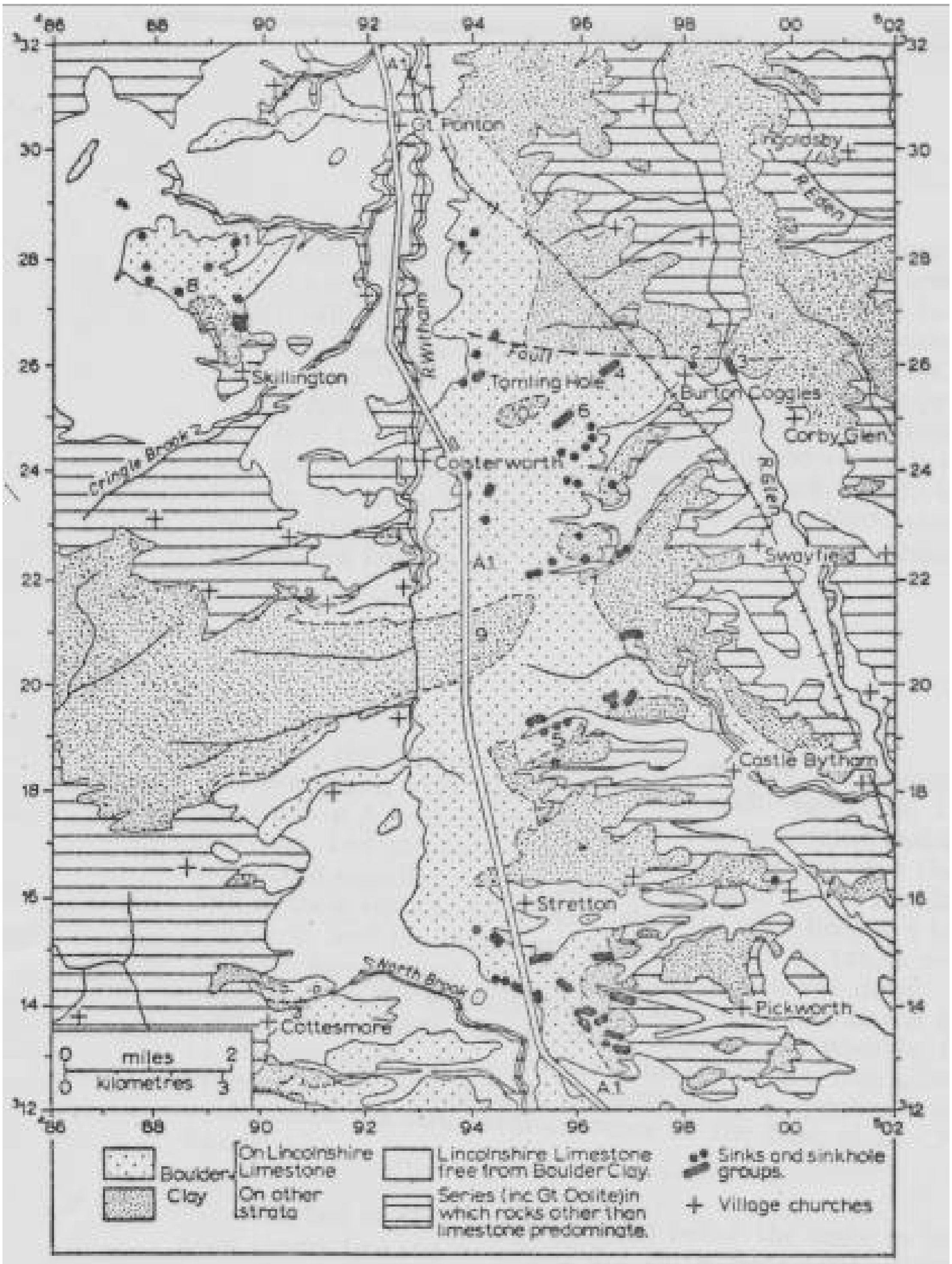


Figure 1.
Sink-holes on the Lincolnshire Limestone between Grantham and Stamford.

Figure 3: Sink holes mapped by Hindley (1965)

SWALLOW-HOLES

PLATE 5.23.

THE RODBECKS SWALLOW-HOLE CLIPSHAM (SK 976 175)

PLATE 5.25.

THERE ARE 3 DISCRETE HOLE IN THE BOULDER CLAY FLOOR. (ARROWED)

A TILE DRAIN INFLOW IS ALSO SEEN.

Figure 4: Two views of Rodbecks swallow-hole (Booker, ms 1982).
In the lower picture, the sinking stream flows from the right and is joined by water from a land drain at back left.

Preglacial drainage, the effects of the Anglian Glaciation and the age of the karst

Glaciation during the Middle Pleistocene radically altered the topography and drainage of the East Midlands and East Anglia. The Wash and Fenland Basin, floored by weak clays, was excavated to bedrock below modern sea level and the regional drainage was entirely re-aligned. The pre-glacial trunk drainage in our area consisted of west-east valleys, aligned parallel to the dip of the Lincolnshire Limestone. Fragments of these valleys survived the glacial erosion and are now filled by glacial till. One is shown in cross section on Fig.2 (west end). They were mapped and described by Wyatt (1971). Figure 5 shows that the present north-to-south rivers cut right across the trends of the infilled palaeo-valleys.

In places quarrying has exploited the pre-glacial fluvial deposits, notably at Witham-on-the-Hill where they reach an altitude of ca. 60m above sea level. The lithology of the pebbles they contain links them to other similar gravels on the east side of the Fenland Basin, which are also covered by a widespread sheet of glacial till firmly assigned to the Anglian stage of British Pleistocene stratigraphy. Uranium-series and ESR dating of interglacial deposits above and below this till has shown that the Anglian Stage is the equivalent of Marine Isotope Stage 12, 420 – 485 ka (Rink et al., 1996; Rowe et al., 1997, 1999; Grun & Schwarcz, 2000; Preece et al., 2007). Before the Anglian glaciation, the area now occupied by the Fens was traversed by a river system that Rose (1994) named the 'Bytham River' after the villages of Little Bytham and Castle Bytham. There the modern valley of the River Tham, a west-bank tributary of the West Glen, roughly follows the course of a pre-glacial palaeo-valley aligned WNW-ESE (Fig.5). The silts and sands of the ancient Bytham River are exposed on the north side of the modern valley, where they have been excavated to construct the earthworks of an important medieval castle. Careful mapping has established the profile of this paleo-river (Fig.6) and the approximate depths of rock removed from beneath it by glacial erosion (Rose, 1994). In the western parts of the Fenland Basin, around Bourne, up to 60 m of bedrock relief was created by differential glacial erosion of the soft Upper Jurassic clays to the east and the more resistant strata to the west. Bourne is now the site of a major artesian spring that derives its flow from the confined Lincolnshire Limestone aquifer ca. 50 m below ground level.

The changes in drainage pattern wrought by the Anglian glaciation across eastern England are summarised in Figs.7 and 8. The upper panel of Fig.7 shows the overall extent of the patchy surviving Bytham River deposits along with those of the proto-Thames, while the lower panel illustrates the directions of ice movement during two phases of the Anglian glaciation and the diversion of the middle and lower parts of the River Thames into their present course. Figure 8 compares the drainage patterns of eastern England before and after the Anglian glaciation (Rose, 1994). The west-east valley through the Lincolnshire Limestone at Stamford (River Gwash, Fig.1) may be a direct inheritance from the pre-glacial drainage pattern. The large gaps in the cuesta at Ancaster and Lincoln are relicts from early courses of the River Trent (Linton, 1951; Straw, 1963) which itself was diverted northwards into the glacially-eroded Humber lowland as a result of Anglian and probably also later glaciations (Straw & Clayton, 1979).

Some uncertainty remains over the age of the Oadby Till that covers the limestone plateau of our area. This glacial till mantles the upland plateau but the Rivers West and East Glen have cut through it to form their present valleys, as have some of their tributaries. Other tributaries, such as the modern Tham, have excavated into segments of pre-glacial valleys. Looked at on a regional scale, the assemblage of landforms, glacial deposits and pre-glacial fluvial gravels strongly suggests that the Oadby Till is contemporaneous with the Lowestoft Till of East Anglia, but all the dated sites are on the east side of the Fenland Basin. South Lincolnshire may have experienced more recent glaciations during Marine Isotope Stage 10 and perhaps Stage 8 by ice that entered the Wash and Fenland basin but did not extend as far as east Norfolk (Westaway, 2010; Straw, 2011 and references therein; see also Rowe et al.,1997). Parts of the till sheet on the plateau might derive from events later than the Anglian.

The small-scale karstic features of the Lincolnshire Limestone plateau clearly post-date the glacial tills. Many sink-holes are located around the edges of the partially eroded till sheet, while others lie inside the mapped areas of till (Fig.3). Thus the karstic features of the present surface must have formed since a latest possible glaciation 250-300 ka ago (MIS 8), although this timescale might be as long as 420 ka if the Anglian ice sheet in MIS12 was the last to cover the area. Although the surface karst is certainly mostly post-glaciation in age, some elements of the sub-surface karstification of the aquifer may have been inherited from the pre-Anglian drainage, as discussed below.

