THE ORIGIN OF THE SILICA SAND POCKETS IN THE DERBYSHIRE LIMESTONE

by

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Summary

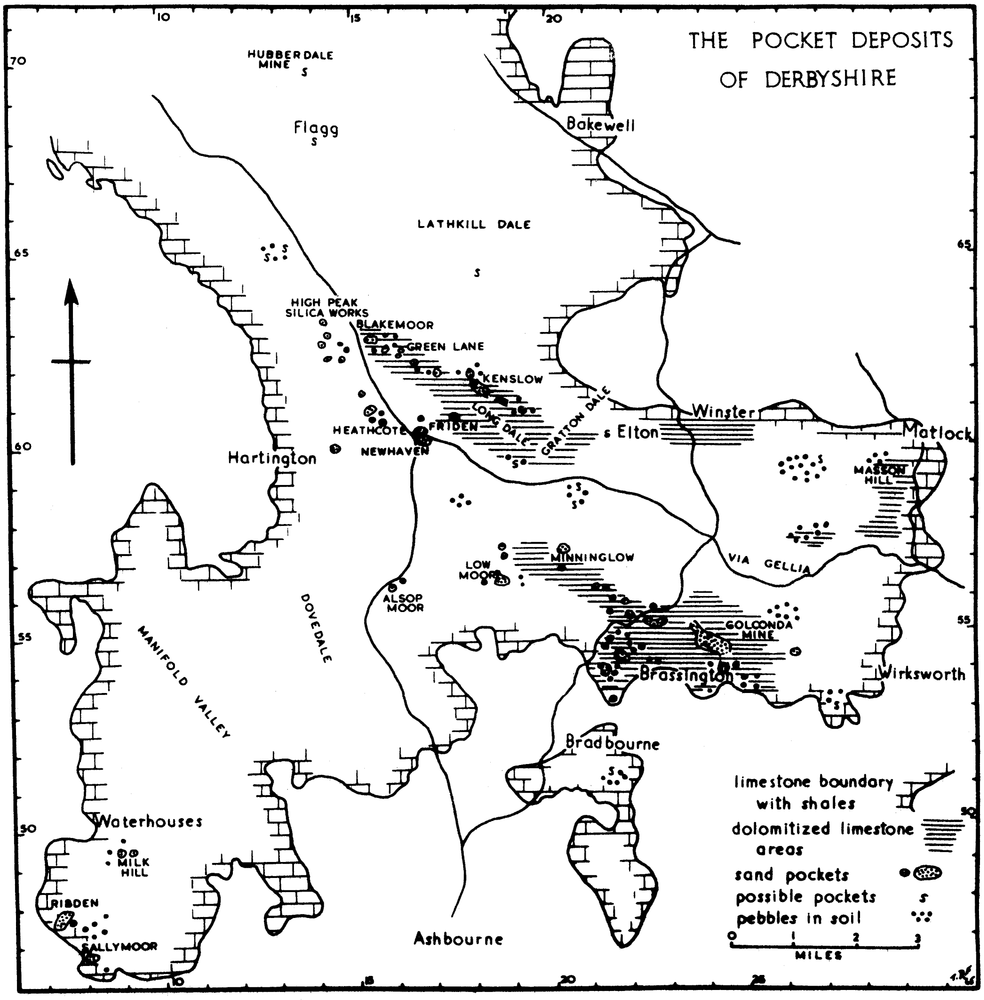
The silica sand and clay-filled solution pockets in the Derbyshire limestone are shown to have a wider distribution than previously noted. Evidence is presented to confirm the hypothesis that the pockets originated by solution subsidence of cave systems; and the existence of related sand-filled caves in various stages of collapse is demonstrated. The distribution of both pockets and caves is shown to be largely controlled by the position of the base of the dolomitized zone of the Carboniferous Limestone; they are shown to post-date mineralization, which is thought to be of late Triassic age. The emplacement of the sands is both contemporary with and post-collapse —but pre-glacial. The sands, though largely composed of Triassic material, are thought to have been deposited in late Tertiary times as a fluvial fan in front of the receding Triassic escarpment.

Comparisons are made with similar deposits elsewhere.

Introduction

The presence of deep hollows on the Derbyshire Carboniferous Limestone plateau, filled with silica sands and clays (often known as "Pocket Deposits"), has given rise to considerable speculation about their possible origin, as either sink-holes or collapsed caverns, and about the provenance and age of the sands. Clay was worked from these deposits for pottery in the late 18th century (Pilkington, 1789, p. 162). The deposits were briefly described by Green *et al.* (1887, p. 163), and by Howe (1896, 1920), Scott (1927), Boswell (1918), and Kent (1957), but the most comprehensive account is a series of private publications by Yorke (1954-61). A summary account has recently appeared in Sylvester-Bradley & Ford (1968). Recent work by the authors in the Golconda Caverns at Brassington has revealed new evidence, not only on the problems of the pockets but also on the mineralization of the district. The latter has been discussed elsewhere (Ford and King, 1965); matters related to the pits themselves are discussed here. The word "pocket" is hereby used to designate a sand-filled hollow; and quarries within these are referred to as "pits".

Yorke has described many of the pockets and their fills in detail; he has discussed various theories about their origin and more particularly about the cover of glacial deposits and their downward intrusion under ice pressure. He concluded (1961, p. 22) that "Triassic


THE POCKET DEPOSITS OF DERBYSHIRE
HUBBERDALE MINE
Flagg
Bakewell
LATHKILL DALE
HIGH PEAK SILICA WORKS
BLAKEMOOR
GREEN LANE
KENSLOW
LONG DALE
GRATTON DALE
Winster
Elton
Matlock
HEATHCOTE
FRIDEN
NEWHAVEN
Hartington
MASSON HILL
VIA GELLIA
MINNINGLOW
LOW MOOR
ALSOP MOOR
DOVEDALE
MANIFOLD VALLEY
GOLCONDA MINE
Brassington
Wirksworth
Bradbourne
Waterhouses
MILK HILL
RIBDEN
SALLYMOOR
Ashbourne
limestone boundary with shales
dolomitized limestone areas
sand pockets
possible pockets
pebbles in soil
0 1 2 3
MILES
10
15
20
25
70
65
60
55
50

Text-Fig. 1

sediments were widely spread over the Dome, and that they were trapped in pre-existing limestone hollows, in part solution cavities, and in part great surface watercourses". This view is widely held and partly supported herein, but, as will be seen later, there are several points requiring further explanation. Kent (1957) concluded that the pockets originated as swallow holes on the edge of residual outliers of Upper Carboniferous shales during the denudation of the Southern Pennines in Triassic times, during which time contemporary Triassic sediments were washed in. Kent has argued also for intermittent solution-subsidence through Mesozoic and Tertiary times, with the Mio-Pliocene 1000-foot surface bevelling both the limestones and the pockets with their fills. Parts of Kent's hypothesis are also supported herein. Ford (1963) described the occurrence of dolomite tors in close geographic proximity to the sand pits and outlined the late Tertiary and Pleistocene history of alternating deep weathering and glaciation responsible for the production of tors. In particular it was noted that tor-like features are still present beneath the sands in places, but that the existing tors were probably exposed by being stripped of their weathering product during and since the Last Interglacial.

