The Mam Tor landslide, geology & mining legacy around Castleton, Peak District National Park, Derbyshire, UK

LAURANCE DONNELLY[1]

[1]*Halcrow Group, Deanway Technology Centre, Wilmslow Road, Handforth, Cheshire, SK9 3FB, United Kingdom. (Email: DonnellLJ@Halcrow.com)*

Abstract: This guide provides information to support a one-day field trip to the Mam Tor landslide and Castleton which is situated in the Peak District National Park, North Derbyshire. The village is surrounded by dramatic, often spectacular and rare sites of geological significance and geological interest. Mam Tor forms the highest point in the area and contains the ramparts of a prehistoric hillfort, on a ridge of sandstone, running almost east to west, separating the Hope Valley (to the south) from the Edale Valley (to the north) This site provides an excellent opportunity to inspect Carbonifeorus stratigraphy showing the relationships between the Mam Tor Beds, Edale Shales (both of Namurian, or 'Millstone Grit' age) which unconformably overlie Limestone (Dinantian, or Lower Carboniferous age). Between about 3000 and 4000 years ago a huge section of the Mam Tor Beds and Edale Shales began to fail. This generated an 80m high scarp on the western face of Mam Tor and a landslide over 750m long and 300m wide. The slipped mass has been in a state of continual, gradual, creep type motion since its generation. The rate of slippage has varied and is thought to be controlled principally by fluctuation in ground water levels following prolonged heavy rain. For almost 200 years this slump earth-flow type landslide has caused extensive, dramatic and spectacular damage to the road which was built across it in 1810, culminating in its abandonment and closure in 1979. The limestone around Mam Tor and Castleton has a long mining legacy which dates back to at least Saxon and Roman times. The primary minerals which have been mined include lead (galena), fluorite (fluorspar or 'Blue John'), calcite and baryte. Other minerals found in the area include silver, sphalerite and hydrocarbons. These exist in epigenetic mineral veins, faults, fissures and caves which occur naturally in the limestone (formed by the slow, gradual dissolution of the soluble limestone by slightly acidic rainwater and groundwater). This has left a dramatic impact on the landscape including steep, narrow, open gullies (where mineral were mined where they outcrop), abandoned mine shafts, mineral tips, soughs (drainage adits) mine entries and evidence for medieval mineral processing techniques (including a crushing circle). The limestone represents part of a coral, apron-reef complex (similar to atolls found today in the Pacific Ocean) and in many places contains abundant fossils including corals, algae, brachiopods, bivalves, crinoids and goniatites. Volcanic activity during the Carboniferous resulted in the deposition of basaltic lava flows and vent agglomerate, which has have been exposed by weathering and erosion.

Résumé: Ce guide fournit des informations en support d'une sortie de terrain sur la zone du glissement de terrain de Mam Tor et du village de Castleton dans le parc national du Peak District, nord Derbyshire. Ce village est entouré de sites rares et spectaculaires, importants et de grand intérêt sur le plan géologique. Mam Tor représente le point le plus haut de la zone et renferme les remparts d'un fort préhistorique, situé sur une barre de grès de direction quasi est-ouest, séparant la vallée de Hope au sud de la vallée d'Edale au nord. Ce site fournit une excellente opportunité pour observer la stratigraphie du Carbonifère, notamment la relation entre la Série de Mam Tor et les Schistes d'Edale (tous deux du Namurien, ou âge des « Grès à meules »), qui surmontent les calcaires (Dinantian, âge du Carbonifère inférieur) en inversion stratigraphique. Il y a entre 3000 et 4000 ans de cela, une énorme partie de la Série de Mam Tor et des Schistes d'Edale a commencé à s'affaisser, ce qui a généré un escarpement de 80m de haut sur la face ouest de Mam Tor ainsi qu'un glissement de terrain de 750m de long et 300m de large. La masse glissée est depuis en mouvement continuel et graduel de type fluage. La vitesse de glissement est variable et il semble que celle-ci soit contrôlée principalement par les fluctuations du niveau de la nappe associées à des périodes de précipitations élevées. Au cours des 200 dernières années, ce glissement de terrain de type affaissement et écoulement de sol a causé des dégâts spectaculaires et étendus à la route construite en son travers en 1810, ce qui a provoqué son abandon et sa fermeture en 1979. Le calcaire autour de Mam Tor et Castleton renferme une longue histoire minière qui remonte au moins aux époques saxonne et romaine. Les principaux minéraux extraits comprennent plomb (galène), fluorite (fluorine, ou « Blue John »), calcite et barytes. D'autres minéraux que l'ont peut trouver dans cette zone comprennent par exemple l'argent, la sphalérite et les hydrocarbones. Ceux-ci se trouvent dans des veines minérales épigénétiques, failles, fissures et grottes qui se forment naturellement dans le calcaire (par la dissolution lente et progressive du calcaire soluble par les eaux de précipitations et souterraines légèrement acides). Ceci a un fort impact sur le paysage avec la formation notamment de ravine ouvertes abruptes et étroites (d'où les minéraux étaient extraits lorsqu'ils affleuraient), puits de mine abandonnés, terrils de minerai, galeries de drainage, entrées de mines et vestiges de techniques de transformation du minerai d'époque médiévale (moulin « à manège »). Le calcaire fait partie d'un complexe corallien de type récif-tablier (comparable aux atolls de l'Océan Pacifique aujourd'hui), et contient d'abondants fossiles en de nombreux endroits, tels que des coraux, algues, brachiopodes, bivalves, crinoïdes et goniatites. L'activité volcanique au cours du Carbonifère a eu pour conséquence le dépôt de laves basaltiques et d'agglomérats de cheminée, désormais exposés suite aux processus de décomposition et d'érosion.

Keywords: landslides, geomorphology, mass movements, engineering geology, geological hazards, geotechnical engineering

INTRODUCTION

The IAEG 2006 UK field excursion will take place around the Mam Tor landslide and village of Castleton, located at the western end of Hope Valley, in North Derbyshire, Northern England, at about 180 metres above Ordnance Datum (mAOD). It is surrounded by hills which rise to over 500mAOD on the north, west and south, whilst the broad, flat-floored valley extends westwards. The region is within the Peak District National Park and large parts of the land are managed by the National Trust. In view of the geological, mineralogical and geomorphological interests and its mining legacy most of the Castleton area has been designated, by English Nature, as a Site of Special Scientific Interest (SSSI) (Figure 1).

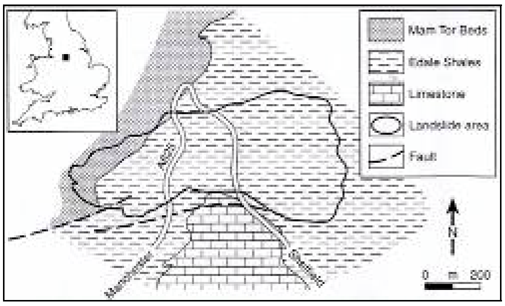

Figure 1. Location of the Mam Tor landslide, approximately 2km northwest of Castleton, Derbyshire, (adopted from Varnes 1978, modified after Cripps & Hird 1992).