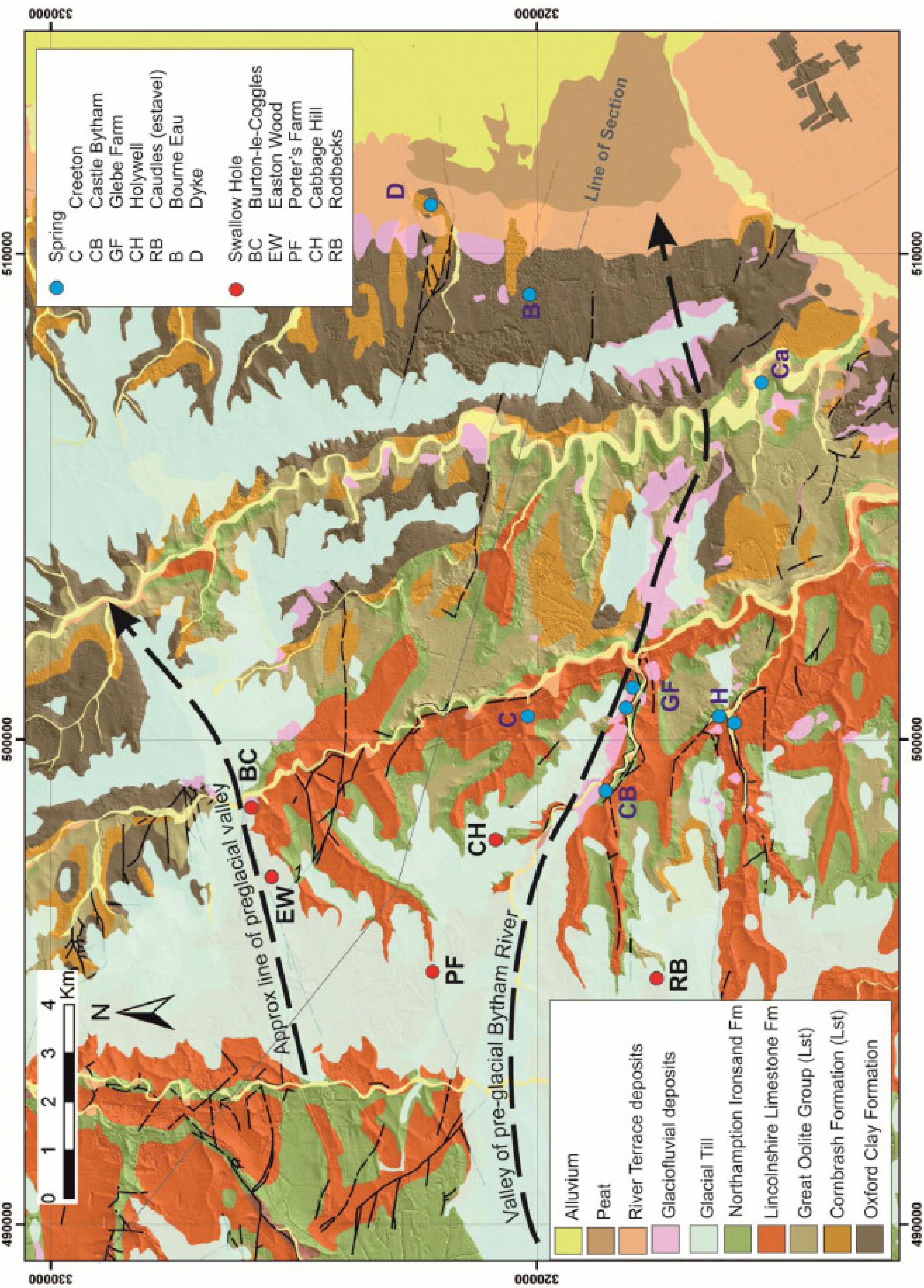


Figure 5 Surficial and solid geology of the study area, over digital terrain model. Grid is GB national grid in metreS

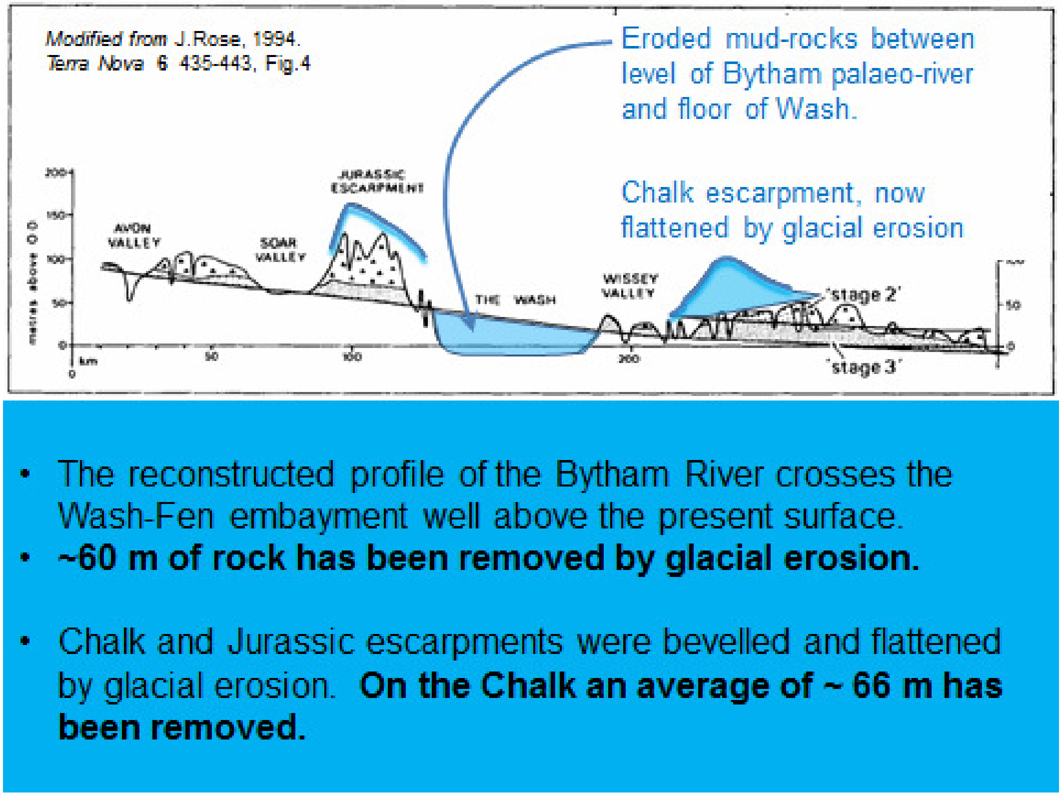


Figure 6: Long profile of the 'Bytham River' showing depths of glacial erosion (after Rose (1994) with additions).

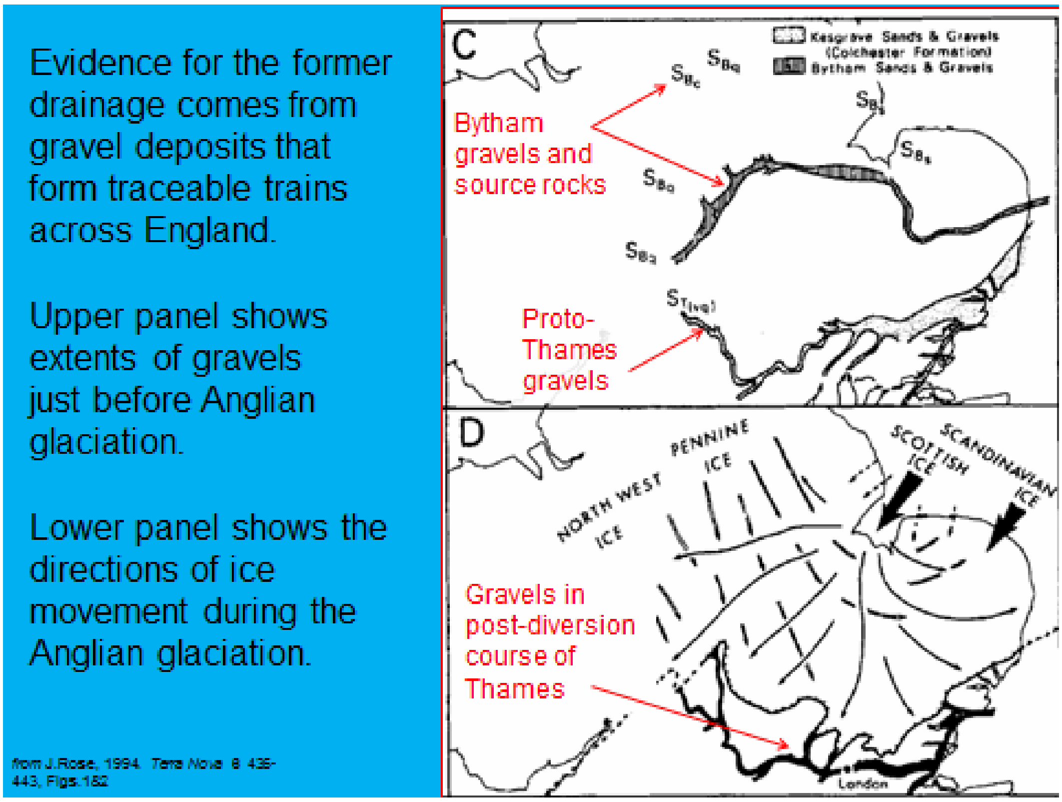


Figure 7: Distribution of gravels of the Bytham and proto-Thames rivers in relation to the extent of Anglian ice (Rose, 1994).