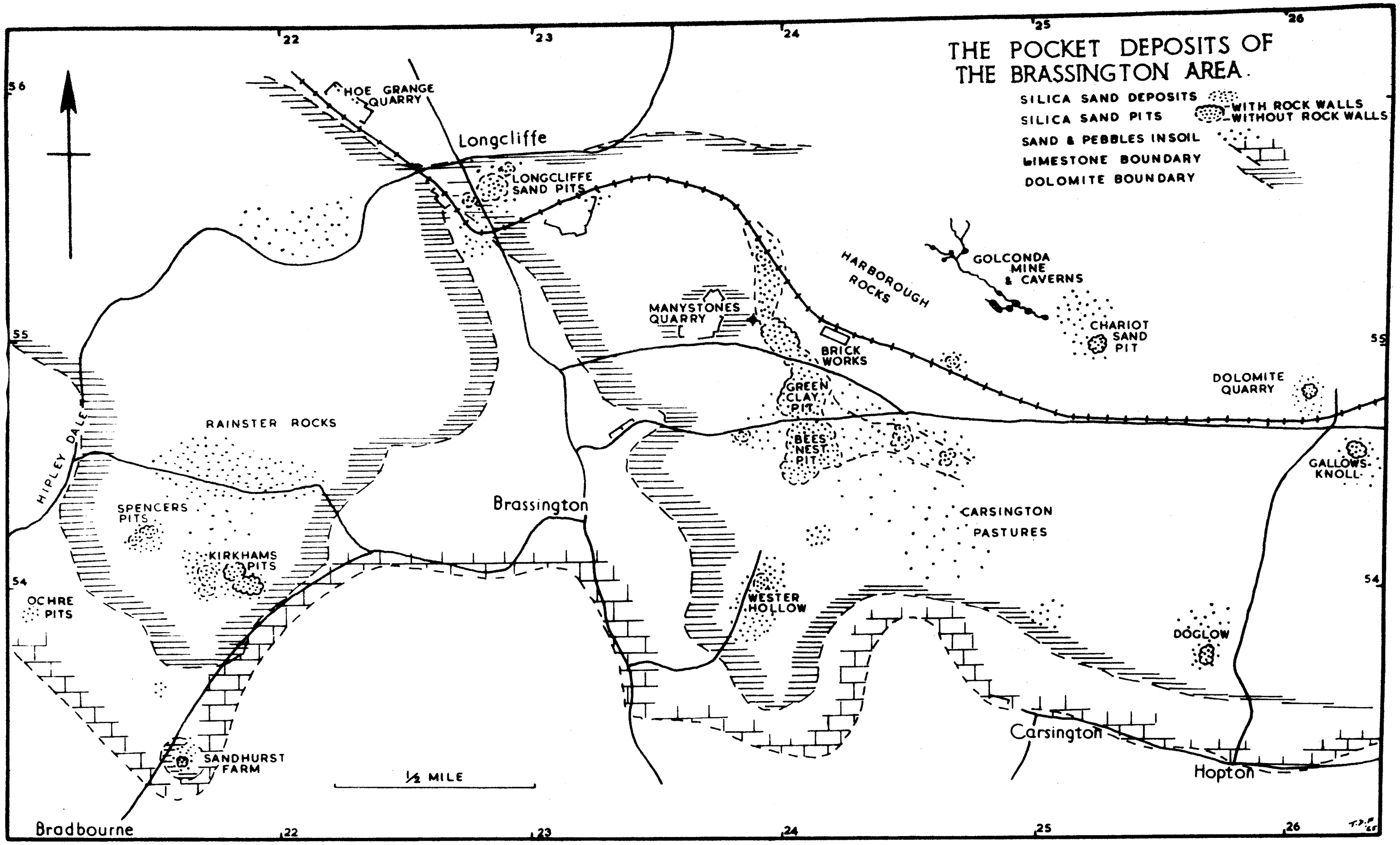
Several factors have been involved in the origin of the pockets and their fills and these will be discussed in turn, as only a full understanding of the interaction between several phenomena can explain the pockets. Of particular importance are dolomitization and its geographical relationship to unaltered limestone, the process of mineral emplacement in the dolomites and adjacent limestones, the provenance of the sands and the history of groundwater movement. In fact, these apparently simple pockets and their fills are but the surface expression of a long and complex geological history; it would be foolish to try to explain them without full appreciation of the implications of all parts of that history.

[NOTE: The greater part of this paper was written in 1964 in connection with a Field Demonstration to the Karst Symposium of the International Geographical Congress. Publication of the "Proceedings" of that Symposium has been indefinitely delayed, so the paper is presented here in a slightly modified form.]

The Pockets and Their Distribution

The distribution of the silica sand pockets is shown on the accompanying map (Text-Fig. 1). Most of the pockets occur along a N.W.-S.E. trend from near Brassington to Parsley Hay, a distance of about 10 miles, in a belt some 3 miles wide. Some pockets are, however, well to the southwest of this trend at Ribden (SK 078474) and near Waterhouses (SK 094492) in Staffordshire. Some other sandy occurrences lie well to the east of the trend, but as they have never been worked their nature is uncertain and they may not belong to the Pocket Deposits proper. These latter are at Hubberdale Mines, near Flagg (SK/137700): Calling Low, near Middleton-by-Youlgreave (SK/182645); and on the Old Moor, west of Castleton (SK/128812). Sandy deposits fill old solution caves at a number of localities on Masson Hill, near Matlock (e.g. SK/285591), but the sands there contain a high proportion of derived fragments of the adjacent rich galena-fluorite deposits, and thus differ in appearance from the sands in the usual pockets. Comparable sands to those of Masson Hill are also known in the open workings of the Royal Mine, Matlock Bath (SK/292579): near Tearsall Farm (SK/265600); and in the Elton-Winster district. The recent Geological Survey 6 inch map (Sheet SK 25 NE) also notes quartzite pebbles and sandy soil in a number of places on and around Masson Hill. Quartzite pebbles are also common near Haven Hill, Bradbourne (SK/215516).