ITINERARY

The primary objective of this field trip is to examine the Mam Tor landslide and to gain an overview of some of the many interesting geological features around Castleton (Appendix I). The rocks which outcrop in the region are Carboniferous in age, belonging to the Dinantian Limestone Series and Namurian (Millstone Grit) Series (Appendix II). There are 20 field visit locations; 10 are on, or near to, Mam Tor landslide; 6 on the limestone outcrop to the south of the landslide and the remaining 4 are located around Castleton village (Appendix III & Appendix IV). It is anticipated that the sites near the village may be inspected if the weather conditions are poor preventing the higher ground from being visited safely. The primary objectives of the excursion will be to focus on (but not necessarily be limited to) the area around the Mam Tor landslide. The excursion has been designed to be flexible depending on local weather conditions on the day of the visit, available time and any other logistical matters. It will involve walking up moderately steep, to steep slopes, wet and uneven ground and to sites beyond the 'normal' tourist zones. Appropriate, sensible outdoor walking equipment, including boots, waterproofs and a safety helmet will be required and delegates are expected to be in reasonable health. Wheelchair access is not possible but wheeled delegates are welcome to attend and may visit the village or the top and foot of the landslide. Access to the caves will not be permitted. Some of the sites are protected sites of scientific importance and at these rock, fossil and mineral specimens may not be collected. Although there will be opportunities for some rock, fossil and mineral specimens to be collected at some sites.

Sources of information and previous investigations

The author has been exploring the geology, caves, abandoned mines, mineral workings, geomorphology, hydrogeology and geohazards around Mam Tor and Castleton for the past least 20 years. There is also extensive literature on the geology of the Mam Tor landslide and the Castleton area. The field trip is based on a combination of the above. No attempt is made here to summarise the vast literature dealing with the geology, caves and mineral deposits, however, further information may be found in the following key references: Parkinson (1947), Stevenson (1972), Stevenson & Gaut (1971), Ford & Rieuwerts (1975), Ford (1954, 1955, 1956, 1986, 2000), Jackson (1958), Eyles & Paul (1983), Waltham *et al.* (1996),. Investigations on the Mam Tor landslide have been carried out by Skempton, Leadbeater &Chandler. (1989), Wedage, Morgenstern & Chan (1997), Cripps & Hird (1992), Waltham & Dixon (2000), Arkwright, Rutter & Holloway (2003), Rutter *et al.* (2003). The Castleton is on British Geological Survey 1:50000 sheet 99 (Chapel-en-le-Frith) and on 1:25000 Geological Sheet SK18 & part of SK17 (Edale and Castleton, 1969) and on SK18 (Castleton, 1975). Ordnance Survey maps which cover the area are 1:50000 sheet 110 (Sheffield & Huddersfield) and OS Landranger series 1 inch to 1 mile for the Peak District, 1:25000 sheet for the Dark Peak and two 1:10000 sheets SK18SW.

Location 1. Odin vein, gorge, cave and mine

The working of minerals around Castleton is of considerable antiquity. Odin Mine was worked for lead in Saxon and Roman times (Figure 1). The mineral vein is exposed as a deep, narrow gully, no more than 3m wide and 20m long. The lode (a local term for mineral vein) is dipping about 45^{o} south and has been almost completely exhausted by mining and mineral collectors. The 'worked out' mineral vein leads to an open shaft, some 20m deep (known as Weasel Pit) opening out to a stope. This is dangerous and inaccessible without abseiling equipment and roped access. The earliest recorded evidence for a mine called Odin was in 1280 (possibly the oldest record of a named mine in Derbyshire). There are records for working the mine in 1663, with references to drainage problems. The mine closed in 1869, with an annual production of 100 to 800 tons of lead ore. The main production periods were in the 1720s, 1770s and around 1800. Workings extend under the southern slopes of Mam Tor for at least 1500m and at a depth of about 70m. Mine plans show that the miners followed a series of interlinking *en-echelon* fractures. A small branch from Odin Mine can be seen on the northern side of the workings. This has white deposits of amorphous clay (allophane) at its entrance. A sough (drainage channel) was proposed in 1772 and completed in 1845. The flat grass covered area at the front of Odin Mine represents the tailings from a spar washing plant in the 1940s. This filled a 6m deep hollow, which buried the original entrance to Odin Mine. The adjacent bedrock is exposed, consisting of mainly crinoidal limestone in a dark, shelly matrix. This is the pre-Namurian boulder bed which rests on coarse crinoidal fore-reef limestone, with blue fluorite. The walls of the worked out vein show horizontal slickensides demonstrating wrench faulting. The overlying shales, exposed at the top of the cut are lower on the south side which suggests that the vein was also subject to normal faulting. Given that there was at least 2m of minerals in the vein then dilation must have also occurred at some time in the geological past. Traces of galena and other minerals line the walls and the marks from miners' picks may still be seen in places along with sockets for stemples (wooden beams across the vein). To the west of Odin Mine is Odin Gorge, this 'gully' is not natural gorge but represents the complete surface extraction of the mineral vein where it outcrops. The reef limestone here is fossilifeorus with abundant brachiopods, algal tufa and outward dipping bedding planes. Odin Cave is located to the south of the Mam Tor landslide, marking the end of the public highway and the start of the road, which climbs the landslide (now closed). The cave is a natural feature but there is evidence that it has been occupied during past mining. Mine waste tips, located to the east of Odin Cave and the road provide a variety of mineral specimens.

The formation, age and origin of the mineralisation

The principal structure of the rocks around Mam Tor and Castleton are Hercynian age. The most distinct feature in the district is the Derbyshire Dome which formed a stable block during the Lower Carboniferous upon which carbonate sedimentation occurred, although this was periodically interrupted by phases of extrusive volcanic activity. The limestones around Castleton form part of the Southern Pennine Orefield, and have been described as 'Pennine-style mineralisation' which is a subtype of the Mississippi Valley Type (Durham 1983, Colman & Cooper 2000). This is a fracture hosted vein and hydrothermal replacement type mineralisation. Mineralisation commenced in early Permian to Triassic and late Jurassic times. The origin of the mineral veins is by the expulsion of mineralising fluids from adjacent shale basins into the limestone massif. The fluids dissolved minerals such as Pb, F, Zn and Ba from clay minerals and secondary alteration products from mud rocks (possibly the Carboniferous shales). These were subsequently transferred up dip via faults and other rock mass discontinuities, where they met cooler, sulphur-bearing, more oxygenated meteoric waters where reactions occurred. At Castleton the northern outcrop of the Derbyshire Dome is apparent, located to the east of the Pennine anticline axis (which can be seen at Rushup edge represented by nearly horizontal strata. Fluid migration occurred during the Hercynian Orogeny, aided by seismic pumping from over pressured basins, via faults. The epigenetic mineralisation occurs in large numbers of steeply dipping ore-shoots in the limestone, which are several kilometres long and less than 10m wide. Two main sets of faults cross the limestone plateau; a north-westerly trend and a dominant series trending from east to east-northeast. These faults provided permeable conduits for mineralising fluids. The mineral suite is mainly galena (PbS) or fluorspar (CaF_2), calcite ($CaCO_3$) and baryte ($BaSO_4$), but over 100 other minerals have also been identified in the region. The epigenetic mineral veins have been traditionally classified into six categories: (1) rakes are principal faults which have been mineralised by hydrothermal fluids; (2) scrins are minor faults and fractured which have been similarly filled with minerals; (3) flats are strata-bound replacement deposits generally lying along bedding planes; (4) pipes are filled ancient cavities in the limestone, notably palaeokarsts; (5) replacements deposits are where minerals have metasomatically (molecule by molecule) replacement of the limestone and (6) the mineralisation of collapsed solution structures (Ford & Rieuwerts 1976, Ford & Ineson 1971, Ford 1976, Ford *et al.* 1993, Butcher & Hedges 1987). The erosion of the overlying strata to expose the limestone, occurred in a number of phases.