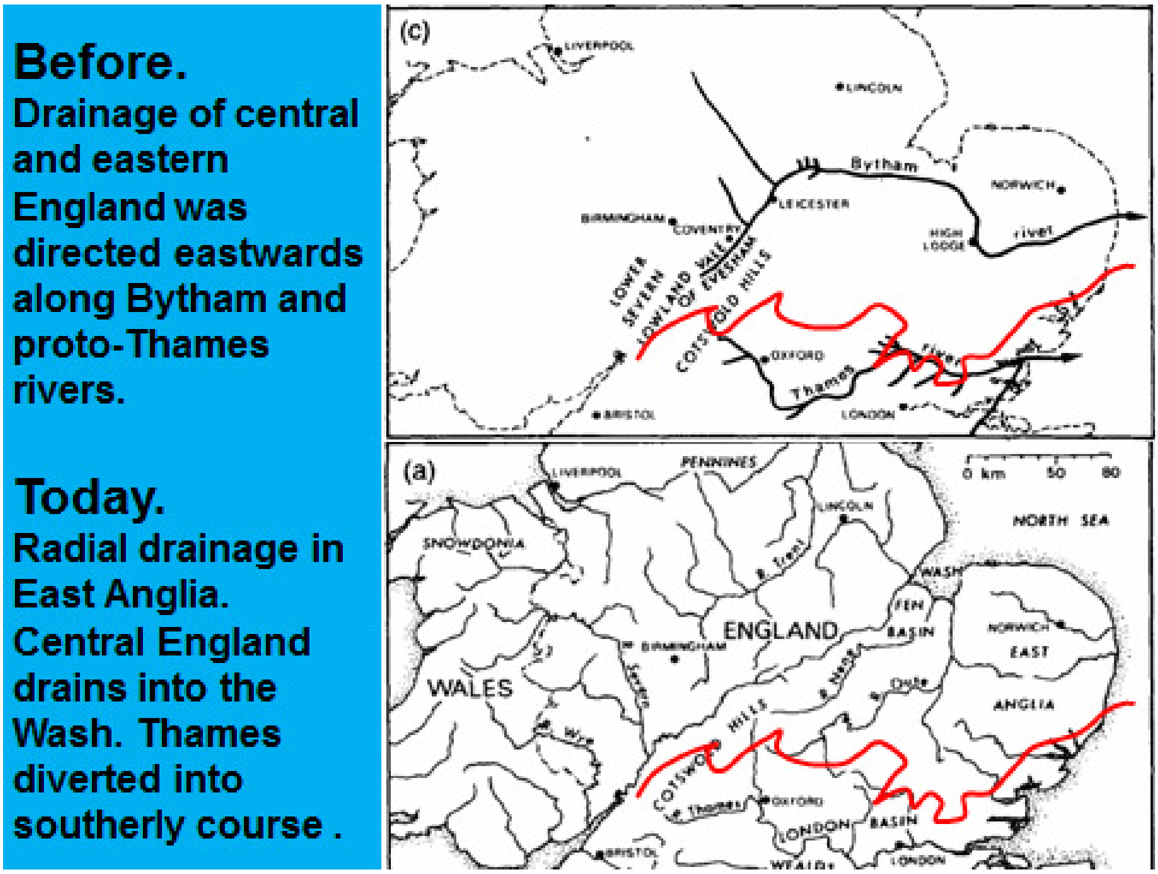
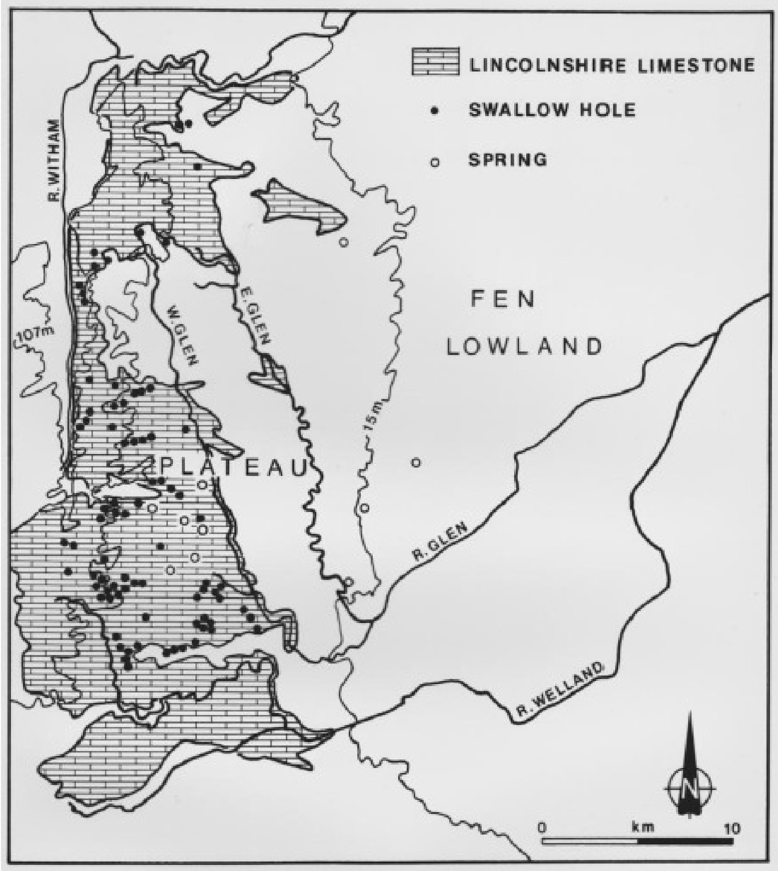


**Figure8: The reorganisation of regional drainage caused by Anglian glaciations.
The southern limit of the ice sheet is in red.**

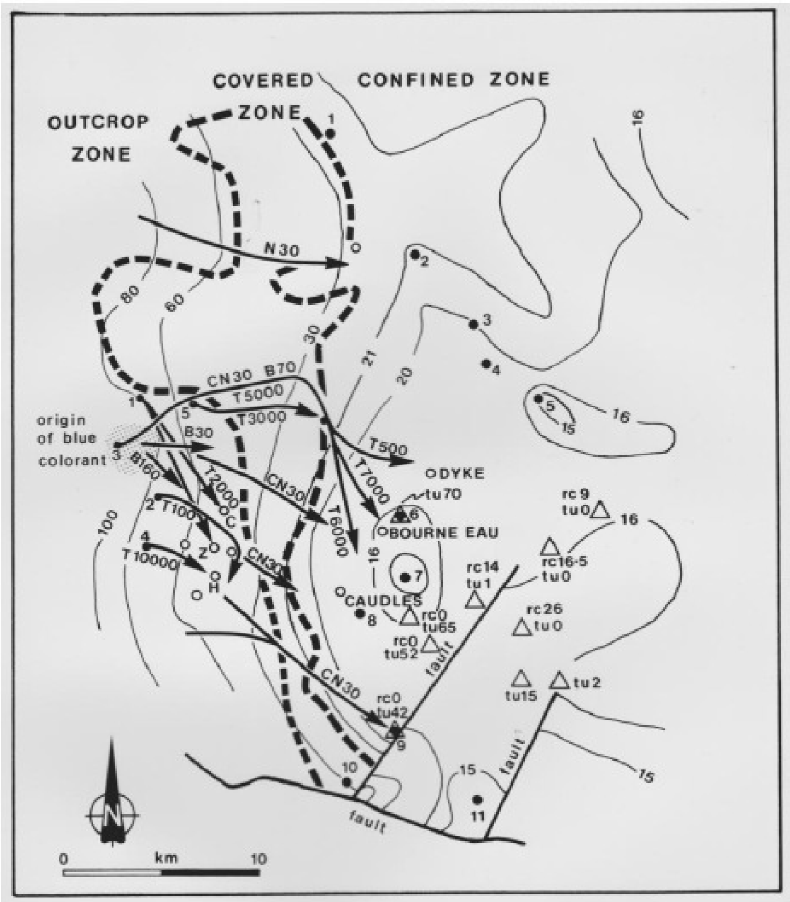
Hydrogeology

The hydrogeology of the Lincolnshire Limestone was described by Downing & Williams (1969), who mapped the eastwards gradient of the water table and noted the importance of the swallow-holes of the West Glen at Burton Coggles in providing point recharge to the aquifer. They also noted that the tritium content of the abstracted water at Bourne Pumping Station was high and varied considerably, suggesting a fluctuating component of very young water. Downing and Williams considered that this component might be derived in part from the Burton Coggles swallow-holes, and noted the potential risk to public water supplies that would be presented by a large surface catchment directly connected to the Bourne water source.

The contours of groundwater head, when compared with the elevation of the top surface of the limestone, show that the aquifer can be divided into three zones (Fig.9b, see also Fig.2a). In the west, the Outcrop Zone receives recharge by infiltration and through runoff into swallow-holes, including those that formerly partially engulfed the West Glen at Burton Coggles. To the east of the East Glen, the aquifer is confined. Between the Outcrop Zone and the Confined Zone is a 'Covered Zone' in which the aquifer is unconfined but covered by younger strata with low permeability. The bulk of the recharge therefore derives from the outcrop zone. In the southern part of the outcrop zone there are perennial and seasonal springs from Lincolnshire Limestone in the valley floors of the West Glen and its tributaries the River Tham and the Holywell Brook. Smith (1979) describes the seasonal operation of these. Fig.9b shows that the groundwater contours form a closed 'cone of depression' around the Bourne water source (marked #6) and a second source (#7) as a result of abstraction by pumping. A large natural spring, the Bourne Eau, lies within this cone of depression and there are also natural springs at Dyke on the edge of the Fens, and at Caudles in the East Glen valley (Figs.9b & 10). However, unregulated over-abstraction from artesian boreholes along the western edge of the Fenland during the 19th and 20th centuries caused the Caudles springs to become estavels (features that alternate between discharging and taking in water), and by the 1970s discharging conditions had become unusual (Burgess and Smith, 1979). To the east of these springs and artificial sources the groundwater contours indicate a very flat gradient in the confined aquifer beneath the Fens, implying very slow groundwater flow. Downing and Williams (1969) noted that the transmissivity at Bourne and the other major abstraction wells (#6,7,8 on Fig.8) was extremely high, up to 10,000 $m^2.day^{-1}$, implying that the aquifer contains open fissures in the western part of the Confined Zone. (The hydraulic conductivity implied by such a high transmissivity is ~300 $m.day^{-1}$, a very high value, *cf.* the karstic Carboniferous Limestone in the Mendips ~90 $m.day^{-1}$ (Atkinson, 1977).)



A. Outcrop, drainage, major sinkholes and springs.



B. Contours of ground water level with summary results for natural and artificial tracers.

T 3000 = Artificial tracer path with velocity of arrival in $m.day^{-1}$.

B 160 = Inferred transport of blue colorant with velocity in $m.day^{-1}$.

CN 30 = Inferred transport of Chloride (C) and Nitrate (N) with velocities in $m.day^{-1}$.

Figure 9: Hydrogeology of the Lincolnshire Limestone

The slow flow in the eastern part of the Confined Zone was confirmed by measuring the amounts of tritium and radiocarbon in the groundwater (Downing et al, 1977). Tritium (derived from 20th century nuclear bombs and power stations) was zero or extremely low and radiocarbon was only a few per cent of modern (pre-nuclear) values, implying that the waters were up to 26,000 years old. On the other hand the Bourne abstraction wells showed high tritium combined with low radiocarbon, implying that the water was a mixture of modern and ancient components. Downing et al. (1977) inferred that the abstractions from the highly permeable western part of the confined zone were partly derived from the ancient ground water to the east and partly from the rapidly circulating modern water in the unconfined aquifer in the west. The gradual impact of abstraction on the eastern aquifer was confirmed by Edmunds and Walton (1983) who reviewed the changes in water chemistry over a ten year period and noted that oxygenated water carrying sulphate derived from fertilisers appeared to be penetrating beneath the Fens, replacing older waters that abstraction had induced to flow westwards into the cone of depression around the wells near Bourne and (#6 & 7 on Fig.9b).