A comparison of the accompanying map with that of Yorke (1954-1961) shows that, whilst he correctly recorded almost all the worked deposits from Brassington to Parsley Hay, he missed some outlying deposits, thus giving a partly false impression. In addition, trial holes and


THE POCKET DEPOSITS OF THE BRASSINGTON AREA.
SILICA SAND DEPOSITS
SILICA SAND PITS
WITH ROCK WALLS
WITHOUT ROCK WALLS
SAND & PEBBLES INSOIL
LIMESTONE BOUNDARY
DOLOMITE BOUNDARY
22
23
24
25
26
56
55
54
HOE GRANGE QUARRY
Longcliffe
LONGCLIFFE SAND PITS
MANYSTONES QUARRY
HARBOROUGH ROCKS
GOLCONDA MINE & CAVERNS
CHARIOT SAND PIT
BRICK WORKS
DOLOMITE QUARRY
GREEN CLAY PIT
BEES NEST PIT
GALLOWS-KNOLL
RAINSTER ROCKS
HIPLEY DALE
SPENCERS PITS
KIRKHAMS PITS
Brassington
CARSINGTON PASTURES
WESTER HOLLOW
DOGLOW
OCHRE PITS
SANDHURST FARM
½ MILE
Carsington
Hopton
Bradbourne
T.D.F. 65

Text-Fig. 2

borings by the various silica brick companies have shown that sands, too thin to be worked economically, spread beyond the confines of the pockets. Unfortunately many of the records of such holes are no longer available and a map of the full extent of the sands is not possible. In addition, farmers not uncommonly report sand having been found when they were erecting gate-posts etc.

The pockets are almost all at altitudes of 1000 to 1100 feet above sea level, but those in Western Hollow, Brassington (SK/239540) are at 930 feet, and that by Sandhurst Farm, Bradbourne (SK/215532) is at only 780 feet O.D. Spencer's and Kirkham's Pits at Brassington are at about 840 feet O.D., and the sand-filled caverns in the Golconda Mine (SK/249551) extend down to about 760 feet O.D. This seems to indicate that the alleged association with a 1000-foot erosion surface (Kent,1957) is incorrect, but,if it is borne in mind that the pockets are solution collapse features below a pre-existing surface, the 1000-feet association may still be correct.

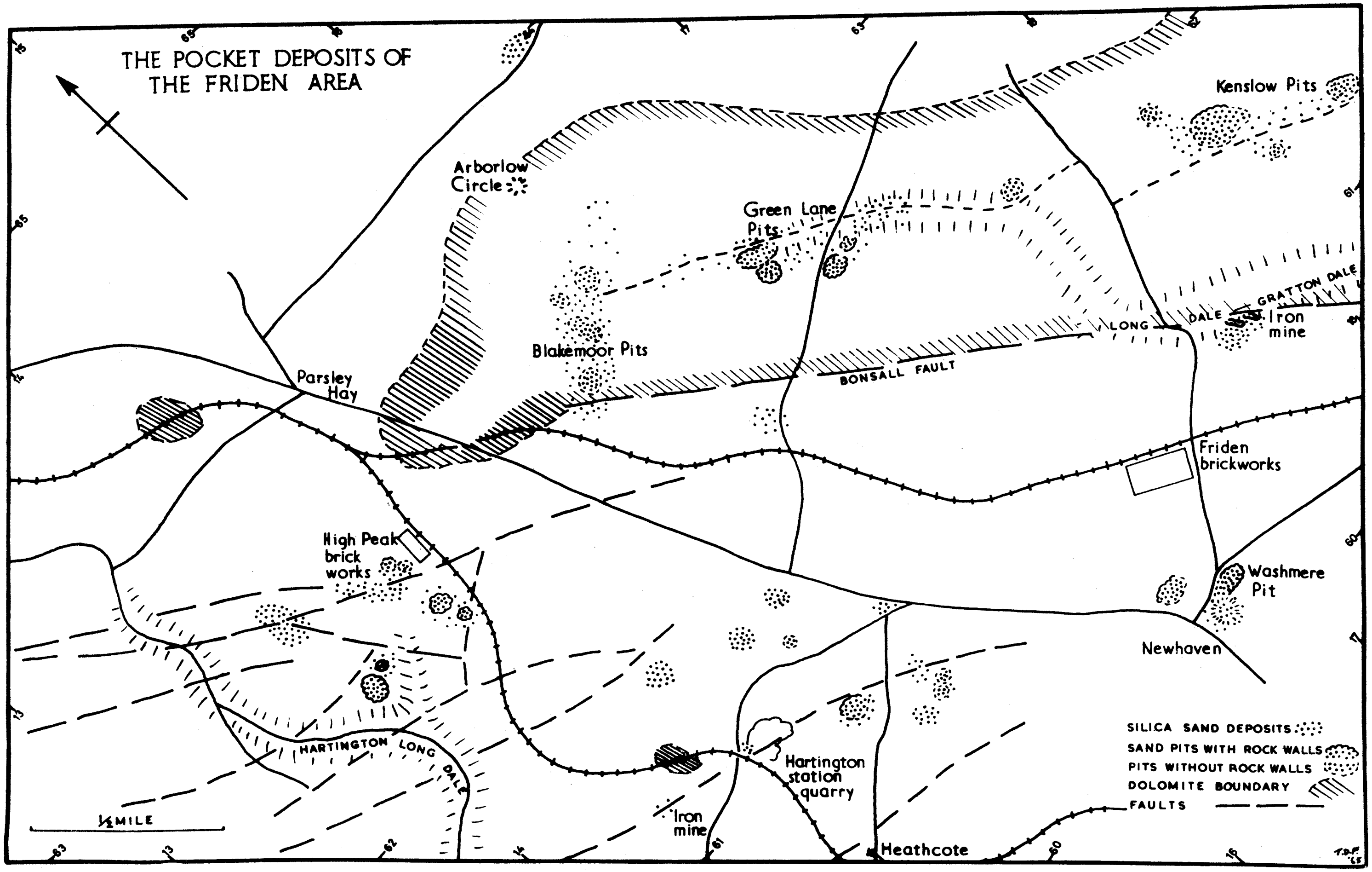
Pitty (1968) has argued that the so-called surface is not a well-preserved relict feature but an erosion surface, developed by differential solution as the cover of impermeable rocks was progressively breached. However, whilst Pitty's findings may partly explain some topographic features, his arguments do not take the full effects of the geological history into account and make little allowance for the glacial and periglacial modification of the landscape. Pitty's study did not cover the dolomitized area or the area with sand pockets.

The pockets show an apparent association, at first glance, with the dry valley system (Warwick, 1964), but closer inspection reveals that this association is fortuitous and that the pockets pre-date the dry valleys. At Long Dale, Hartington (SK/140625), a pocket on the plateau is separated by only a few yards of limestone from the dale, here incised 100 feet below the lip of the pocket. Similarly, one of the Green Lane pockets (SK/167624) has only just been by-passed by the incised dale, whilst another (SK/166626), in the floor of the dale, was only revealed by working and shows a sinuous pattern across the floor, with solid terminations both upstream and downstream. The map of the Brassington area (Text-Fig. 2) shows that some pockets occupy the floor of a shallow valley between Harborough Rocks and the hill to the west, whilst others are indiscriminately spread on hill tops or dale sides. The Low Moor pockets also occupy a valley floor (SK/188566), but working has shown that two extend into the hillsides and that, prior to working, there was no topographic expression of these.