Figure 1. (Left) Odin Cave and Odin Mine, note the mine waste tips on the lower right of the photograph. (Right) The worked-out Odin mineral vein with mineralised, horizontal slickensides on the hangingwall.

Location 2. Crushing Circle & Knowles shaft

The crushing wheel, constructed in 1823, consisted of a Millstone Grit Sandstone wheel, about 2m in diameter, 300mm wide and had a square hole passing though the centre. It had an iron tyre about 50mm thick and it ran on a circular iron track about 310mm wide and around 4.5m in diameter. The track was bedded into granular material (mining waste and gangue minerals) and consisted of 8 segments, about 50mm thick and was bolted together on the under side. Most of the power was provided by carthorse the waste rock being manually shovelled onto the crushing circle (Figure 2). To the east of the road, the continuation of Odin vein is marked by the presence of mine waste tips. Knowles Shaft is still open, although flooded, and now probably collapsed; it was constructed to a depth of about 75m to intersect the mineral vein. A series of soughs were constructed, in 1711 to 1713 and 1810 to 1821, to drain the mine workings and evidence for these can be seen to the east of Knowles Shaft. Some of the waste containing galena and fluorite particles has washed onto adjacent farmland which is grazed by animals and is a health hazard to breeding stock. From this location the fore-reef slope is visible towards Treak Cliff, less than 100m away.

Figure 2. (Left) The Odin Mine crushing circle and wheel. Note that the crushing circle is now tilted and slightly buckled due to 'recent' movement on the landslide. (Right) Model of a crushing circle (model by H. E. Chatburn, H. M Parker, in Ford & Rieuwerts 1975).

Location 3. The toe of the landslide (debris flow) & Blacketlay Barn

Mam Tor is one of the most easily accessible, dramatic, impressive and active inland landslides in the British Isles (Figure 3). The landslide is of the slump-earthflow type according to the classification by Varnes (1958). The failure consists of a large arcuate scarp where the Mam Tor Beds are seen to dip 5 to 10^{o} NNE. The crest of the scarp forms the summit of Mam Tor at about 500mAOD. The landslide has a total length of over 750m, from its crest to its toe; it reaches 280 m high, a maximum width of 450m and covers an estimated area of 34 hectares. The average slope of the sliding mass, from the base of the scarp to the toe is about 12^{o}. The landslide reaches a maximum thickness of about 30 to 40m. It contains $3.2Mm^3$ of slipped material. The angle of the original hillside has been estimated at 30 to 35^{o} and the mean slope angle of the slipped material is around 12^{o}. The landslide consists of four distinct zones; (1) the scarp; (2) the upper slipped/slumped mass; (3) the central (or transition) zone and (4) the lower debris flow (Figure 4).

Figure 3. View of the main back scarp of the Mam Tor landslide consisting of interbedded sandstone, siltstone and shale sequences (Mam Tor Beds), which overlie the Edale Shales (exposed on the lower left).

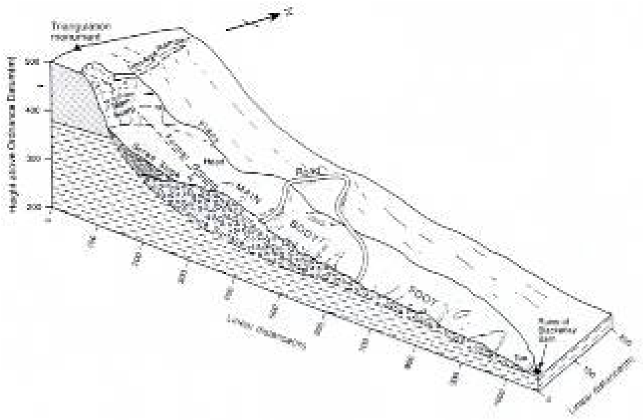

Figure 4. The main features of the Mam Tor landslide. Distances in metres, height in metres above Ordnance Datum (modified after Varnes 1978, in Cripps & Hird 1992).

The lower zone of the Mam Tor landslide (sometimes referred to as the toe or foot) is a bracken and hawthorn-covered debris flow where main body of the 'slump' transforms into the head of the 'earthflow'. The earthflow has moved as a plastic deformable mass which extends for about 420m. It has a hummocky topography with transverse compression ridges, pools of standing water and gentle slopes at about 5 to 10°. Ground movement are likely to have taken place by translation on, or just below the original ground surface. Seasonal variations in groundwater levels result in the appearance of numerous seeps, springs, ponds and marshy vegetation in local depressions and troughs. A traverse across the toe of the landslide shows clearly defined flow lobes that may be seen to stand proud and contrast strongly with the smooth, original, natural ground alongside (east) the toe of the landslide. Some ground fissures, the misalignment of electricity poles (to the north), bending trees and overturned vegetation provide evidence for ongoing movement of the landslide toe. Barnsfield Barn collapsed in the early 1980s and has since suffered further damage by the advancement of the landslide. Fences recently constructed beyond the toe of the landslide give a general appreciation of the periodic progression of the landslide. Borehole evidence suggested that the sliding surface was about 10 to 20m below current ground level (Skempton *et al.* 1989). Measurements for the rates of advance of the landslide toe range from 0.25m/yr between 1981 and 1983 (Al-Dabbagh 1985) to 0.07m/yr (Skempton *et al.* 1989) (Figure 5).

Figure 5. (Left) View of the toe of the Mam Tor landslide advancing from the right and the ruins of Blacketlay Barn. (Right) The landslide toe with a tree growing horizontal from an advancing lobe and the flat glacial head filled Hope Valley to the left of the fence.