The published hydrogeological investigations up to about 1980 present a picture of a limestone aquifer in which karstification is evident from surface features in the west, with groundwater flowing eastwards towards a zone of abstraction from wells and springs where radiochemistry shows mixing of young and old water in a region of confined aquifer with exceptionally high permeability. Records show that the wells along the edge of the Fens were originally artesian, with naturally overflowing heads of water. It may be inferred from this that the large spring at Bourne Eau and probably the smaller one at Dyke are fed by upwards flow from the Lincolnshire Limestone, perhaps along faults. Further east, the lack of a natural outlet from the aquifer caused stagnation of the ground water since the Last Glacial period, with modern abstraction inducing a slow flow westwards in places and eastwards in others, accompanied by mixing.

The karstic nature of flow in the western part of the aquifer was also inferred by Fox & Rushton (1976) who found that groundwater models of the aquifer had to incorporate a rapid transfer of recharge from outcrop directly to the confined zone in order to simulate transient changes in head in the latter. Though this idea was quite consistent with presence of swallow holes in the Outcrop Zone, it was highly unconventional in the context of groundwater modelling at that time (cf. Rushton, 1975). Fox & Rushton's work pre-dated any attempts to detect such rapid flow by groundwater tracing, though they would have been aware of the speculation by Downing and Williams (1969) regarding a connection between the Bourne abstraction point and the influent West Glen at Burton Coggles.

Water tracing using artificial and environmental substances

(a) Artificial tracers and rapid ground water flow

Between 1977 and 1979 Ian Booker undertook 9 water tracing experiments using artificial tracers injected at 6 points. Five input points were swallow holes and one a borehole. In 1994 Emma King repeated Booker's experiment at Easton Wood Swallet (Stop 1) using artificial recharge under conditions of very low natural flows with the influent stream dry (King, 1994). The pattern of flow revealed by both sets of experiments is shown in Fig.10, with velocities of the first arrivals of tracer in Fig.9b. The results are summarised in Table 1.

The artificial tracers showed that groundwater velocities of ~1000 to ~10,000 m.day^{-1} occur in all three zones of the aquifer. Though the flow paths from swallets on the outcrop to Bourne had to be established as a series of segments, the results indicate an overall transit time of a few days for the most rapid component of flow, confirming the suspicions of Downing and Williams in their 1969 report.

The regional flow pattern showed two distinct parts (Figs.9b & 10). Input points BC, EW and PF (Fig.10) are all sinking streams from which tracers moved eastwards at 1000 to 5000 m.day^{-1} to be detected at a borehole at Elsthorpe ('E' on Fig.10). Thus there is a zone in the northern part of the area across which rapid flow takes place from west to east, more or less parallel with the groundwater gradient, reaching the edge of the confined zone at Elsthorpe. This borehole was subsequently used as an injection point for tracer that was detected at the Bourne Eau spring and at five boreholes, with velocities of 500 to 7000 m.day^{-1}. In this segment of flow the aquifer is confined. The general direction of flow was southeast and there was considerable lateral dispersion, subtending an angle of at least 40^{o} (Fig.10). The dispersion and range of velocities are consistent with flow through a mesh-like network of intersecting karstic fissures.

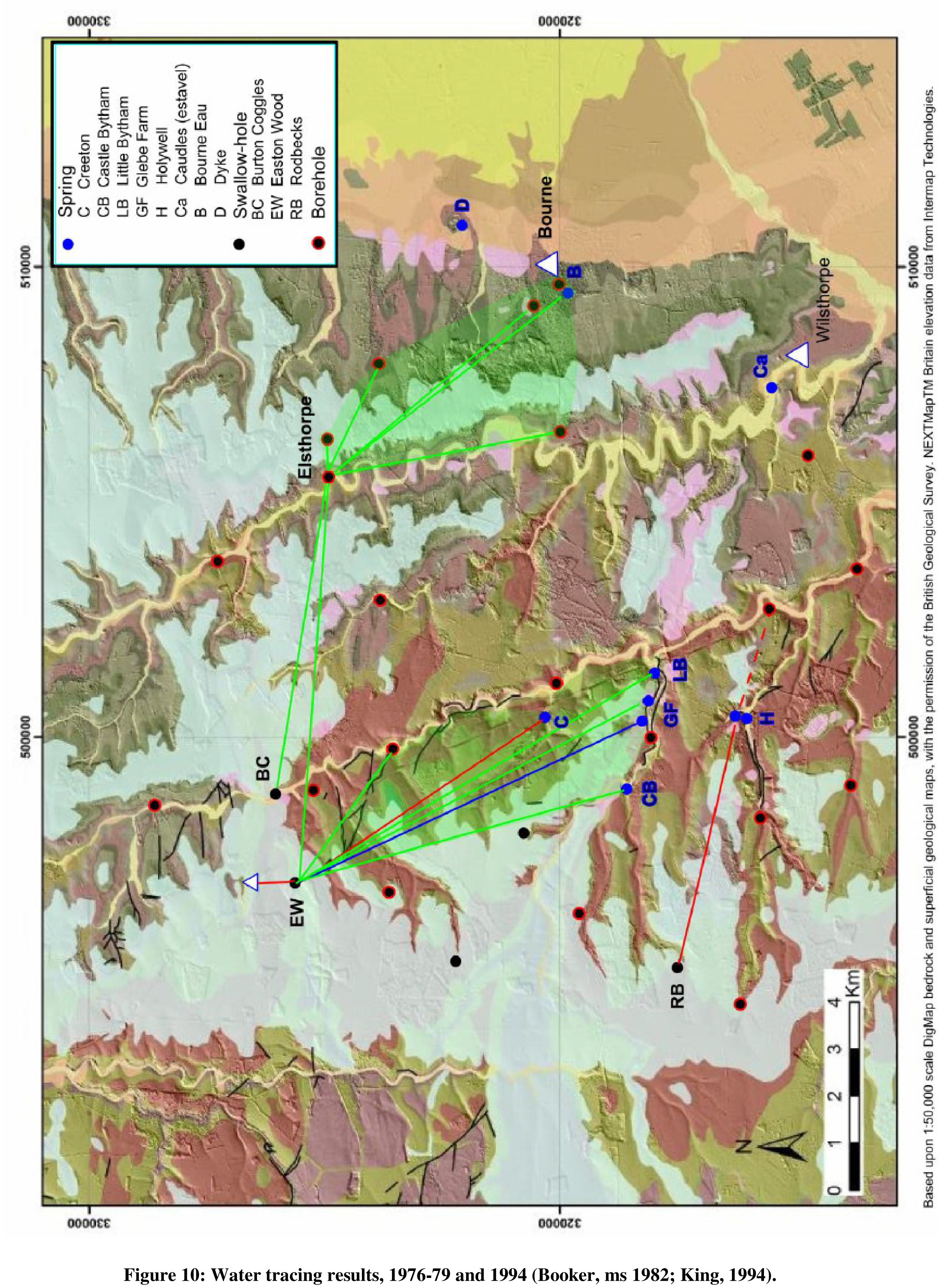


Figure 10: Water tracing results, 1976-79 and 1994 (Booker, ms 1982; King, 1994). Red – Rhodamine WT, Blue – Photine CU, Green - Fluorescein

Table 1: Tracer tests, 1977-79 (Ian Booker) and 1994 (Emma King)

(Letters in col.1 refer to sites on Figs.5 & 10; numbers relate to Fig.9b).

)	**Tracer injection site**	**Tracer and amount**	**Monitoring sites tested as positive**
EW/1	Easton Wood swallow-hole (SK 968 259)	(a) Rhodamine WT, 2.26 kg	Allied Potato Services bore-hole (TF 968 265) Creeton springs (TF 005 203)
		(b) Photine CU, 19 kg	Glebe Farm Springs at TF 004 182
	(Emma King, 1994)	(c) Fluorescein, 4 kg, Photine CU, 5 L	Castle Bytham springs (SK 989 186) Glebe Farm Spring at TF 008 181 Little Bytham spring (TF 015 179) River Tham at TF 018 179 River West Glen at TF 018 179 Swayfield borehole (SK 998 233) Elsthorpe borehole (TF 056 249)
CH/2	Cabbage Hill swallow-hole (SK 979 207)	Lissamine 7FF, 3 kg	Careby borehole (TF 026 155)
PF/3	Porter's Farm swallow-hole (SK 953 222)	Rhodamine WT, 5 kg	Irnham borehole (TF 037 273) Elsthorpe borehole (TF 056 249)
RB/4	Rodbecks swallow-hole (SK 977 175)	Rhodamine WT, 5 kg	Holywell spring (TF 005 163 to 003 165) Careby borehole (TF 026 155)
BC/5	West Glen at Burton Coggles (SK 988 260)	(a) ^{82}Br, 10 mCi	negative
		(b) ^{82}Br, 340 mCi	Elsthorpe borehole (TF 056 249)
		(c) Fluorescein TF, 20 kg	Elsthorpe borehole (TF 056 249)
	Elsthorpe borehole (TF 056 249)	Fluorescein LT, 15 kg	Bourne Eau spring (TF 095 198), Bourne Eau borehole (TF 095 198) Hanthorpe borehole (TF 079 239) Elsthorpe Grange borehole (TF 062 249) Pasture Hill borehole (TF 066 201) Bourne Woodlands Nurseries borehole (TF 092 205)

The breakthrough curve at Elsthorpe for 20 kg of Fluorescein injected at Burton Coggles (BC on Fig.10) is shown in Fig.11. The peak occurs almost immediately after the first arrival and is followed by an exponential decline in concentrations until over 80 days after injection. This is similar to the behaviour produced by a well-stirred tank and implies that the tracer does not follow a single path but moves through a network of fractures and fissures with a wide range of apertures and local velocities, and with frequent intersections to produce mixing. However, there must be direct connectivity among the fissures with large aperture to produce the rapid initial arrival and rise in concentration, and the early peak.

The second part of the regional flow pattern is revealed by tracer transport in the aquifer west of the West Glen. Booker made two experiments at Easton Wood swallet (point EW, Fig.10) under high and moderate flow conditions. Both showed rapid south-eastwards flow to springs at Creeton and in the Tham valley, but dilutions of tracer were very large and mass balance showed low recoveries. No tracer was seen at Elsthorpe borehole. King (1994) repeated Booker's test from this site under dry conditions, bringing water in a tanker to make the tracer injection. This tracer showed the same rapid flow to the south-east but was detectable at more sampling points, and appeared to spread in a fan-shaped plume with an apical angle of about 30^{o}. Velocities were 1500 to 7000 m.day^{-1} but tracer concentrations were very low at all sites where it was detected. In King's experiment, one of the two tracers used was also detected at Elsthorpe borehole (Fig.10).