At Blackwell (SK/2549), some 4 miles south-east of Brassington, a hill-top outlier of sand and gravel, of similar aspect to the sediments in the Pockets, was referred to by Clayton (1953) as outwash from the Berrocian (early Pleistocene) glaciation. Re-examination of the overgrown pits suggests that erratics from a veneer of drift have fallen down and contaminated the main body of sand and gravel, which is now thought to be of similar origin to the fills of the other pockets. It is here resting on Millstone Grit and no solution collapse phemomena are involved.

Dolomitization

Parsons (1922) has demonstrated that the process of dolomitization was subsequent to the deposition of the Carboniferous Limestone; from the relations of ore-bodies at Matlock and in the Golconda Mine, Brassington (Ford and King, 1965), it is seen to have been earlier than the introduction of the mineralizing solutions. Moorbath's isotopic dating of galenas from Derbyshire in 1962 suggests that the mineralization was very late Triassic or early Jurassic; and Ford (1968) has demonstrated the close relationship between some mineral deposits and the Triassic geology of the region. Thus dolomitization appears to have occurred during Permo-Triassic times, though Yorke suggested it may have been partly penecontemporaneous with limestone sedimentation.


THE POCKET DEPOSITS OF THE FRIDEN AREA
Arborlow Circle
Green Lane Pits
Blakemoor Pits
Kenslow Pits
GRATTON DALE
LONG DALE
Iron mine
BONSALL FAULT
Parsley Hay
Friden brickworks
High Peak brick works
Washmere Pit
Newhaven
HARTINGTON LONG DALE
Iron mine
Hartington station quarry
Heathcote
½ MILE
SILICA SAND DEPOSITS
SAND PITS WITH ROCK WALLS
PITS WITHOUT ROCK WALLS
DOLOMITE BOUNDARY
FAULTS
T.D.F. '65

Text-Fig. 3

Dunham (1952), Kent (1957) and Ford (1968) have suggested it was due to magnesian solutions infiltrating from a transgressive Permian Zechstein sea across the Southern Pennines, but, from the amount of dolomite in skerry-bands in the Keuper Marl, the process of dolomitization could have continued as the subsurface effect of magnesian hypersaline groundwaters beneath the Keuper evaporite lagoons.

The amount of dolomitization, i.e. the degree to which the dolomite molecule has replaced the calcite molecule, is highly variable and it appears from Parsons' figures never to have gone to completion. The dolomitized areas are mostly high ground but not necessarily the highest points (see Ford, 1963a). Dolomitization does not follow any particular stratigraphic horizons and beds from low in the D_1 subzone to high in the D_2 subzone are affected. The depth to the base of dolomitization can be plotted in a few deeper valleys, but under the plateau it is generally not known. As a result of the investigations of the area around the Golconda Mine, dolomitization is now known to penetrate to a depth of 500 feet below Harborough Rocks, i.e. down to about 700 feet O.D. The contact with unaffected limestone undulates considerably and is now known to plunge 120 feet almost vertically within the Golconda Mine. In Manystones Quarry (SK/236551) the contact is at about 1100 feet O.D.; it can be seen to undulate by as much as 60 feet. Such undulations led Parsons to map apparent faulted junctions between dolomite and limestone, but some such junctions in Manystones Quarry are clearly not along faults. "Islands" of unaltered limestone occur completely surrounded by dolomite; these are often either reef facies limestones, in which the lack of bedding has apparently excluded the magnesian solutions, or patches of bedded limestones protected by local clay beds. Dolomitization has often followed joints in the limestone downwards, with the abundance of dolomite rhombs in the limestone rapidly falling off either side (though later mineralization may obscure this.) In Manystones Quarry it may also be seen that dolomitized joints have been etched out by later groundwater movement to form small caverns.

In short, then, it may be said that the base of dolomitization is an undulating zone transgressing the strata, with downward plunges along major joints. Since the dolomite is much more porous that the unaltered limestone (Parsons gives porosities of up to 10% for the former and "negligible" for the latter), ground waters (and mineralizing solutions) can move through it much more readily; and evidence from the Golconda Mine ore-bodies shows that the base of the zone of dolomitization is a preferred path for such movement, particularly in the hollows of the undulating contact. Ground-water solution at this contact resulted in numerous small caverns prior to mineralization; since solution preferentially removed calcite from the dolomitized zone, dolomite crystal grains were released to accumulate as a sediment on the cavern floors (Ford and King, 1965).

Mineralization

The mineral-depositing solutions are generally thought to be of deep-seated hydrothermal origin (see Ford, 1961, for reviews of concepts), rising via fissures to form rake-veins and locally spreading out under impervious "Toadstones" or shales to form pipes and flats (Ford, 1968). The deposits of the Golconda Mine clearly show that the solutions also travelled outwards along the basal dolomite-limestone contact, and that, as a result, the small caverns were filled in with layers of precipitated galena, baryte and derived dolomite crystal "sand" (Ford and King, 1965). The early phases of mineralization appear to have resulted in further decalcification of the dolomitized zone, with collapse of joint blocks. This has resulted in breccias of ores and dolomite partly or completely filling small caverns. Subsequently ground-waters deposited calcite to cement some of these breccias, but later phases of decalcification have resulted in further collapse of dolomite joint blocks.

Late stages of mineralization have produced carbonates and other oxidized minerals replacing the early sulphides, thus indicating a change in the environment of the mineral solutions from reducing to oxidizing.

Hydrology

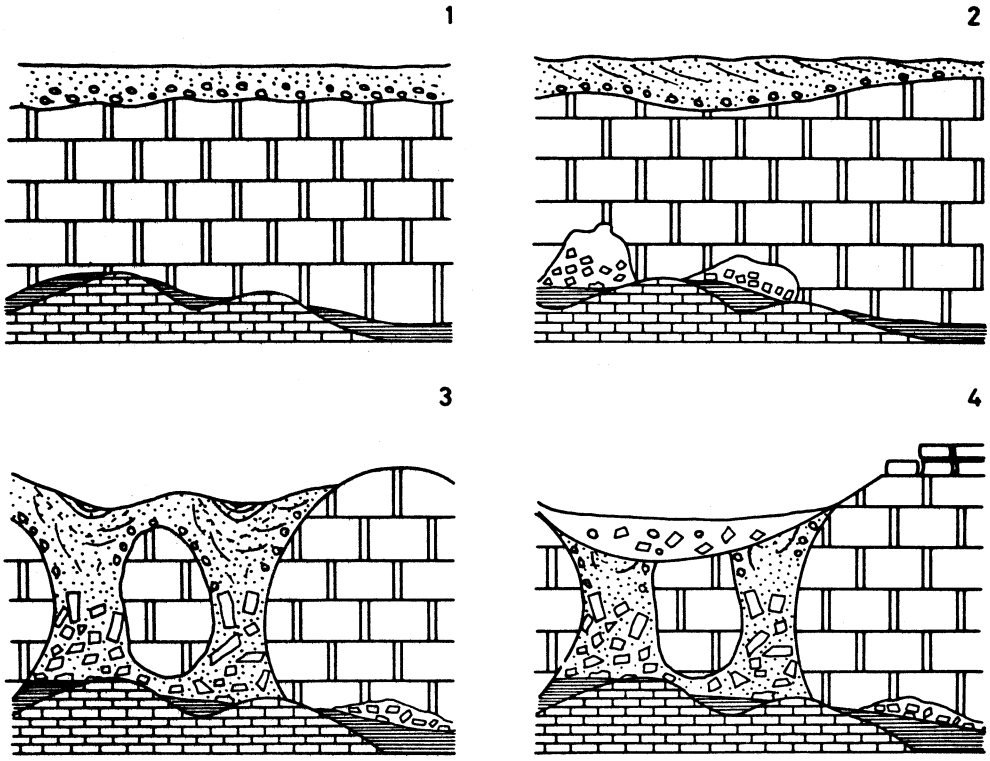
It will be evident from the above that at least three hydrological phases have already been passed through - dolomitization, local cavernization, and mineralization (with its subphases of fill, brecciation and collapse). Together these phases provided an irregular network of cavities, with or without mineral fill and collapsed joint blocks. These are clearly visible and spread throughout the area of the Golconda Mine workings (about a quarter of a square mile) and old mining records indicate that the network, though perhaps less rich in minerals, is present under much of the Brassington area. Though less obvious, the same type of network is believed to be present under much of the Gratton-Long Dale area [e.g. Mouldridge Mine (SK/194596)] and around Masson Hill at Matlock, though the presence of "toadstone" lavas at the latter has obscured the picture, and much of the evidence has been removed by mining. The hydrological relationship of the mineral deposits has been discussed by Ford (1968).