Pliestocene events at Mam Tor and in the Hope Valley

The glacial history of the Hope Valley region is not fully understood. The flat floor of the Hope Valley, located to the east, can bee seen to contrast strongly with the landslide. Striated erratics exposed in glacial till in the Hope cements works suggests that Hope Valley formed in the Anglian stage of the Pliestocene 'Ice Age' (420,000 to 480,000 years before present, BP) beneath a zone of inactive ice protected by the higher ground to the north. Ice flow, in a westerly direction along the Hope Valley may have been deflected north by the spur of reef limestone onto the face of the slopes, which now form Mam Tor. This may have caused the over steepening of the valley slopes, therefore contributing to instability. During the Hoxnian and Ipswichian interglacial periods (the former being at least 125,000 years BP), fluvial processes would have further eroded and deepened the Hope valley. During the last (Devensian) 'Ice Age' (some 10,000 to 80,000 years BP), ice did not cover the area but it was subjected to intense periglacial weathering and erosion. It was during this period when the majority of landslides in the Pennines were initiated. The Castleton valley (and other surrounding valleys such as Edale, Alport, Ashop, Derwent and Longdendale), all contain extensive, massive landslides. Glacial tills of Devensian age were deposited on the west flank of the Pennines, at altitudes of 300mAOD, about 5km from Mam Tor. Devensian tills to the north are 40km away and none exists to the south. Although the area was not covered by ice it would have been subjected to periglacial conditions. This would have resulted in the acceleration of mass wasting of the valley sides and the blanket deposition of solifluction and head deposits, which cover many of the valley slopes. These consist of layers of coarse, loose, clay-soils with mudstone and sandstone clasts, deposited by the by freeze-thaw process of solifluction, even on very gentle slopes. (Stevenson & Gaunt 1975). Borehole records show head deposits to reach 2.7m thick downslope from the toe of the landslide (Skempton *et al.* 1989). The current landscape and topography has changed very little in the past 10,000 years apart from landslides and larger streams which have eroded the head deposits and deposited alluvium in their lower reaches. Blanket peat now covered the high ground forming over 7000 years BP (Tallis 1964). On the limestone plateau the turf lies on a thin, ochrous, silty-clay soil cover less than 1m thick. The soils contain microscopic finely dispersed quartz, feldspar and mica. The texture of the quartz is consistent with that of a wind-blow transportation, possibly originating from the Millstone Grit to the north. This loessic clay has been subjected to bioturbation and forms a blanket on the interfluves. Large quantities of this clay have been washed into fissures and the cave systems around Castleton lining them with a light-brown, cohesive clay deposit.

Location 4. Transition zone (centre of the landslide)

The central part of the landslide, known as the ‘transition zone’, forms most of the ground between the two stretches of road and is located between the upper slide block and the lower debris flow. This is composed of unstable blocks and slumped ground, producing an irregular ‘hummock’ topography, fissures and compression humps. Groundwater flows through the landslide emerge at the foot forming marshy ground with reed beds, seepages, springs and standing pools of water. Here, minerals derived from the weathering and breakdown of the Edale Shales are redeposited on the floors of the ponds and seepage points. These include various iron oxides and iron hydroxides (such as limonite) as well as gypsum precipitated from the groundwater.

Location 5. Lower road segment

The former Manchester to Sheffield (A625) road crosses the landslides at two locations due to the presence of a hairpin bend. The road has suffered repeated, extensive, displacements and damage. It was finally closed to traffic in 1979, following ground movements, which severely damaged the road in 1977. This, in conjunction with the absence of large-scale remediation and stabilisation measures and the slow rate of erosion of debris from the toe of the landslide, provides a unique opportunity to examine a complete active landslide. The lower road segment has suffered considerable misalignment and deformation, which may be observed as stretching, horizontal distortion and local subsidence. Adjacent to the road the edge of the landslide is marked by a 2m high compression ridge which has been generated by uplift and a component of motion at right angles to the direction of main (downslope) failure. Faults, generating vertical steps and tears across the road and grass verge, near to the ‘turning circle’ demonstrate that this lower segment is still active.

Location 6. Hairpin road bend & cross sectional view of the landslide

The hairpin road bend provides an ideal opportunity to see the cross sectional profile of the landslide, including the prominent scarp, the upper zone of depletion, the transition zone, the lower zone of accumulation and the toe of the landslide. These contrast strongly to the undisturbed, flat floor of the Hope Valley (to the east) and the limestone escarpment forming a conspicuous ridge at Odin & Treak Cliff (to the west) and Long Cliff (to the south).

Location 7. Traverse of the upper slide zone (slump) and upper road segment

The upper slide zone is a slipped, slumped mass, which extends south-easterly from the scarp towards the upper road segment. Movements have occurred by the non-circular, rotational failure of the original ground surface. This is supported by the presence of rock slices and a series of back-tilted strata dipping between 30 to 50°. The upper road segment may be followed, across the main body of the landslide, from the road bend towards the scarp. Here the road has been spectacularly, severely damaged by localised ground deformation and over-steepening. Several metres of ground movements have occurred since the road was originally built in 1810. Numerous layers of tarmac and gravel (with mini-unconformities) may be seen in disturbed and back-tilted cross sectional slices. These represent various historical efforts to stabilise the landslide and repair the deformation. On the road there are numerous, extensive, graben, tension cracks, active fissuring and vertical displacements of up to 4m, indicative of present movements of the landslide. Secondary toppling and rotational sliding occurs on many of the subsidiary scarps. The remains of white painted central road alignments are truncated abruptly laterally and vertically displaced and are useful in providing a ‘bench mark’ indicating the scale and magnitude of ground movements. In some areas the entire width of the road has been rotationally displaced downslope causing the stretching and spreading of the displaced slice. The hard, brittle, nature of the tarmac responds differently from the underlying bedrock and the relatively more plastic Edale Shales. These properties are reflected in the type of displacements observed. The road tends to fracture and shear whereas the shales tend to ‘flow’ and buckle (Figure 6). Displaced, rotated blocks of Mam Tor sandstones are exposed on the sides of the road and are back-tilted in a westerly direction at angles of up to 20°. Orange-brown ochrous deposits coat the road surface and represent iron-oxides deposited from groundwaters flowing from the Edale Shales. The landslide predates road construction in 1810. Records and observations of movements are available for about the past 200 years. Geological evidence however, suggests that the landslide has been active for at least 3600 years before present (BP) and will possibly remain active for at another 2400 years.

Figure 6. Severe damage to the A625 Manchester-Sheffield road which crosses the Mam Tor landslide. The road was finally closed to traffic in 1979 following repeated ground movements. Note the partly rotational slipped blocks with inward dips of up to 45°.

The influence of man: mining

Landslides in active and abandoned mining areas often raises concern as to whether mining has been a significant factor in influencing the initiation or reactivation of the landslide (Bell & Donnelly 2006). Mining may have an effect on landslides and induce ground movements and this has been document and discussed for other parts of Derbyshire (Cobb, Jones & Siddle 2000, Donnelly, Northmore & Siddle 2002). There earliest evidence that mine workings at Odin Mine influenced the stability the landslide was about 1710, when groundwater draining from the mine was diverted into a ditch which impinged the lower edge of the landslide. This may have had a negative effect on the slide stability but there are no records of movements (Ford & Rieuwerts 1976). Knowles Shaft was sunk in the 1820s into the toe of the landslide. It is currently blocked at about 5m deep, but there are no records of this having had an affected the landslide instability. Two drainage soughs, the Knowlegates Sough and Trickett Sough were constructed into the limestone in 1713 and 1821 respectively. These would have significantly lowered the water table below the foot of the landslide, having a positive effect upon the stability of the landslide. There is no evidence to suggest that the mining at Odin vein was responsible for any major movements of the landslide.

The influence of man: roads

The main method of transport across Derbyshire in the 17th Century was packhorse and horse-drawn wagons via the Winnats Pass gorge. The steep gradient of this gorge made it difficult to ascend and descent resulted in the construction of a turnpike road in 1810, following the easiest topographic route across the landslide. Although this road was probably disturbed by landslide movement's records were not kept. Derbyshire County Council began to keep a record of ground movement and landslide events from 1907 onwards (Derbyshire County Council 1977, 1978). Stabilisation and numerous repairs were carried out. Damage to the road was probably exacerbated by increased traffic, especially the transporting heavy loads of minerals and rock from nearby quarrying and mining operations. The main remediation dates were 1912, 1933, 1946 and 1952 (Brown 1966). Severe cracking of the road in 1977, following renewed ground movements resulted in the road being finally closed to traffic in January 1979 (Table 1).