Injection point RB also demonstrated flow to springs west of the West Glen, but in this case south of the former 'Bytham River'. The sinking stream and land drainage illustrated in Fig.4 was proved to resurge at a spring at Holywell 3 km away. Fig.11 (upper) illustrates the breakthrough curve which shows two components, a narrow peak followed by a long tail that persists for over 200 days. This strongly suggests rapid flow along a connected fissure pathway combined with dispersion into smaller fissures and fractures, possibly with storage and release of tracer by diffusion between fractures and porous matrix (the porosity of Lincolnshire Limestone is several per cent). The velocity of the rapid component was 10,000 m.day^{-1}.

Tracer from RB was also detected down-gradient from Holywell at a borehole on the West Glen (shown as a broken red line on Fig.10), with a delay that suggested a transport velocity of ~100 $m.day^{-1}$. A separate tracer input at site CH showed a similar velocity to the same borehole but was not detected at any other site. The tracer concentration was close to the threshold of detectability. (This pathway is not shown on Fig.10 but CH is indicated on Fig.5. See Table 1.)

The breakthrough curves in Fig.11 demonstrate a wide distribution of residence times for groundwater, from a few days to several hundred days, corresponding to a ~100-fold range in tracer velocities in the aquifer that is also seen in the range of first-arrival velocities between sites and under different flow conditions. This large range of rapid flow velocities suggests that flow must be via networks of intersecting voids with a wide range of apertures, but with large voids sufficiently frequent to ensure that in many cases part of the tracer travels with very high velocity. It is also likely that portions of the tracers were delayed by diffusion into very slow moving water, either in blind fractures or in the pores of the rock matrix. Sorption on aquifer materials may also have occurred. Both processes would account for the great dilutions observed following injections of very large amounts of tracer (up to 20 kg of fluorescent dyes; 340 microCuries of ^{82}Br).

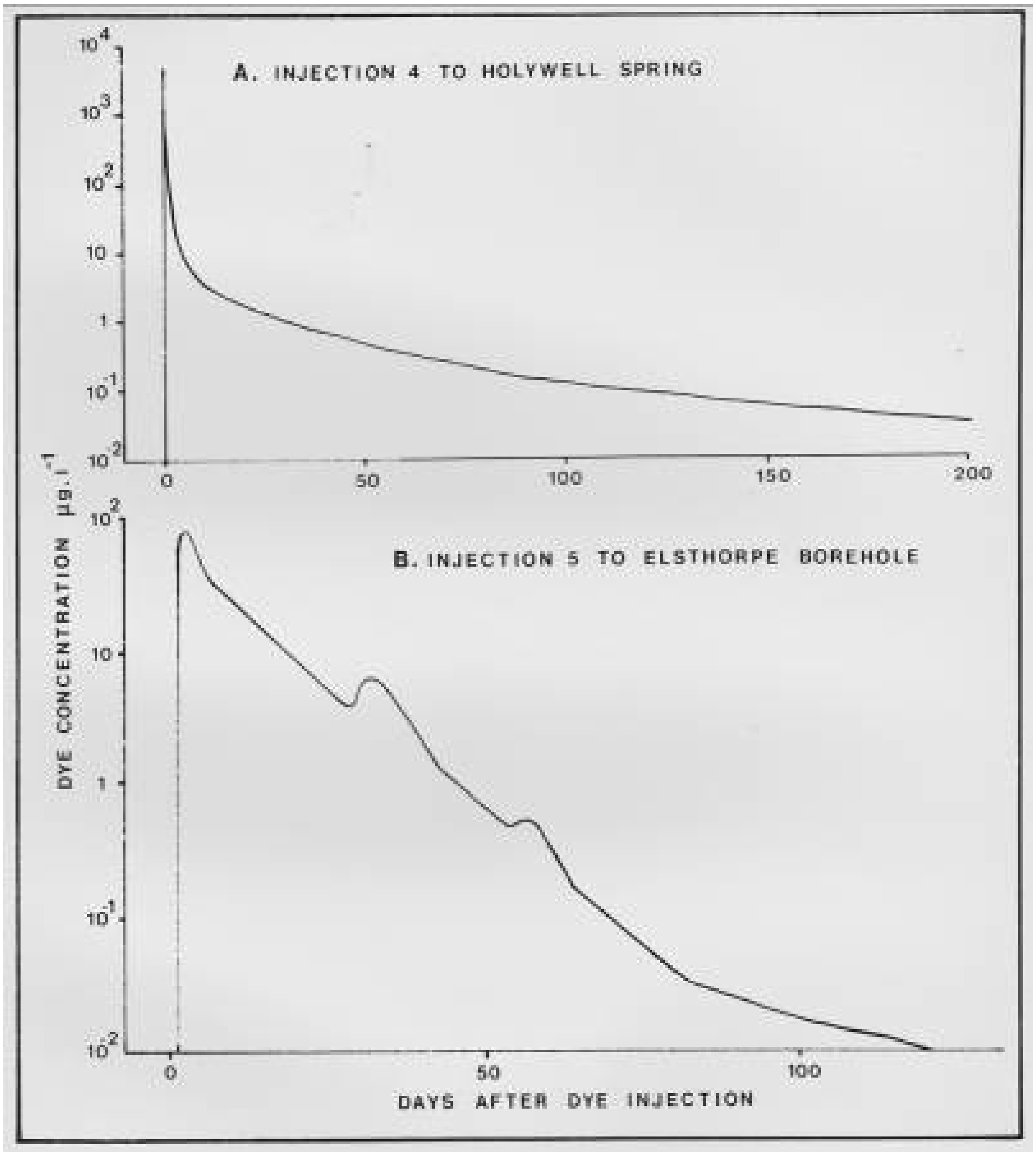


Figure 11: Breakthrough curves from two water tracing tests (Booker ms 1982)

(b) **Environmental tracers**

Booker observed two types of environmental tracers. One was the quite adventitious discovery of a blue colorant that appeared to be spreading through the aquifer from a source in the vicinity of injection point PF, where there was a former WWII airfield on the site of what is now Twyford Wood. The colorant appeared as a sorbed phase on cotton calico detectors that were being used to monitor the aquifer for optical brighteners prior to the first tracing tests. It appeared during the winter of 1976-77 when groundwater levels were at the highest levels since monitoring began. ICI Laboratories tentatively identified the colorant as resembling dyestuffs used to mark aviation and tractor fuels to inhibit sale on a black market during W W2. It may be that the high water levels flushed one or more caches of spilled dye that had remained in the unsaturated zone since the 1940s. Whatever the source, Booker was able to observe the gradual spread of the colorant from borehole to borehole over a period of several months, with the same patterns of flow as shown by the artificial tracers, but velocities of only 30 – 160 $m.day^{-1}$, i.e. 10 to 100 times slower.

The second environmental tracer was based on the fluctuations of nitrate and chloride concentrations in the groundwater, as mapped over the aquifer by monthly sampling from the boreholes shown in Fig.10. This revealed seasonal changes in which raised concentrations could be seen spreading from west to east over a distance of up to 10 km across the aquifer, before dropping back to their initial levels. The timing of these fluctuations reflected the origins of the two anions. Chloride appeared to derive from road salting on the A1 in winter, whereas nitrate derived from fertilisers and mineralisation of crop residues following ploughing in late summer and autumn. The regional velocities indicated by both anions were around 30 $m.day^{-1}$.

The environmental tracers suggest that the average flow rates in the aquifer are tens of metres per day. This is consistent with flow through un-karstified fractures. The artificial tracers show breakthrough curves that are consistent with this. For example flow at 30 $m.day^{-1}$ would take about 100 days to cover the 3 km from injection point RB to Holywell, and this is the mid-time of the tail in the breakthrough curve (Fig.11). For Injection point BC (Burton Coggles sink of the River West Glen) the fit is not as good. Flow at 30 $m.day^{-1}$ would take about 230 days to reach Elsthorpe borehole, whereas the tracer became undetectable at after about 120 days (Fig.11). Nevertheless, the maximum discrepancy between slow moving tracer and the 30 $m.day^{-1}$ suggested by NO_3" and Cl', is only a factor of two. As noted above, the longest residence times for tracer may reflect storage by diffusive exchange with static water in pores of the rock matrix.

Karst processes in the aquifer and the origin of high permeability

The karstification of the Lincolnshire Limestone seems to have occurred in two contexts. One is the dissolution of small shafts and cavities by infiltrating water in the outcrop zone. (An example will be seen at Stop 6). Study of groundwater chemistry in this zone has been limited, but Roberts & McArthur (1998) demonstrate that DOC levels are lower in groundwater than in infiltrating streams, implying that oxidation of DOC to H_2CO_3 may be a source of acidity for karstification, in addition to dissolved CO_2 derived from the soil.

The second location is more puzzling. Hydraulic conductivity in the western part of the confined zone is extremely high, and tracers suggest a dispersive pattern consistent with fissure networks. Therefore karstification must have occurred in confined parts of the aquifer that are remote from outcrop. The source of acidity for this development is not well understood. Roberts & McArthur (1998) found that both DOC and dissolved oxygen were low in groundwaters of the proximal part of the confined zone, so it is conceivable that prior oxidation of DOC to H_2CO_3 occurred as the waters migrated down-gradient from the west. Borehole records from this zone indicate that the central parts of bedding-plane bounded blocks of limestone are often blue in colour, whereas the outer parts that are adjacent to fissures are pale brown or tan. If these colour contrasts reflect an 'oxidation front' of iron compounds in the rock matrix, they would imply that water in the fissures must be a source of oxidising agents that have diffused into the matrix, albeit a weak one. Examples of similar, 'blue-heart' blocks of limestone may be seen in quarries (Stop 5) in the outcrop zone, where they are commonest in thickly bedded calcarenites beneath a cover of Upper Estuarine Series mudrocks. The latter are normally dark grey to black but are altered to yellow or tan colours in the beds immediately overlying the fissured limestone. One may speculate that oxidation of iron compounds, possibly dispersed pyrite, and/or organic matter in the Upper Estuarine Series may have been a source of acidity for development of the open fissures, many up to 150 mm wide, that have been recorded in the quarries at Stop 5 of the excursion.