It is evident that, through the greater part of the dolomitized area, there is a network of cavities at or near the base of the dolomitized zone and thus, at any subsequent time, these must have been the preferred routes for groundwater movement. Much of such movement would no doubt have been slow, deep phreatic flow, but, with the 180 million years or so since the Triassic, this could accomplish a considerable amount of solution. Post-mineralization solution caverns up to 300 feet long are present in the Golconda Mine; and mining tradition indicates that they are widespread through the dolomitized areas. Deep solution such as this was accompanied by continued collapse - as can be seen in the Golconda Mine - and there is little doubt that some of the collapses worked their way through to the surface, to form the present sand pockets. Such collapses would of course provide the easiest routes for the percolation downwards of rainwater, with consequent modification of the pocket walls. One collapse has actually been seen in action at Spencer's Pit near Brassington. A heavy rainstorm flooded the excavation to a depth of several feet, but after a "popping noise", all the standing water and some sand drained away into a hole in the dolomite wall (which subsequently collapsed.) Hipley Dale, nearby, has traditions of a strong spring bursting forth at intervals of many years, which could come from the area of Spencer's Pit.

In view of the boulder clay cover of the sand fills and the later Pleistocene draining of the dolomitized zones by incisiion of the main Derbyshire Dales, it appears that deep phreatic solution was probably active until well into the Pleistocene Period; thus the sands must have been deposited in the pockets before the onset of Pleistocene Glaciation.

The Silica Sand Fills

The composition of the sands has been dealt with by various writers, and need only be summarized here (see Howe, 1920; Scott, 1927; Yorke, 1954-61). Some pocket fills have gravel-free sand only, some have bands of coarse gravel (up to 6 inch pebbles), whilst others have thick light grey clay beds. Rounded quartz grains are common and were probably derived from Triassic sandstones, with some additions from the Millstone Grit. The rounded pebbles include quartzites closely similar to those in the Bunter, though with the colouring bleached, and vein quartz, occasionally tourmaline-rich. Unpublished statistical work by D.B. Thompson has suggested that these could have been derived from the Lower Keuper Sandstones, as well as from the Bunter. Coal Measure sandstones and gainsters also occur as rounded pebbles; and a few Lower Carboniferous chert pebbles have been found, though these are usually less well rounded. Other pebbles include jaspers; various igneous rocks such as granites, microgranites, rhyolites; quartz conglomerates;



Text-Fig. 4

1. Triassic: Bunter Pebble Beds rest on dolomitized Carboniferous Limestone with unaltered limestone beneath. Solution cavities along the contact of dolomitized and unaltered limestone are filled with layered galena-baryte deposits.

2. Tertiary: The Bunter escarpment has receded from the Carboniferous Limestone leaving fluvial fans of Tertiary clays, sands and gravel resting on the dolomitized limestone. Increased ground-water movement has led to solution of the residual calcite in the dolomitized limestone and thus to cavern collapse in 'favourable' areas.

3. Late Tertiary: Continued collapse of the cavern roofs has allowed the Tertiary sand and gravel cover to sag into the "Pockets". Ponds in the tops of the sags receive plant debris from surrounding heath-lands in addition to aquatic vegetation.

4. Pleistocene: Glacial scour removes most of the remaining sand and gravel cover, leaving only the "Pocket Deposits", in the solution collapse hollows. Till lies across both Pockets and adjacent wall rocks. In late Pleistocene times dolomite hills are weathered into tors.

quartz vein breccias; and green and black slates.

Current-bedding and shallow channelling can be seen in some pocket-fills; their character suggests a fluvial environment of sedimentation.

A kaolinite pellicle is present round the quartz grains and serves to bind the sand in refractory brick manufacture. It may have been derived from the former cover of Triassic marls, but could also have come from the breakdown of felspar grains in the Millstone Grit. Alteration of the kaolinite pellicle has locally produced halloysite deposits (Ford, 1963b). Leaching subsequent to deposition has removed iron and manganese oxides from much of the sands; these oxides have been redeposited in some of the sand-filled caverns below or against the dolomite walls of the pockets, e.g. Kirkham's Pits, Brassington. Elsewhere baryte has been deposited at a late stage in the sands, as in Kenslow Pit at Friden; in sand-baryte rosettes associated with limonite boxstones at Spencer's Pit, Brassington; and in open cavities, as at Arborlow and Masson Hill (Ford and Sarjeant, 1964). Detrital baryte breccias occur as residual breccias or alluvial lenses at or near the base of the sand fills in the caverns of the Golconda Mine. White lead ore (cerussite) is said to have been worked from several pits (Green et al., 1887), including Green Clay Pit, Brassington; Washmere Pit, Friden; and Wester Hollow, but no evidence of this has been found in present day exposures. The cerussite probably resulted from the oxidation of galena veins in the adjacent limestones.

The sands of a few pockets are very sporadically cemented to form sandstones. One bed about a foot thick in Bees Nest Pit is a crumbly sandstone; but in Blakemore Pit, Friden, and in Low Moor Pit, scattered blocks of sandstone resembling the sarsens of Southern England may still be found.