Location 8. The Edale Shales

This Edale Shales lie unconformably above the Dinantian Limestone. In their unweathered state they consist of fissile, dark grey, laminated marine shale, with silty, sandy or calcareous beds, layers of bentonite clay, ironstone horizons and nodules. The shales are also poorly fossiliferous although goniatites (sometimes pyritised) may be found in the shale at this location. Pyrite occurs at several locations in the form of finely disseminated crystalline aggregates. Scattered ironstone (siderite) nodules occur and may reach 2m wide and 0.5m thick. The Edale Shale has suffered rotational failure and is too high to be stratigrahpically in place and therefore a concealed fault may be inferred along the foot of Mam Tor with a downthrow to the northwest. The Edale Shales are susceptible to valley bulging and the Edale Valley contains numerous exposures of structures indicative of valley-bulging, including sharps, symmetrical folds, straight limbs, low-angled thrusts dislocations and minor folds. These are also present in the vicinity of the, Alport and Ashop valleys. They were seen in trenches and excavations for the foundations of the Ladybower and Derwent Dams in the 1930s. At the Ladybower Dam site thrusts and folds were seen to affect the strata to at least 100m below the original ground level. These were caused by the squeezing of the relatively weak strata into the adjacent load free valley areas. There is the possibility this may exist on the lower slopes, of the northern side of Hope Valley and it may facilitate landsliding. Unfortunately to-date no large excavations have been dug to verify this. The Edale Shale is susceptible to chemical weathering where it is exposed or outcrop near to ground surface. Groundwater seepages emerging from the shale are acidified by the oxidation of the pyrite within the shale (Vear and Curtis 1981). The clay minerals and carbonates in the shale breakdown during weathering to produce dissolved calcium, magnesium, aluminium and potassium. Autotropic bacteria become more active in acid conditions (pH of 2.4) and increased temperatures (40°C) and exacerbate the exothermic chemical decomposition of the shale. During the degradation, breakdown and decomposition of the shales the porosity and permeability are increased and the strength decreases. This is caused by the removal of pyrite, the diagenetic carbonate cement, cation exchange on the surface of clay minerals (Steward & Cripps 1983). These types of chemical processes may also reduce the residual shear strength of clay minerals developed on the main failure surfaces. The removal of cements and clay minerals from the shale results in their precipitation, following a change in chemical conditions such as temperature and pH. This causes the deposition of a variety of minerals including jarosite, limonite and the growths of gypsum crystals along joints and bedding planes (which in turn may lead to further weathering of the rock mass). Because of the high rates of weathering vegetation does not become established and therefore the shale slopes are fully exposed.

Location 9. The back scarp and the Mam Tor Beds

The back scarp forms an impressive, dominant feature of the landscape. It is 70 to 80m high and stands at an average slope of 45^{o} although this varies locally. Alternating sandstone and siltstone units (the Mam Tor Beds) are exposed along the entire face of the scrap. A large gully, some 30m wide and 40m long has been eroded in the eastern part of the scarp caused by 'recent' fluvial erosion. An apron of talus and colluvium (scree slope) extends from the foot of the scarp, at about 25^{o}, formed of material which has fallen from the scarp and fine-grained hillwash sediments (which form a gentle slope at the toe of the scree). The regression of the scarp has partially cut across the remains of the ramparts of a hill fort (Coombe & Thompson 1979) ^{14}C dated at 1180BC, once thought to be early Iron Age but now regarded as Bronze Age. The upper part of the main body of the slipped mass contains Mam Tor Beds which have been displaced and back-tilted by about 50^{o} to the west. The sandstone units exposed on the back scarp are 0.1 to 0.5m thick, well-jointed, blocky and 'stand proud' from the intervening weaker, fissile shales due to preferential weathering. The undercut sandstone blocks are susceptible to sliding and spalling form the main scarp face and fall onto scree slopes.

Table 1. Record of ground movements, road stabilisation and the influence of man on the Mam Tor landslide (modified after Waltham & Dixon 2000).

Recorded and observed movements	
Year	**Observations**
1910	Crack to the road surface in December
1912	Road fractured and distorted in January
1915	2.5m of subsidence in January
1919	0.3m of subsidence in January
1920	Gradual, steady movements in December 1920 to January 1921
1930	Major slip in December 1930 to January 1931
1931	Slip with 60 m fissure in January to February
1937	1.2m of displacement in February
1939	0.25m of subsidence, fissure 100m long in January
1942	0.1m of subsidence, fissure 30m long in October 1942
1946	Extensive failure in February
1947	Renewed movements in November 1946 to start of 1947
1948	200m of subsidence in February
1950	Failure in December
1952	Major failure in January
1955	Large movements, repairs to road
1966	Failure with 1.5m high displacements, December 1966 to February 1967
1977	0.4m of subsidence, fissures in road
1978	Continuation of movements
1983	Winter movements of 0.7m
1984	Subsidence and ground movements observed but not measured
1987	Subsidence and ground movements observed but not measured
1988	Subsidence and ground movements observed but not measured
1994	0.6m of ground movements in winter
1995	0.6m of ground movements in winter
1991 to 1998	Ground movements when rainfall exceeds 210mm between November and February or during a winter that follows a 6 month period with greater than 750mm of rainfall (Waltham & Dixon 2000)
1992 to 2003	Average slip rates have been determined at 150 mm/yr at the toe and 350-500 mm/yr within the slipped mass (Arkwright *at al.* 2003, Rutter *et al.* 2003)
2003 to 2006	Visual evidence for ongoing movements, severe damage to upper and lower road segments and creep movements along the toe of the landslide

The influence of man (mining and road construction)	
Year	**Observations**
c1710	Stream at Odin Mine diverted away from gorge into a ditch on southern edge of landslide, negative effect on slide stability
1712	Knowlegates Sough driven into the limestone, lowered water table by at least 30m, positive impact on stability
c1810	New turnpike road constructed across landslide to replace old packhorse route through Winnats Pass
1820s	Knowles Shaft constructed through toe of landslide, influence of stability and drainage.
1822	Trickett Sough driven into the limestone, lowered water table by another 40m, positive impact on stability
1869	Odin Mine abandoned but limestone continued to drain freely, positive impact on stability
1912	Remediation of road by Derbyshire County Council
1933	Remediation of road by Derbyshire County Council. Shallow drains installed into marsh are behind main slide, above the upper road (positive impact), however they silted up and lost efficiency.
1946	Remediation of road by Derbyshire County Council. Upper road realigned by cutting into the slipped blocks and dumping on lower section of road (positive impact). Large volumes of crushed rock and lead mine waste added to slopes (negative impact)
1952	Remediation of road by Derbyshire County Council
1966	Remediation of road by Derbyshire County Council
1977	Remediation of road by Derbyshire County Council, road temporary patched, four drainage adits and realignment proposed (cost over £2M), but works cancelled indefinitely
1979	Road closed, never reopened