Karstification and landscape history

The evidence of former exposures in Medwell's Quarry (Stop 5, Fig.12) is that karstification occurred under phreatic conditions immediately beneath a cover of Upper Estuarine Series, probably dating from a time in the past when local saturation levels were higher than today and sites currently in the outcrop zone were in or on the edge of the contemporaneous confined zone. Thus, karstic fissures can be seen today which are inherited from a time before the aquifer was drained to its present level, i.e. when base levels were higher than today and rivers ran at higher levels than the present drainage. Regional base level within the aquifer corresponds to the groundwater heads at the edge of the confined zone, roughly 20 m above sea level (Fig.9b), whereas the relict karst fissures at Stop 5 are at ca. 70 m asl, a height difference of about 50 m.

Figure 62A. Karstic fissures in calcarenites capped by Upper Estuarine Series mudrocks (Booker, ms 1982)

Figure 12B Joint guided fissures and bedding plane tubules in calcarenites, Medwells Quarry, Clipsham, ca.1979. (Photo Ian Booker)

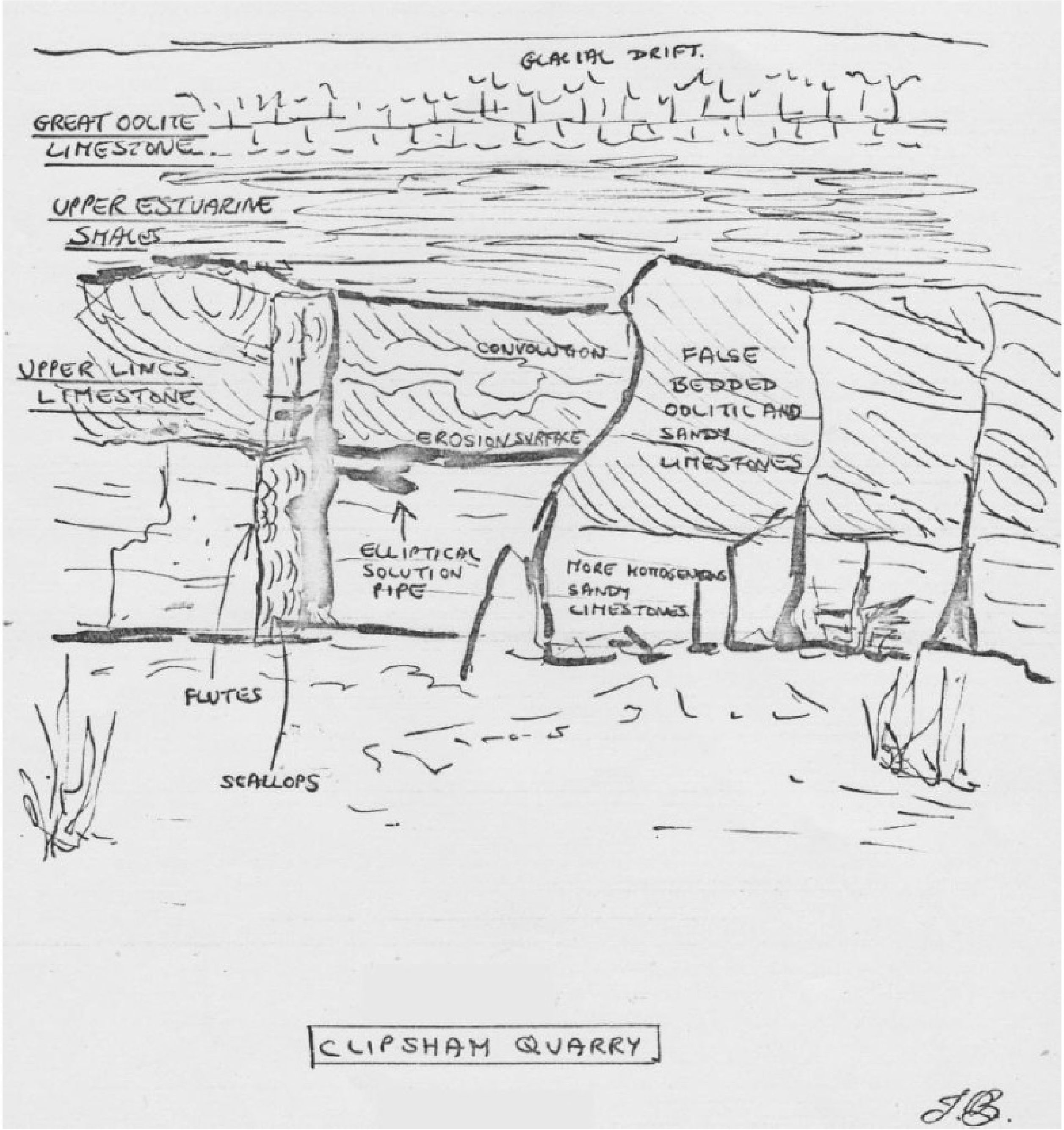


Figure 12C: Field sketch by Ian Booker recording scallops and flutes on fissure walls in uppermost bed of Lincolnshire Limestone, indicating turbulent flow under confined conditions. (Booker, ms 1982).

This suggests that the karstification of the fissures may have occurred prior to the drainage re-organisation and base-level changes brought about by the Anglian glaciation. At that time the palaeo-valley of the 'Bytham River' was locally the trunk stream, and it would have provided a local control for base-level at 50 – 70 m asl, depending on the degree to which the river had incised its course into the limestone (Fig.6). Groundwater flow would likely have been towards the Bytham River with karstification occurring within the western part of the contemporaneous confined zone, i.e. within what is today the outcrop zone. Thus, the rapid NE to SW movement of groundwater west of the West Glen, proved by the tracers, may reflect an inherited permeability development related to the pre-glacial state of the aquifer. The rapid flow of groundwater from west-to-east (Easton Wood and Burton Coggles to Elsthorpe) follows the present gradient of the water table and must reflect the lowering of water levels brought about by incision of the post-glacial rivers, the East and West Glen. The development of artesian conditions at Bourne and Dyke undoubtedly reflects the lowering of ground levels in the Fens by glacial erosion during the Anglian, but the springs themselves may be sited on geological weaknesses in the confining strata, such as minor faults, though these have not been detected. It is notable, however, that the tracer injected at Elsthorpe borehole migrated towards the Bourne Eau spring with a pattern almost identical to that shown by groundwater west of the West Glen (Fig.10), suggesting a similar development of karstification.

Conclusions

Fig.13 is a conceptual model of flow in the Lincolnshire Limestone, drawn in the late 1970s during the tracing programme. Tracer is imagined as travelling through networks of karstic fissures that also intersect with narrow fractures. Flow from west to east beneath the West Glen is inhibited in this model by horst-like structures that may be due to valley bulging. The principal outlets west of the West Glen are springs in the Tham valley, and these coincide with the course of the pre-glacial 'Bytham River'. It is possible, therefore, that some of the subsurface karstification west of the Glen took place in pre-Anglian times, perhaps reflecting deeper incision of the Bytham than of the palaeo-valleys to the north. The karstic element of the aquifer persists eastwards into the Confined Zone, as far as the Fen Edge where transmissivities and borehole yields are extremely high, reflecting fissure development in the aquifer. However, it appears that karstification is limited to the western part of the Confined Zone, and that natural groundwater flow rates further east are ~1 $m.year^{-1}$. Abstraction over the past two centuries has induced slightly higher flows in this zone, with ancient water being pulled westwards towards the abstraction points.

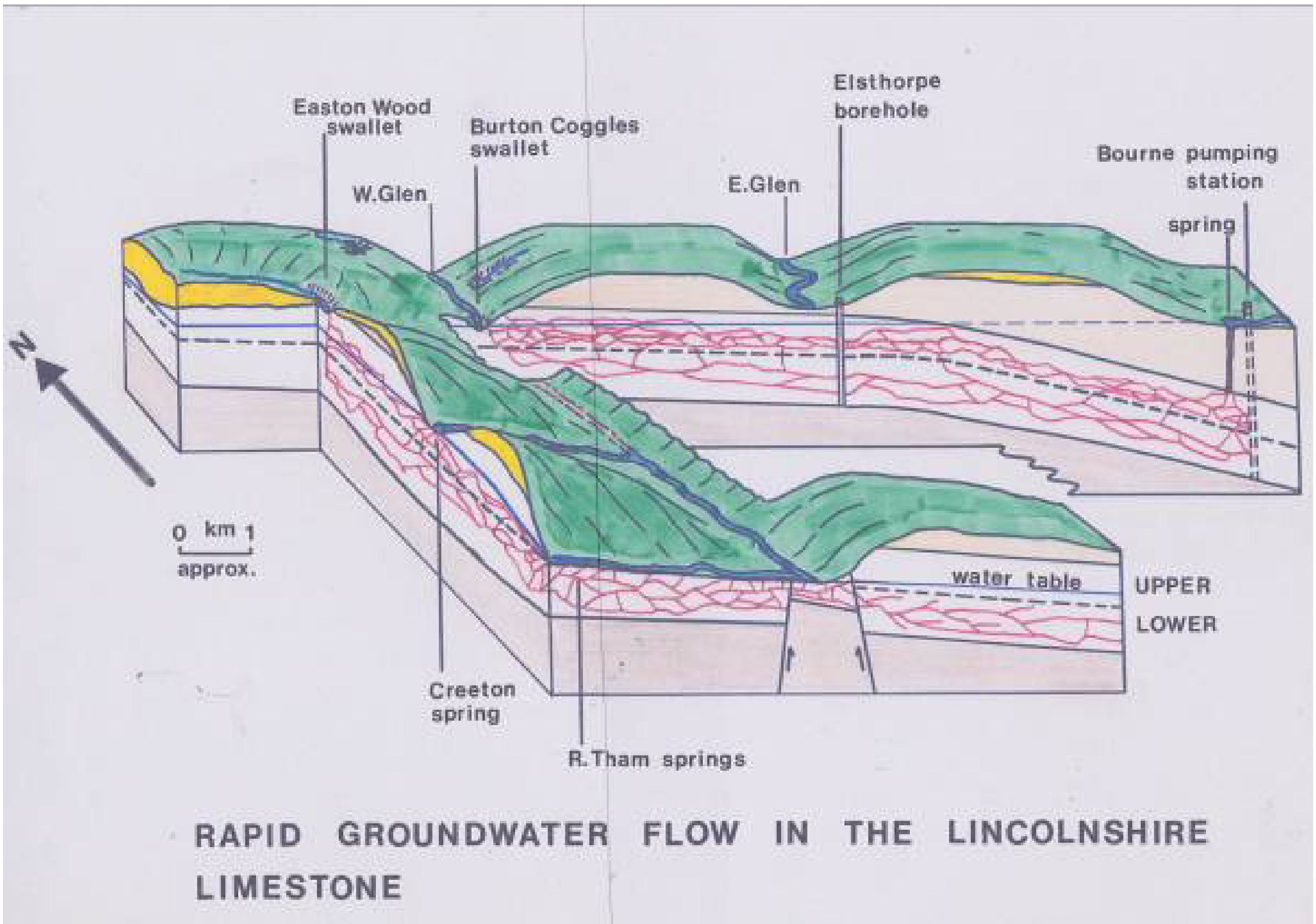


Figure 13: Conceptual model of regional karstification and ground water flow in the Lincolnshire Limestone aquifer.