Thus, whilst the sand fills are dominantly of Triassic material, they also include a few later contributions, and have suffered some later mineral changes. Yorke noted the absence of angular chert, limestone and dolomite gravels from the pocket-fills, in contrast to their wide distribution on the surrounding plateau and in the glacial drift cover. The early attempts to fit the sands and clays into a standard Triassic stratigraphic sequence (e.g. Boswell, 1918) cannot be upheld; a comparison with the Tertiary sands and clays of the East Dorset and West Hampshire areas, which also include derived Triassic material, seems possible. This comparison is further supported by the occurrence in Belgium of sand-and-clay filled solution pockets in the Carboniferous Limestone, clearly related to a Tertiary peneplain, and with derived Lower Cretaceous material rather than Trias in the fills (Calembert, 1954).

Since the sands can be shown to cover in part a dolomite tor landscape near Brassington, it seems that some pockets were already open to the surface when the sands were derived from surrounding Triassic outliers, whilst, elsewhere, continuing solution beneath a Tertiary sand cover has allowed collapse. Such open pockets and tors indicate a low water-table, which in turn suggests at least some incision of major valleys below the 1,000 feet erosion surface.

Some of the sand pockets have been recorded, by Yorke and others, as occurring in unaltered limestone. As many of these as are still accessible have been re-examined, and it has been found that, though the walls are dominantly limestone, the joints often show dolomitization; such pits are sometimes on or close to faults, where strong jointing may be expected. From this it may be deduced that the reason for the siting of such pits was that they represent a local downward penetration of dolomitization. This may be seen again in the Golconda Mine, where the lowest 50 feet or so of the Shaft Cavern have walls of limestone but show etched-out dolomitized joints.

The sand-fills do not generally exhibit clear bedding structures owing to their homogeneity, but, where bedding can be seen, the fill structure falls into one of three categories:

(a) undisturbed horizontal bedding, showing at the most a little sagging owing to compaction.

(b) highly disturbed bedding due to repeated subsidence collapse, sometimes with inward dips from all sides giving a funnel-shaped appearance.

(c) disturbance in the upper parts of the sand owing to downward glacial intrusion or to cryoturbation. Slickensided masses of red clay appear in many pits, and are similar to slickensided masses in the Golconda Mine where the pressure has obviously been due to roof subsidence. In the open pits the cause is thought to be the weight of overlying ice,

A single pit may show all three of the above in different parts, or more commonly (b) and (c) only. No fans of broken-down wall dolomite have been seen in the pits showing (a) above, indicating that the pits were complete entities and were then filled. In the others detached blocks may be found at times in the sand close to the walls, due to limited subsidence as in (b) above. The sand-filled caverns in the Golconda however, frequently show alluvial dolomite and baryte breccias set in sand, apparently at the base of pocket-cum-cavern systems. Quartz pebble bands frequently show "wash-out" features in any of the above categories.

The highest sub-till fills of two pits consist of dark blue grey clay with plant remains. At both Kenslow Pit, Friden, and Bees Nest Pit, Brassington, this grey clay forms the core of a synclinal sag of the fill into the solution hollows, so that it appears to be a direct continuation of the sedimentation which covered the area. No unconformity can be detected beneath the plant-bearing clay, so that any palaeobotanical age established for the plant remains, should at least give a minimum age for the sands and almost certainly indicate the age of the sands themselves. Boulter & Chaloner (in press) have obtained remains of nearly 30 species of plants, from which they deduce a probable Pliocene age. The ecology of the plants suggests accumulation in ponds surrounded by heath land; from this it may be deduced that some sagging of the fills into the solution hollows had already started by Pliocene times, but that much of the surrounding area was covered by sandy heathland and thus little of the limestone was exposed. The plants recorded include Sequoia or Taxodium wood, sphagnum, pine, willow, heathers, Calluna, and Lycopodium. Another plant bearing clay locality was recorded by Howe (1896) at Minninglow Pit, but nothing is exposed now.

Excavations for the foundations of a magnesium factory at Hopton (Early & Dyer, 1964) have revealed a series of small clay and sand deposits, in solution cavities averaging 20 feet in diameter and up to 40 feet deep. Some of these were found to have brown plastic clays rather than the more usual white sands and clays. Similar brown clays have been seen in workings at Kirkham's Pits west of Brassington, and in the Bees Nest Pit, near Harborough Rocks. In both these cases, the brown clay appeared to lie on top of the white sands and also showed fine lamination, suggestive of rhythmic deposition in a pond overlying the sand-deposits in pre-glacial times. Glacial disturbance and compaction have allowed the brown clay to sag into the white sands.

Pressure-pitting of the under-surfaces of rounded Coal Measure sandstone pebbles (analogous to the pitting of quartzite pebbles in the Bunter) has been observed in situ in the Blackwall pits, suggesting that no great thickness of overlying sediments (and ice?) is necessary to produce this phenomenon in less indurated rocks.

The Pockets in Relation to Glacial Deposits

This topic has been covered by Yorke (1954-61) with numerous illustrations; little need therefore be said except to summarize. Many of the pockets show a cover of 10 feet or so of glacial till, composed of limestone, dolomite and chert fragments in a brownish clay matrix. A few far-travelled erratics are present, chiefly from north-west England. The till also encloses blocks up to several feet across of Namurian Shale brought from the surrounding Millstone Grit country, presumably in a hard frozen state. Patches of chert gravel are also found in the till; they are believed to be relics of a former widespread cover of chert gravel on the limestone plateau, analogous to the Clay-with-Flints of the Chalk downs. Such patches of gravel again appear to have travelled as frozen blocks. Large dolomite blocks are present in tills downstream from the tors of Harborough Rocks.

Loosely cemented limestone scree overlies the sands of one Low Moor Pocket (SK/187566), in a position comparable to the cemented screes of the Manifold Valley described by Prentice and Morris (1959). At the top of these sands at Low Moor, there are several glacial "downward intrusions" of blocks of Namurian Shale, forming the only surviving relics of a till cover high on the sides of what is now a dry valley. Otherwise no pocket in a dry valley has been seen to have a cover of till. Thus it may be deduced that most dry valley incision post-dates the last spread of glacial till. Warwick (1964) has argued that the pattern of dry valleys suggests superimposition in pre-Pleistocene times from a former Tertiary cover.

Where glacial till rests on the sands of the pockets, there are numerous erosional features attributable to ice pressure, so that wedges of till extend into the sand [the "downward intrusions" of Yorke (1954-61)] and balls of sand are enclosed in till. Once below this disturbed zone, no pocket has yet been found to show evidence of glacial action or deposits. Several tills appear to be present at Kenslow Pit (SK/182617) and Green Clay Pit (SK/240548), but the detailed history has not been studied. The brown till of the Bees Nest Pit at Brassington sometimes shows strong lamination and locally has either very sparse pebbles or none at all, suggesting that at least some of the till may have been deposited in sub-glacial waters.