More recent falls can be distinguished from the older fallen sandstone by the presence of orange-brown joint surfaces on the newly exposed and fallen sandstone blocks, compared to the dark brown to buff coloured older ones. The scree slopes also contain shales likely to have been deposited by surface sheet wash and groundwater percolation channelling from the main scarp. Shale flow lobes are deposited on the top of vegetation because of the rapid infiltration of water into the ground. A lobate, sandstone and shale rich inactive mudflow can be seen at the toe of the scree slope. Slickensides are exposed at the bottom of the main scarp, near the top of the scree slope but are not accessible due to the steep slopes and risk of rock falls. The Mam Tor Beds are cyclic deposits, a typical sequence may consist of fining upwards sequence, for example; (1) massive micaceous sandstone; (2) laminated sandstone; (3) laminated siltstone; (4) shale and (5) mudstone. This is consistent with turbidite sequences that formed in the distal part of a submarine delta. The strata have been subject to mild tectonic deformation resulting in a series of open east-west trending folds, with gentle dips of about 10^{o} on the rocks. Few major faults exist, numerous minor faults and at least two joint sets in the rocks of Namurian age. The Edale Shales and Mam Tor beds were deposited at the beginning of the Namurian age, some 318 to 332 Ma, following the late Brigantian uplift and erosion. This marked the onset of a dramatic change in palaeogeography and sedimentation around Castleton, with the incoming of the Millstone Grit Series. The main source of the clastic sediments was remote from Mam Tor and Castleton, being caused by tectonic uplift in the Caledonian Highlands in Scotland. Huge complex river and delta systems spread southwards, through northern England, now forming the Pennines. Initially only distal mud (the Edale Shales) was deposited at Mam Tor, in anoxic conditions. These subsequently were replaced by cyclic distal fan fringe, deltaic-turbidites now seen exposed on the main back scarp. Flute casts, drag marks, load casts, scratch and groove marks, trails, flame structures and shale-pellet conglomerates preserved on the underside of micaceous sandstones suggest currents moving NNE to SSW. The mica flakes sparkle on the sandstone bedding planes and were probably derived from the Dalradian schists of the Scottish Highlands. Fragments of Carboniferous vegetation are common, including occasional tree trunks, braches and stigmarian roots. The Mam Tor Beds were overlain by more proximal sandstones of the Shale Grit, Grindslow Shales and massive Kinderscout Grit. These are not present in the Mam Tor area, but outcrop on the higher Kinderscout plateau to the north of Edale (Figure 10).

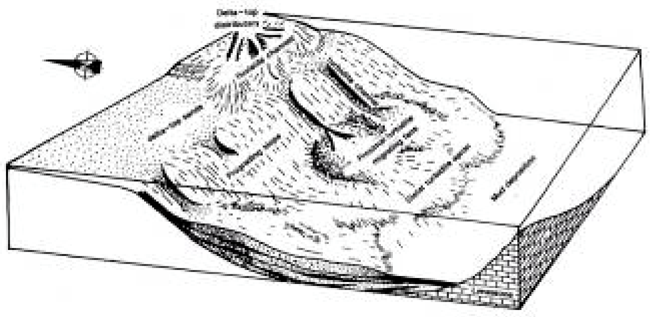

Figure 10. Palaeogeographic illustration showing the diachronous sedimentary facies during the deposition of the Millstone Grit delta (after Ford 2000).

Ground investigations & monitoring: boreholes

Ten, 108mm diameter boreholes were drilled thought the slipped mass using conventional water-flush diamond drilling techniques (Skempton *et al.* 1989). These show a grey-clay at the base of a brecciated shear zone with mudstone fragments and several slip surfaces. This was interpreted to represent the landsldies slip surface at depths from 7 to 32m below the slipped mass.

Ground investigations & monitoring: surveying

Monitoring of the landslide by conventional surveying was carried out in the 1980s by the universities of Manchester and Sheffield (Al Dabbagh 1985) and was continued by Nottingham Trent University in the 1990s (Waltham & Dixon 2000). Waltham & Dixon established a chain of 46 survey stations long the upper section of the road and two base stations on stable ground to the north and south of the landslide. Monitoring took place on a regular basis, from 1991 to 1998, using a variety of optical and electronic theodolites with electronic distance measurements (EDM), electronic total station measurements, precise levels and GPS receivers. This investigation confirmed the earlier work by Skempton *et al.* 1989 and showed the continuity of landslide movements were. This also demonstrated that movements were exacerbated after periods of prolonged heavy winter rainfall that caused an increase in groundwater levels in the slipped mass. The results clearly show contrasts in the rates of movement during the wet winters of 1994 and 1995 with those of the relatively drier winters between 1992 and 1998. The correlation of rainfall and surveying data with landslide demonstrate an increased movement of the landslide when rainfall exceeds 210mm in a calendar month, between November and February, or during a winter that follows a 6 month period with greater than 750mm of rainfall. Between 1992 and 2003 further surveying work was carried out by the University of Manchester using angular electronic distance measurements (Rutter *et al.* 2003, Arkwright *et al.* 2003). This utilised existing survey stations along the road and established new survey stations off the road to provide a more comprehensive assessment of the ground movements taking place, resulting in 38 stations (14 were off road). This investigation supported the results obtained by Skempton *et al.* 1989 and Waltham & Dixon 2000, and showed how relatively wet preceding winters caused increased rates of movement for that year. Strain values were derived from the surveying data and show the directions of principal distortions. These indicate a two-fold division of the landslide, a relative shortening and stretching of the upper and lower parts respectively. This also correlates to the observed different modes of failure. Extension and thinning occurs in the upper part and may be observed as a series of listric slip surfaces, which have severely disrupted the road. Whereas the lower part of the slide fails as continuous, thickening, bulging mass with less tendency to form faults and dislocations.

Initiation and age of the Mam Tor landslide

Skempton *et al*. 1989 suggested that the initial collapse of the Mam Tor landslide occurred between 3200 and 4000 years BP. Since then the toe of the landslide has advanced approximately 320m, or at a rate of 100 mm/yr. This has been determined from the radiocarbon dating of a peaty soil and pollen analysis of an alder tree root. The upper part of the landslide was reported by Skempton *et al*. 1989 to have advanced no more that 50mm/yr. However, according to Arkwright *at al.* 2003 average slip rates have been determined at 150mm/yr at the toe and 350 to 500mm/yr within the slipped mass. It has been shown that winter rainfall is likely to be the main factor controlling slip rates. According to Arkwright *et al.* 2003 the relatively higher present day slip rates may be related to the wetter climate we experience today, compared to 3000 years ago. The creep of landslides may therefore serve as possible sensitive indicator of short-term climatic fluctuations.

Duration of the Mam Tor landslides

Mam Tor landslide was compared with other Derbyshire landslide in the region (Skempton *et al*. 1989). These included Coombes Tor (near Charlsworth), Didsbury Intake (to the west), Tintwistle Knarr and Millstone Rocks (along the north side of Longdendale Valley), Lawrence Edge (on the south side of the Longdendale Valley) and Mam Nick (in the Edale Valley). Many of these landslides were much older than Mam Tor, their ages being determined by a combination of geological mapping, estimations of erosion and weathering rates, radiocarbon dating of peat and pollen analysis (Franks & Johnson 1964, Johnson 1965, Tallis & Johnson 1980, Johnson & Walthall 1979). In general, it was found that large landslides in Namurian mudstones remain unstable if the slipped mass exceeds about 11°. It was also found that a period of approximately 8000 years is required for these types of landslides to attain a state of permanent equilibrium, although creep movements, weathering and erosion will continue long afterwards. Given that the Mam Tor landslide is thought to have been initiated some 3200 to 4000 years ago this implies that the landslide may continue to remain active, in it current condition, for at least another 4000 years.