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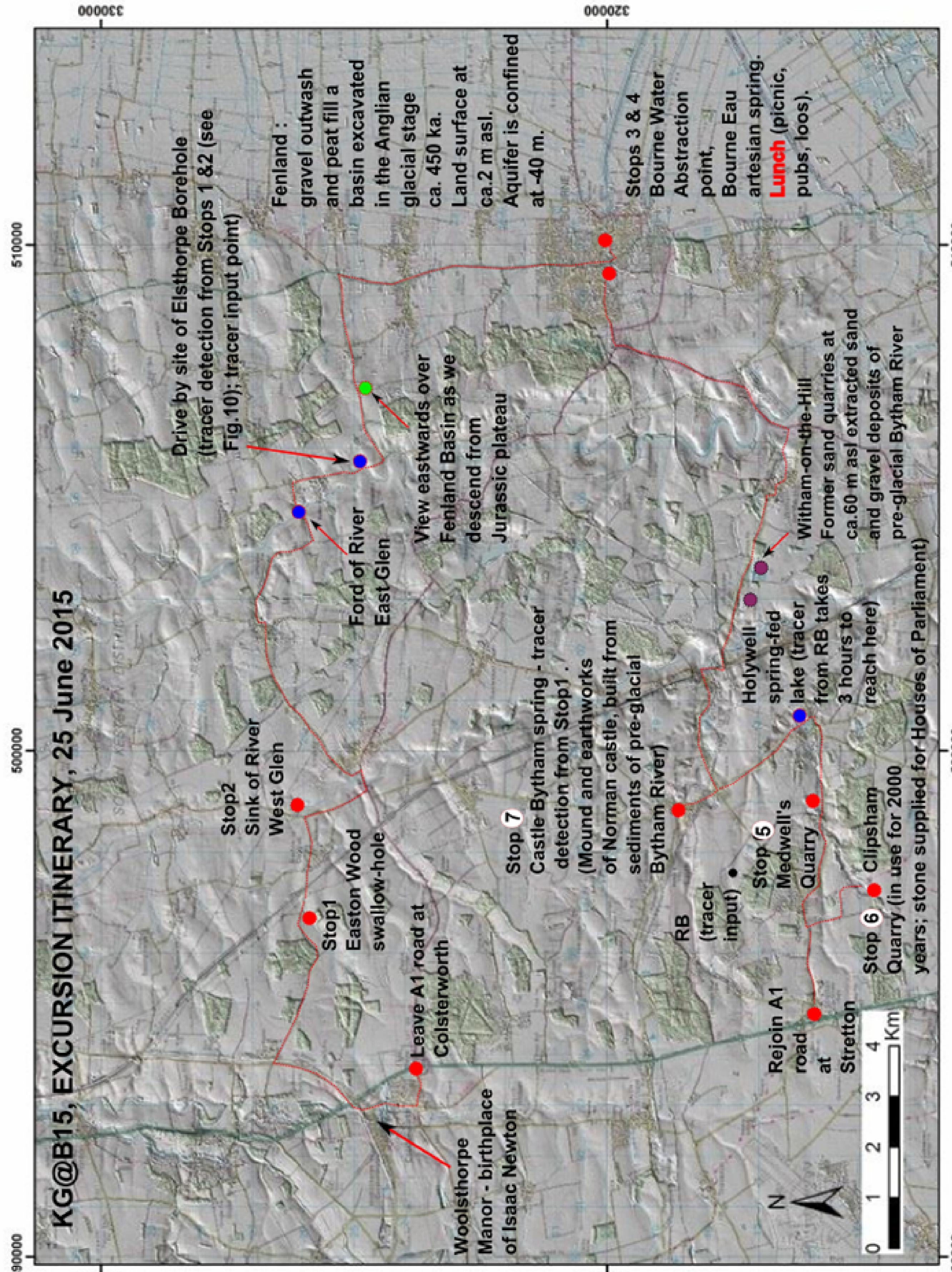
KG@B15, EXCURSION ITINERARY, 25 June 2015
Woolsthorpe Manor - birthplace of Isaac Newton
Leave A1 road at Colsterworth
Stop1 Easton Wood swallow-hole
Stop2 Sink of River West Glen
Ford of River East Glen
Drive by site of Elsthorpe Borehole (tracer detection from Stops 1 &2 (see Fig.10); tracer input point)
View eastwards over Fenland Basin as we descend from Jurassic plateau
Fenland : gravel outwash and peat fill a basin excavated in the Anglian glacial stage ca. 450 ka. Land surface at ca.2 m asl. Aquifer is confined at -40 m.
Stops 3 & 4 Bourne Water Abstraction point, Bourne Eau artesian spring. Lunch (picnic, pubs, loos).
Witham-on-the-Hill Former sand quarries at ca.60 m asl extracted sand and gravel deposits of pre-glacial Bytham River
Holywell spring-fed lake (tracer from RB takes 3 hours to reach here)
Stop 7 Castle Bytham spring - tracer detection from Stop1. (Mound and earthworks of Norman castle, built from sediments of pre-glacial Bytham River)
RB (tracer input)
Stop 5 Medwell's Quarry
Stop 6 Clipsham Quarry (in use for 2000 years; stone supplied for Houses of Parliament)
Rejoin A1 road at Stretton
N
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500000
510000
320000
330000

Excursion Itinerary – Karst Hydrogeology of the Lincolnshire Limestone

(KG@B15 – International Conference on Groundwater in Karst, 25 June 2015)

Map: OS Landranger 1:50,000 sheet 130, Grantham, Sleaford & Bourne.

DEPARTURE from Birmingham at 08.30. The drive to Colsterworth will take 2-3 hours depending on traffic conditions.

At **Colsterworth**, leave the A1 road and proceed west on the B676 (signposted Colsterworth, Stainby, or Melton Mowbray). Descend the hill into Colsterworth village and turn R (north) at the cross roads onto the B6403 into the main street. Proceed northwards.

> (Isaac Newton's birthplace is at Woolsthorpe Manor, along a side road to the west. (National Trust, open to the public – you can see the fabled apple tree *and* the cupboard where he did his optical experiments . http://www.nationaltrust.org.uk/woolsthorpe-manor/ for details.).

Do not rejoin the A1. Instead turn R (signposted B6403) onto a new road that crosses over the A1 on a bridge, to reach a T-junction. *Do not turn left for the A1.* Turn R (B6403, signposted Ancaster). After 1500 m turn R at a corner by factory buildings (SK 939 265), signposted Burton Coggles.

> Just before this turning the B6403 picks up the line of the Roman road Ermine Street which ran from London to Lincoln and York, much of it in a straight line along the Lincolnshire Limestone cuesta. Parts of the A1 road follow it but from here to Ancaster it is the B6403 that follows the Roman road).

Proceed 3 km along this road to Stop 1. Park either in the entry to a track on the left (SK 967 260) or in a tarmac lay-by on the left 100m before the railway bridge beyond Stop 1 (SK 971 260).

Stop 1: Easton Wood swallow-hole (SK 968 260). The Easton Wood stream can be seen sinking in a blind valley in the field south of the road. A short walk upstream brings one to a gauging station, installed in the 1970s by the (then) Anglian Water Authority to monitor point recharge to the aquifer. In very high flow the sinks at the end of the blind valley cannot take the full flow (up to 0.3 $m^3.s^{-1}$) and a small lake forms. Very occasionally this overflows across the road. Tracers from Easton Wood were detected in boreholes and springs between Swayfield (SK 998 233) and Castle Bytham (Stop 7), defining a NW-SE plume of tracer transport and rapid groundwater flow. In 1994 a second tracer pathway was proved from this site to the borehole at Elsthorpe (TF 056 249) on the edge of the confined zone.

Continue on the same road eastwards, beneath the railway arch and through Burton Coggles village, forking L by the church. Park on the verge just before the T-junction where the lane joins the B1176. (*Do not park on the B1176 itself. This road carries fast traffic and care is needed walking along it to the next site.*)

Stop 2: The West Glen at Burton Coggles sinks (SK 988 260). Walk north along the B1176 and across the river West Glen. A gauging station can be seen on the left. The upstream catchment area is almost 30 km^2. Turn into the field on the right of the road, on the north bank of the river.

In this field a small stream flows from the north and sinks in a fenced sink hole at the foot of the north slope of the valley side. To the south (right), follow the river bank to fenced and overgrown enclosures. These are the sinks of the West Glen. In the 1970s most of the river disappeared underground here, and the channel was diverted to place the sinks in a backwater in hope that they might silt up. This seems to have worked.

In the 1970s Booker undertook a staged series of tracer injections here, commencing only after experiments at sites west of the West Glen had all failed to produce any tracer detections to the east of the river. The Anglian Water Authority were understandably nervous that dyes introduced here might colour their source at Bourne, so they sponsored the use of radioactive ^{82}Br in a collaborative experiment with the Water Research Laboratory at Medmenham (now WRC Ltd). ^{82}Br emits an energetic gamma with a radioactive half-life of 35 hours, producing a stable daughter. Thus it is a 'self-cleansing' tracer which can be followed for 1 to 10 days, depending on the amount used and the dilutions encountered.