The Silica Sand Pockets in Relation to Faulting

It has often been hinted that the pockets mark the position of faults; for example, Kellaway (1964) has referred to "a NW-SE trending fault and fissure belt associated with piped masses of sand silt and pebbles in .... Derbyshire ... wholly or in part of Tertiary age". An unpublished report by H. Milner has also raised the possibility of the pockets being aligned on three parallel NW-SE faults running from Friden to Brassington. Field evidence to support these hypotheses is inconclusive, however. Those pockets which have sufficient of their walls exposed have been examined thoroughly; no undoubted evidence of faulting has been seen, though the lack of stratigraphical marker horizons in the limestone makes faulting difficult to detect. Zones of fractured rock are present in the walls of several pockets (e.g. those south of the High Peak Silica works), but they suggest solution collapse rather than faulting, since the bedding appears to match on either side. Pockets now obscured, but which were shown on Yorke's photographs (e.g. the Green Lane gorge pocket, north of Friden at SK/126626) similarly show little evidence of faulting. Some pockets in the Hartington area do, however, lie close to the line of ESE-WNW faults mapped by Sadler and Wyatt (1966). Unpublished resistivity work by Dr. C.D.V. Wilson, in the area around the High Peak Silica works, supports Dr. Sadler's mapping in part by showing linear trends through some pockets, whilst others occur isolated away from these trends. A pocket at the junction of two trends has a zone of fractured rock across it but no clear evidence

Fig. 1. Three of the Pocket Deposits near the High Peak Silica Brick works, Parsley Hay, Derbyshire. (SK/145628).
The middle and further pits show a thin cover of till.

Fig. 2. The Bees Nest Pit, Harborough Rocks, Brassington (SK/241545).
White sands are overlaid by till in the background. In the left centre coloured sands and clays dip steeply towards the observer, and the slumped clay in the left foreground is the plant-bearing stratum.

of faulting, though solution and collapse may have obscured this. The pockets in the Friden area lie close to the line of the NW-SE Bonsall Fault as mapped by Shirley (1958); but they are not on the line of the fault itself, though they may be on subsidiary fractures. The Kenslow Pockets unfortunately do not expose the solid walls; the Green Lane Pits, in contrast, are well exposed and show well-developed jointing but not faulting. The workings of the Mouldridge Mine (SK/194595), close to the line of the Bonsall Fault, show some small sand-filled solution cavities comparable with those of the Golconda Mine, in an area of mineralized solution cavities and flats close to the base of the dolomitized zone; but no faulting has been recognized in the mine itself.

The pockets in the Brassington area are not on any recognized faults, though the Harborough deposits are elongate in a NW-SE direction parallel to the main jointing of the area and to the many small mineral veins. The sand-filled caverns of the Golconda Mine similarly show a NW-SE trend, but this is clearly related to the effect of jointing on the undulations in the base of the dolomitized zone.

At Ribden, Staffordshire, some of the pockets are close to, but not on, faults (see Ludford's map, 1951).

A number of apparent sand deposits, inadequately exposed through not having been worked, are well away from the alleged NW-SE trend of faultings. These include Calling Low near Middleton-by-Youlgreave (SK/182646), Hubberdale Mines near Flagg (SK/1469) and Alsop Moor limeworks (SK/158564).

Both the Bonsall fault and the faults near the High Peak Silica works are post-mineralization fractures; Shirley (1958) noted that the topographic expression of some of these indicates that the faults are "geologically recent". Most writers have assigned them to the Alpine earth movements in early-to-mid-Tertiary times; since none of the pockets or their fills show any signs of having been fractured, it can be deduced that the pockets are post-faulting and thus probably mid to late Tertiary age. Thus they are also younger than the faulting in the Cheshire Basin, often assigned to Jurassic or Cretaceous times.

Comparisons with Similar Deposits Elsewhere

As the Derbyshire pocket-deposits have been referred to both Triassic and Tertiary ages, usually without too close a lithological and structural analysis, it seems desirable now to offer comparisons with similar deposits elsewhere.

Firstly, comparisons must be made with undoubted basal Triassic deposits where they rest on Carboniferous Limestone at other localities in the Midlands. At Breedon, Leicestershire, Keuper Marl rests on dolomitized Carboniferous Limestone, with but a thin and well-cemented breccia between. This thickens locally as fillings of pre-Triassic wadis. Exactly comparable associations of Marl and thin basal breccia are seen resting on the Precambrian rocks of Charnwood Forest in Leicestershire. No solution collapse phenomena are visible at Breedon; and none would be expected in Charnwood. Along the southern margin of the Weaver Hills in Staffordshire, Keuper Marls and Sandstones rest on both unaltered and on dolomitized Carboniferous Limestone. The sands and conglomerates are red-coloured and loosely consolidated, in contrast to the bleached and completely unconsolidated sands of the Ribden Pockets only $1\frac{1}{2}$ miles away. The latter obviously include derived Triassic material, but they have been leached of their iron oxides and disaggregated at some later date by solution, and they have collapsed into a pocket.

At the Snelston inlier (5 miles south of Ashbourne (SK/154403), silica-cemented sands formed quartzite dykes where the Keuper Sandstone rested unconformably on the Carboniferous

Limestone (Bemrose, 1904).

In North Wales, Maw (1865) described two pockets filled with sands and gravels and white clays near Llandudno. One of these, at Nant-y-Gamer (SH/801816), is still visible and is clearly a solution cavity in dolomitized Carboniferous Limestone which was once filled with unconsolidated red sands, with lenses and bands of chert gravel. Patches of these, and of kaolinite clay like the halloysite of the Brassington pockets (Ford, 1963b), are still to be seen adhering to the walls. The lithology of these sands in quite unlike that of the Trias of the nearest outcrops in the Vale of Clwyd and in Cheshire. Maw (1867) also described a series of similar pocket deposits in Flintshire; the sites of most of these have been visited, only to find that the pockets have long been abandoned and are now overgrown or filled in. One, at Ffrith-Garreg-Waen (SJ/131750), yielded small exposures of unconsolidated white and yellow sandy chert gravel and one patch of blue clay with gastropod shells. This is probably the clay referred to by Maw as lignitic, but it is close to a present day pond and may represent no more than an earlier stage of the same pond. The inference is that these pockets too are Tertiary rather than Triassic. The fills may even be Pleistocene outwash. Green et al. (1887) commented that the Derbyshire deposits were probably of the same age as those in North Wales.

A solitary clay, sand and gravel filled pocket at Flimston, south Pembrokeshire (SR/928953) forms a hollow in a Tertiary peneplain cut across Carboniferous Limestone. Within a mile or so are Triassic "gash" breccias of quite different lithology, though apparently of similar origin by solution collapse, as indicated by stalagmitic layers and fragments among the red marl matrix. Dixon (1921) referred this deposit to the early Tertiary on grounds of lithological resemblance to the Bovey Tracey Beds; he also noted comparisons with the Derbyshire and North Wales deposits.

Permian sandstone "dykes" fill solution cavities in the Devonian limestone of Berry Head, Brixham (SX/937568). Fully cemented, these sandstones enwrap recrystallized stalactitic calcite bands, but no large collapse phenomena have been seen (Richter, 1966).

The sandy marginal facies of the Oligocene lake basin at Bovey Tracey, Devon, are very similar in appearance to the Derbyshire pocket deposits. These sands and clays have long been regarded as filling a fault-bounded trough, but it is possible that solution of Devonian limestones (or back-reef evaporites?) has had some effect at depth.