Location 10. Summit of Mam Tor

The summit of Mam Tor provides a rewarding, spectacular view of the landslide and the opportunity to identify the interrelationship with the constituent parts of the landslide. The scarp has dissected the rampart of a Bronze to early Iron Age hill fort. It is unlikely that this would have been constructed in this way and loss of part of the rampart is probably caused by instability, which post-dates its construction. A steep ridge, running from Rushup Edge (to the west) to Loosehill (to the east), separates the Edale and Hope valleys. The ridge is composed entirely of Mam Tor Beds and is covered with a veneer of colluvium. Extensive landslides occur on the north facing flank Rushup Edge and the southern side of the Edale Valley (including Mam Nick, Black Tor and Little Mam Tor landslides). These are not as well preserved at the Mam Tor landslide, not as active and many of these may be much older and relatively more stable. Streams drain southwards off the edge of Rushup Edge and plunge into swallet caves on meeting the limestone. To the south can be seen a series of lenticluar reef masses, with the fore-reef limestone dipping northwards. The massive back-reef to lagoonal facies of the limestone plateau extends further south, well beyond the village of Castleton. The northern margin of the Derbyshire Dome is marked by a conspicuous ridge, which rises from the floor of the Hope Valley. It extends form the eastern flank of the landslide towards Winnats Pass, Castleton village and Hope cement works. The limestone plateaus and escarpment is dominated by an irregular topography. These represent combinations of nodular reefs limestones, circular subsidence troughs (caused by the collapse of caves and karst), crown holes (caused by the collapse and migration of lead and fluorspar mines), linear gullies (due to the complete excavation of mineral deposits along the outcrop of faults and mineral veins) and areas of tipping and digging which may be attributed to archaeological and historical mining and mineral processing of ores. To the north can be seen the Edale Valley which contains the Edale Shales along its floor. This valley is aligned along an anticline with the bedrock dipping gently to the north and south. An oil exploration borehole drilled near the railway station was unsuccessful and intersected limestone at a depth of about 100 metres below the valley floors. Beyond the Edale Valley rises the bleak, high plateau of Kinder Scout forming the highest ground in the southern part of the Pennines rising to 624mAOD. It consists of Kinder Scout Grit of Namurian age; these 'mountains' are amongst the wettest and remotest parts of inland Britain. A veneer of peat, which can reach 5m thick, but is more commonly 1 to 2m thick, caps most of the moorland plateau. Steeply incised valleys dissect the moorland plateau; many have been used for the construction of dams and reservoirs, in particular in the Longdendale and Alport valleys (the latter includes the impressive Alport Castle landslide). Landslides develop of the flanks of the valleys and have been investigated by various authors (Doornkamp 1990, Franks & Johnson 1964, Johnson 1965, Johnson & Walthall 1979, Tallis & Johnson 1980, Donnelly *et al.* 2002). During the Permo-Triassic times the Coal Measures and Millstone Grit was removed from the crest of the Pennine anticline. Renewed stripping of the cover rocks took place in the mid-Tertiary times and the general form of the limestone plateau was exposed by the onset of the Pleistocene glaciations. The last erosion phase was the incision of the Hope Valley by the lowering of the water table to generate the complex cave networks.

Location 11. The Dinantian Limestone and Namurian Shales stratigraphic contact

South east of the landslide and immediately east of 'Blue John Mines' the stratigraphic contact is exposed in a stream bed; shales outcrops on the north bank and limestone to the south. The limestones are of upper Dinantian age, deposited about 336 to 339Ma (during the Asbian stage) and show a change from massif (lagoonal) to reef complex basin facies (Figure 11). The Namurian shales rest unconformably on the limestone and overlap the reef complex. The massif facies (also known as the shelf or lagoonal facies) are mainly a crinoidal calcarenite with corals and brachiopods (coarse grained limestone) whereas the back-reef facies contain more rounded clasts, some ooliths and calcareous algae. In the reef facies fine-grained fossiliferous limestones is dominant, whereas in the fore-reef (also known as the apron-reef) there is abundant fossils of many types, in both fine-grained and coarse-grained shelly detritus. The fore-reef has outward depositional dips of about 30^{o}. These deposits are consistent with present day shallow, warm, marine seas with coral reefs, such as those which occur in the Pacific Ocean.

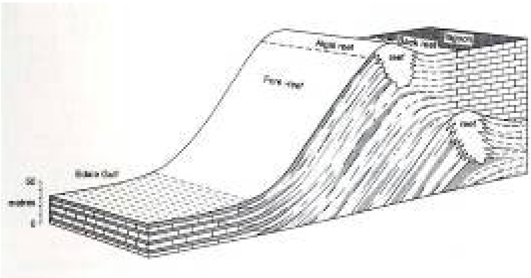

Figure 11. Schematic diagram to illustrate the Carboniferous Limestone facies relationship across the marginal reef delta (after Ford 2000).

Location 12. Blue John Cavern

Blue John is a variety of fluorite (also known as fluorspar or calcium fluoride, CaF_2) which has been mined for ornamental and industrial purposes since at least the Middle Ages. Apparently the Romans discovered the Blue John mine, some 2000 years ago. Two vases of 'Blue John' are reported to have been discovered in the ruins of Pompeii. Now a tourist cave this was a working mine and is one of 4 'show caves' in the area. It was discovered by miners' in 1770 and worked in the 17^{th} and 18^{th} Century for galena and fluorite. A steep descent along a narrow fissure leads into a series of vadose stream caverns, most of which are now dry. The cavern terminates at a sump adjacent to Odin Mine. The origin of this cave system so close to the northern edge of the limestone is inexplicable since there does not appear to be sufficient catchment for a stream large enough to erode these large caverns (Ford 1955).

Location 13. Windy Knoll

Windy Knoll, located to the west of Mam Tor and south of Rushup Edge, is a small cave and a quarry exposed in Asbian apron-reef complex. The reef is narrow but expands to the northeast reaching 300m wide. It has a steep frontal slope dipping up to 30^{o} to the southeast but in the centre of the reef the bedding is horizontal. Neptunian dykes of dark, grey-black crinoidal limestone and breccia pipes are exposed in the walls of the reef. These sedimentary infillings were probably contemporaneous with carbonate sedimentation. The cave, when excavated in the 1870s, yielded over 6400 animal bones of Pleistocene (Ice Age) mammals including wild ox, deer, hyena, bears, wolves and deer. These have been interpreted by archaeologists as representing evidence that man occupied this part of Derbyshire during 'Ice Age' (Dawkins 1875). The quarry was excavated, not for the limestone, but hydrocarbons. At least 30 varieties of hydrocarbons have been recorded including paraffinite, olefinite, carbonite, elaterite and mutabilite. The hydrocarbons 'ooze' from the limestone and vary greatly in viscosity and appearance. Some are rod-like solid and break with a concoidal fracture, others are sticky, yellowish-brown, soft, plastic and may be moulded by hand (having the consistency of putty). These hydrocarbons may represent the residue of a former oil reservoir. Mineralising solutions distilled organic traces from the limestone and redeposited them in discontinuities (such as joints bedding planes, faults and dissolution voids). The hydrocarbons were mined as a local source of fuel. Some of the hydrocarbons result in deformation of the atomic lattice in fluorspar which gives the purple/blue discolouration to 'Blue John'. However, the distinctive discolorations may also be caused by the presence of other minerals such as iron, asphalt, manganese dioxide, calcium permanganate and rare earth elements. In addition to the hydrocarbons specimens of pyrite, galena and flourspar have also been found. A shaft with waste heaps near the entrance of Windy Knoll marks a former mineshaft sunk to interest a mineral branch from Odin Rake.