An initial injection of 10 mCi produced negative results, so a second injection of 340 mCi was made. This seemed also to produce negative results, but close inspection of the data subsequently showed a slight but significant increase in count rates at Elsthorpe borehole, 7 km to the east, for several days after injection. The low signal from ^{82}Br persuaded the water quality personnel in AWA that it was safe to let Booker inject fluorescent dye into the sinks, so an injection of 20 kg of Fluorescein LT was made. This gave an excellent breakthrough curve at Elsthorpe (Fig.11), confirming the second ^{82}Br result, but was undetected at Bourne.

Journey to Bourne

Return to the vehicles. From here the route follows approximately the path of the rapid groundwater flow to the Elsthorpe borehole, crossing the river East Glen via a ford. The Elsthorpe borehole is at TF 056 249, about 1500 m beyond the ford, but as there is no parking we shall not visit it. (There isn't a great deal to see, anyway).From the Burton Coggles parking place, turn R (south) to the junction of the B1176 and A151. Turn L (east), cross the channel of the West Glen and take the first turning R into Corby Glen (signposted Irnham). In Irnham follow the road through a L-R dog-leg turn just beyond the church and on leaving the village take a lane on the L (signposted Bulby) at TF 030 270. Follow this past two sharp bends, first R then L, to a ford through the River East Glen, then to Bulby. In the village turn R at a T-junction, onto the road running down-valley towards Elsthorpe. The Elsthorpe borehole is located in the verge 1200 m from Bulby, where the river channel and road are at their closest.

Beyond the borehole, but before the hamlet of Elsthorpe is reached, turn L at TF 057 244, up a hill past Elsthorpe Grange Farm. Tracer injected at Elsthorpe borehole was detected in a farm borehole here. Continue along the lane. The view ahead from the crest of the hill (60 m asl) looks over the Fenland basin where the land is close to (or in some places below) sea level. The eastern edge of the 'Jurassic upland' is a fairly abrupt scarp.

> In their natural state the Fens were a huge area of marshland and swamp. The land was drained from the 1600s onwards, initially by Dutch engineers. The Lincolnshire Limestone aquifer dips eastwards beneath them at depths of 50 m and more, but gradually thins eastwards. The groundwater in that part of the aquifer is chemically reducing, has high chloride content, and a radiocarbon content indicating ages of 10 – 26 ka b.p..

Continue down the hill through Stainfield (L-R dog-leg junction) to meet the A15 road at TF 094 253. Here the altitude is 24 m. Turn R and proceed south to Bourne. In Bourne follow North Road towards the town centre. To reach a parking place turn L off North Road into Harrington St, immediately R into Meadowgate and Hereward St, where there is a shoppers car park. There are public toilets here (but only two). [Alternative: continue past the shoppers' car park and turn left into Manning Road, then right where it crosses Recreation Road to reach Abbey Road, a principal street in Bourne. Turn R (west) and park on the left by Abbey Lawns gardens.]

Stop 3 & 4: Bourne Waterworks and Bourne Eau spring (TF 095 198).

We shall walk to these stops from the parked vehicles.

Bourne was the site of the first artesian well to be drilled in Britain, ca. 1795 by horsepower. Natural ground water heads would have been about 21 m asl (ca. 12 m above ground level) but pumping has reduced these to about 15-16 m. We shall view the site of the modern waterworks from the outside, then walk along Abbey Road to the crossroads at the town centre. Turn along South Street to reach the Memorial Gardens and Well Head Fields on the R (east) side of the street. The watercourses on the edge of the gardens are fed by the Bourne Eau spring, a circular pool surrounded by landscaped grounds, once the site of the medieval Bourne Castle.

The spring is artesian and fed by groundwater from the Lincolnshire Limestone. Tracer dyes from Elsthorpe were detected in the spring itself and in a overflowing borehole (now sealed and covered over) that lay on the embankment immediately east of the spring. No tracers were detected at the abstractions at Bourne Waterworks boreholes.

Time in Bourne is limited by the need to reach the next two stops within working hours. Please be back at the buses for prompt departure at 1400 h.

Journey to Clipsham

From Bourne take the A151 west, then turn L on a sharp bend at TF 080 199 (A6121 to Stamford). Follow this through Toft and across the valley of the East Glen. At the top of the hill on the other side turn R to Witham-on-the-Hill. (This is a very dangerous turning, hidden until one has almost reached it. Caution advised.) On passing through Witham, the woods on the R (south) conceal extensive former quarries where sand and gravel deposits of the pre-glacial 'Bytham River' were extracted. The top of the deposits is at altitude 55-60 m asl.

Continue down the hill into the West Glen valley, to a T-junction at Little Bytham. Turn R, then L after passing beneath the main London-Edinburgh railway line. In Little Bytham turn left at a T-junction onto the road to Castle Bytham.

Between Little Bytham and Castle Bytham the valley of the Tham (a tributary to the West Glen) is excavated into the deposits of the 'Bytham River'. There are several springs along it, where tracer from Easton Wood (Stop 1) was detected.

Continue to the cross roads on the edge of Castle Bytham (SK 992 178) and turn L (signposted Holywell). The road descends and crosses a dry valley. 2 km from the cross roads the road crosses an ornamental lake that is fed by Holywell springs. A tracer test from Rodbecks swallow hole, 3 km up the dry valley just passed, had a first arrival velocity of 10,000 m,day^{-1} but tracer persisted in the spring for 200 days. (Figs. 4, 10, 11).

Just past the Holywell lake turn R and then R again on a hill, into the road signposted to Clipsham (TF 005 158). After almost 2 km a lane on the R leads to Medwell's Quarry. A board (not easily seen) announces 'Stamford Stone Company'.

The Lincolnshire Limestone has been used for building stone since Roman times. The more massive calcarenites and oolites not only make excellent masonry but are easily carved into statues, traceries etc. Different localities have given rise to specific names for local stone. Clipsham Stone has been quarried in this valley since the Roman period. Many medieval churches are built from it, as are many of the older colleges in Cambridge and the Houses of Parliament in London. Medwells Quarry (Stop 5) is about 100 years old, while the Clipsham Quarry (Stop 6) has been in operation for much longer. In both quarries masonry stone is won without the use of explosives, being split by wedge and feather techniques. This allows geological visitors to see the jointing and karst features in a natural state, without blast damage.

Web addresses: Stamford Stone Company : www.stamfordstone.co.uk

Clipsham Stone : www.clipshamstone.co.uk

Stop 5: Medwells Quarry, Clipsham (SK 986 159). We shall be met here by the owner, George Wilson of Stamford Stone Company.

This quarry does not use explosives at all, but works stone by removing blocks and splitting them by wedge and feather techniques, then sawing into slabs. Sawn masonry blocks are the main product, but some stone is sold in larger blocks. Unlike the next site, Medwells Quarry has 'blue-heart' stone – blocks with a core of blue limestone surrounded by buff stone. The colour change is due to the oxidation state of iron present as a trace metal, and the preservation of the blue, reduced form in the hearts of the blocks suggests that there has been little movement of oxygenated water into them.

The area on the west (left) side of the quarry is now partly filled with reject material and overburden. This area was being worked by hand in the 1970s, and large fissures were exposed. Other solutional features were small tubules aligned along major bedding surfaces. Poorly-formed scallops were present on the walls of one or two fissures, suggesting that groundwater flow was turbulent when the site was below a former level of the water table. (See photos and field sketch, Fig.12).

The new extension of the quarry shows fissures up to 100 mm wide in the floor (possibly covered by clay or dust). George Wilson has suggested that widened fissures are a sign of large blocks of stone – a desirable find. There may be a tendency for fissures to develop better in massive calcarenites and oolites than in thinner or more rubbley beds. If so, this might explain the large spread of flow velocities in the aquifer, as fissure networks would only occupy a part of the rock volume.

The geological succession above the aquifer is easily seen, with the cross-bedded calcarenites of the Lincolnshire Limestone overlain by the lowest two members of the Great Oolite Group, the Upper Estuarine Series (dark clay) and a thin limestone (the Great Oolite limestone, here not 'great' at all). Glacial till caps the succession (Oadby Till). The Upper Estuarine clays act as the confining layer in the Confined Zone east of the East Glen valley.

Stop 6: Clipsham Quarry (SK 967 154).

Rejoin the public road, and turn R (east). Continue to T-junction. Turn L into Clipsham. On leaving the village, turn L into lane to Clipsham Quarry. Pass farm and turn L through gate onto haul road. Follow this to the top of a ramp into the quarry floor. Drive down the ramp to a weighbridge on the quarry floor.
We shall be met here by the quarry owner, Sue Thomas of Clipsham Stone.

Clipsham Quarry has produced masonry stone since Roman times. Today the quarry has one face worked with conventional modern methods using explosives to produce aggregate and 'clipped' walling blocks. In another area, thick beds of calcarenite are worked by using a back-hoe to loosen joint-bounded blocks which are lifted from a low working face, stored and cut for masonry or slab stone. While blasting creates new fractures, the machine-dug method of working preserved the original fracture pattern more or less intact. Small karst features should be visible in the machjine-dug area.

Return to cars and retrace the approach route to Clipsham village. Continue east on the road towards Castle Bytham. On reaching the cross roads (SK 992 178) turn L. In the village centre, fork R down a hill, just before a sharp left-hand bend. This descends to a triangular green. Park here.

Stop 7: Castle Bytham springs (SK 989 186).

The River Tham flows in the channel alongside the road. On the other side (west) is a spring-fed pond that discharges into the Tham via a pipe beneath the road, A sign to Water Lane is a giveaway – there are many small springs here, and an antique public pump – restored but sadly not working. Walk up the lane and see how many springs can be found. The number fluctuates with the state of the water table, as the springs are of the 'water table intersection' type.   Tracer from Easton Wood swallow-hole (Stop 1) was transported to this point, as well as several other springs further east along the River Tham.

Castle Bytham is right on the course of the pre-glacial 'Bytham River', the modern valley having been in part excavated along the line of a west-east palaeo-valley that carried the river through the Jurassic upland (see Fig.5 of Field Trip Guide).

The castle can be seen from the field gate by the River Tham. Unfortunately there is no access to the earthworks themselves, and visitors are asked to remain on the path that skirts them and climbs up the hill on their north-west side. A notice explains the castle's history.

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