The iron-ore filled "sops" in the Carboniferous Limestone of Cumberland and Furness (Smith, 1924) are partly metasomatic replacements of the limestone by haematite and quartz, with a little fluorite and baryte, and partly Trias-filled solution collapses with cavities lined with crystalline haematite and quartz. The sops and their fills are of probable Triassic origin· the degree of lithification of the sands and the haematization make them quite unlike the Derbyshire pocket deposits. Iron-ore filled cavities and replacements like those of Cumberland occur in the Forest of Dean and South Wales (Sibly, 1919) and are also of Triassic age.

Near Killarney in Eire, Walsh (1960) described a mass of Cretaceous chalk, 150 miles from the nearest outcrop, which has subsided into the Millstone Grit apparently owing to solution of the Carboniferous Limestone beneath. Subsidence was intermittent during deposition of the Chalk, as shown by spreads of shale fragments within the Chalk. Since the Chalk is a marine sediment, this implies that the solution leading to collapse may have taken place beneath the sea floor. Also in Eire, Maw (1867) described some sand-filled pockets near Caher in Tipperary, which appear to be comparable to the pockets of North Wales and Derbyshire. No Trias is known anywhere near Caher; and, as the fills contain lignitic clays, they again appear to be late Tertiary or Pleistocene in age.

Fig. 3. One of the Green Lane Pits, Friden (SK/167624), after excavation of almost all the sand-fill.

In South Wales, Thomas (1954a & b, 1959, 1963) has described solution subsidence collapses which have let down masses of Millstone Grit into the limestone beneath by as much as 800 feet. These are thought to have been in action from Triassic times onwards, though most of what is visible today is thought to be of Tertiary age. No Triassic or Tertiary sediments have been recognized in any of the pockets of derived Millstone Grit.

In Belgium, a number of large pockets of sand and clay are found filling hollows cut in the Tertiary peneplains across the folded Carboniferous and Devonian Limestones. One visited east of Dinant was very similar to the Derbyshire pocket deposits. Belgian geologists such as Calembert (1954) have long assigned these pockets to the Tertiary, since no Triassic is known to have been deposited across the area and because the feather-edge of the Tertiary beds is only a few miles to the north, where the latter show a similar lithology. The sands are thought to have been derived from Lower Cretaceous deposits nearby. A well-known but incompletely studied example is the "Iguanodon Mine" of Bernissart, where solution of the Carboniferous Limestone allowed a cover of some hundreds of feet of Coal Measures to collapse, leaving an open pothole into which some 20 large reptiles and numerous smaller animals fell to their death during Wealden times. Later Cretaceous and younger sediments subsequently filled this pocket.

Finally, it must be noted that pockets of Tertiary beds filling solution collapses in the Chalk of southeast England are quite common, though few approach the size of the Derbyshire pockets (see Kirkaldy, 1950).

Conclusions

It is concluded that the silica sand pockets are due to the collapse of solution caverns beneath, as has long been suggested, but several modifications to the hypothesis seem necessary. The controlling factor in distribution is the form and position of the base of the dolomitized zone of the Carboniferous Limestone. This is now shown to have large solution collapse caverns, as at the Golcona Mine; also to have downward projections along major joints, e.g. Manystones Quarry, some of which have been so etched out as to leave pockets with apparently unaltered walls of limestone. Faulting in itself is inadequate to explain the distribution, but joints and minor fractures, opened by faulting and which have been dolomitized, appear to have been important in places.

Intermittent solution collapse under varying hydrological conditions has led to a variety of features, including (a) caverns with or without a partial sand fill, sometimes overlying breccias of dolomite or mineral fragments; (b) caverns which have had their collapses work right through to the surface either before sands were available to fill them, or, more often, after the sand cover had been laid down; (c) collapses which have worked through to the surface sufficiently long before the arrival of the sand fill for subaerial erosion to modify their forms, giving buried dolomite tors and buried former surface watercourse-gorges, e.g. the "gorge Pit" of Yorke (1961, p. 19) at Friden (N.G.R. SK/166626) and the great Harborough Rocks gorge embracing the Bees Nest Pit, Green Clay Pit and two old pits. No evidence can be found to support Yorke's early concept of a great river course from the Trent to Cheshire, running through these pits.

The age of the pockets and their fills is now clearly established as not only post-mineralization, i.e. post-Triassic, but also post-faulting and of probable late Tertiary date. Solution collapse was probably acting intermittently beneath the surface through Mesozoic times, reaching a culmination of topographic effect in the late Tertiary. The fills themselves are at least partly of Tertiary age, with a high proportion of redistributed Triassic material from a former Triassic cover. There seems to be no need to invoke swallow holes at the edge of a retreating

Namurian shale cover to explain the pockets as was suggested by Kent (1957); indeed, the pockets bear little resemblance to the swallow holes at the present Namurian shale margin west of Castleton.

The total lack of flint pebbles in the fills suggests that the Chalk (or at least the flint-bearing Chalk) may not have been laid down across the Peak District.

The distribution of the pockets along a NW-SE line through Friden and Brassington is misleading in view of the occurrence of sands well outside this, including some as yet untested deposits near Flagg and the long-abandoned pits at Ribden. The apparent association with the 1,000 foot erosion surface is also misleading, though probably partly correct. Sand pits occur in Wester Hollow at Brassington at only 900 feet O.D. and the sand filled caverns of the Golconda descend to 700 feet O.D. It seems that, in places, the existence of a sand-filled pocket has been exploited as a weakness in later Pleistocene valley cutting, whilst elsewhere the pockets have been by-passed, e.g. the Kenslow Pit at Friden and the pocket above Long Dale, Hartington. More accurate plotting of the distribution of sand deposits by shallow drilling is needed to complete the picture.

The Blackwall outlier indicates a former extent of the sands and gravels on to the Millstone Grit country around the limestone massif.

The fills thus demonstrate the existence, in late Tertiary times, of a widespread fluvial sand and gravel fan over the South Pennines, with local ponds carrying aqueous vegetation and receiving transported heath vegetable remains from the surrounding area. The fluvial nature of this fan and the high proportion of derived Triassic material indicate that it was probably derived largely from the retreating Triassic escarpment, after the final mid-Tertiary uplift. The pockets and fills thus provide evidence of a former sheet of Tertiary sediments on the South Pennines; and it is of interest to speculate on the possible former extent further afield. Hey (verbal communication) has found evidence of early Pleistocene gravels in East Anglia, carying bleached "Bunter" pebbles closely similar to those of the Pocket Deposits, which occur in fluvial deposits apparently derived from the west. It thus becomes possible that the Pocket Deposits are not only the relics of a South Pennine Tertiary Sheet, but that the sheet spread as far east as East Anglia, or, alternatively, that the East Anglian gravels were derived from the South Pennines by meanders of a river flowing eastwards in early Pleistocene times.

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