Location 14. Winnats Pass and Speedwell Cavern

Winnats Pass is a steeply incised gorge, which dissects the margin of the reef limestone complex. It is approximately 600m long, 400m high, 300m wide at its top and less than 50 m wide at its base. The valley sides range from about 45^{o} to vertical. The lower slopes are partially obscured by a cover of thin soil and turf or less steep scree accumulations, composed entirely of blocky limestone (Figure 12).

Figure 12. Winnats Pass, to the west of Castleton and south of the Mam Tor landslide. The entrance to Speedwell Cavern is on the lower left (south) side of the pass. Fan-shaped beach beds are exposed along the foot of the pass and continue along the foot of the hill slope towards Treak Cliff Cavern. Lines of shafts, hollows, surface excavations and waste tips mark the course of mineral veins which have been historically worked on either side of the pass.

The origin of Winnats Pass gorge has been subject to debate by geologists. It probably began as an inter-reef channel in Brigantian times eroded between the reefs, occasionally swept clear by tides washing in and out of the lagoon. It was deepened further and subsequently filled with sandstone and shale by the Namurian deltas prograding from the north. Further deepening occurred during the Pliestocene (Ice Age) which subsequently eroded the weaker Namurian deposits to re-excavate the channel thorough the reefs. This was likely to have been further deepened by stream/river erosion during periglacial periods when the groundwater was not able to flow through the frozen ground, in otherwise highly permeable limestone bedrock. The pass has a little catchment area for the highly erosive stream that once must have flowed through it, unless a tongue of ice occupied the Rushup Valley and provided the melt waters in the vicinity of Windy Knoll in late Wolstonian times. There is no evidence to suggest that the pass originated by the collapse of a cave system. The Castleton reefs do not always show a mound like form and this has generated much controversy concerning their origin. However, it is now generally agreed by geologists that they represent an apron-reef, a margin facies between a deeper marine basin (extending to the north) and a shelf plateau (extending to the south). The structure of the reefs may be divided into three distinct areas; the back-reef, algal-reef and fore-reef. Winnats pass provides a cross section through the reef complex. Fan-shaped beach beds are exposed at the foot of the pass and represent a fossil beach or debris which has washed down the pass from the lagoon. Steeply inclined reef limestones dip towards the mouth of the pass (adjacent to Speedwell Cavern) in then general direction of the relatively deeper marine basin. Near the bend of the pass nearly horizontal beds lie on top of outward dipping fore-reef beds. Shelf facies, then apron-reefs (forming the high ground on either side known as Shining Tor on the south and Old Tor on the north), to flat-lying lagoon limestones are exposed in the slopes at the top of the pass. Numerous abandoned mine adits are exposed along the entire length of the pass (such as Old Tor Mine at the top of the gorge and Suicide Mine and the bottom of the gorge). A mediaeval trackway known as the ‘Roman Hollow’ is located near to the top of the north side of the pass which leads to worked ground representing a former opencast fluorspar mine which was worked during World War II. An abandoned limestone quarry also occurs at the top, south side of the pass near the small entrance to Winnats Cave. This leads to a huge cavern on the southern side of Winnats Pass, about the size of cathedral, of which there is no surface expression to infer its existence. Blue John Fluorspar is exposed on the sides of Winnats Pass and may be found in the scree slopes along the toe of the gorge.

Speedwell Cavern (now a show mine accessible by boat) is located at the bottom of the pass. This was an unsuccessful lead mining venture in 1771 to 1778 which involved the construction of an exploratory cross-cut drive; through the fore-reef limestone aimed a striking new lead veins at Faucet Rake and providing a roadway for the transportation of ore and waste. This was designed so that the mine could be worked by boat haulage similar to the canal tunnels which worked the Duke of Bridgwater’s coal mines at Worsley, near Manchester. However, the miners’ excavated into natural caverns (some are at least 2km long and 100m high), with substantial stream flow from west to east. As a direct consequence the mine was flooded and the mining venture was abandoned.

Location 15. Speedwell vent

Contemporaneous volcanic rocks are associated with the Carboniferous Limestone and include lavas, tuffs and agglomerates. A structurally intrusive volcanic vent is situated near the southern part of the opening to Winnats Pass, to the south of Speedwell Cavern and about 700m west of the Peak Cavern. The vent is small (about 200m long) and its original is controversial. It may have been associated with explosive, extrusive volcanic activity in the marginal province or it may represent a spill from the Cave Dale lava, from the lagoon down the fore-reef. It is probably associated with Hercynian tectonic activity and represents the throat of a small volcano. The vent is filled with highly altered fine agglomerate and lapilli tuff in a poorly sorted basaltic groundmass which has been calcified. Another vent in the Castleton area occurs beneath the floor of the Blue Circle Cement quarry (Ford 2000). These sometimes deposited fine clouds of ash (known as ‘clay-wayboards’) and some examples of this are exposed in Cave Dale. These provided easier excavation into the rock during hand excavations for minerals.

Location 16. Castleton village and Peak Cavern

Castleton is situated at the western end of the Hope Valley, about 6km northeast from Buxton, 10km west from Sheffield and 25km east of Manchester. It has a population of less than 1000 and may be considered as a typical, tranquil, quaint English village with a variety of old cottages, a network of small byways, pubs, show caves and many breathtaking beauty spots. The village is steeped in history and it derives its name from Peveril Castle. This dominates the village, it was founded by William Peveril, and dates from the Norman Conquest of Britain (begun at the Battle of Hastings in 1066 which introduced the practice of castle building into Britain). The Doomsday survey shows that there was a castle on this site in 1086 (O'Neil 1985). Castleton is situated at the boundary of the White and Dark Peaks, the former extending to the south as a limestone plateau and the latter to the north forming peat-covered gritstone moorland. These were designated as Britain's first National Park (the Peak District) established in 1951 in view of the scenic and cultural heritage. The Peak District separates the major industrial conurbation of the east and west Midlands, Lancashire and Yorkshire. Half of the population of England live within 40km of the Peak District National Park. This area of outstanding natural beauty became popular form Victorian times (about 1900) onwards, by visitors wishing to escape form the surrounding towns built up during the 'Industrial Revolution' and dominated by heavy industry such as mining and cotton mills (Queen Victoria visited the cavern in 1834 and 1842). Peak Cavern occurs at the foot of a vertical limestone gorge face, some 40m high, on top of which sits Peveril Castle. The cavern has a large entrance, at least 30m wide and 20m high forming the largest cave entrance in Britain and the second largest in the world (exceeded by the entrance to Genolian Caverns, New South Wales, in Australia). A resurgence spring issues from the foot of the face and flows northwards forming the main stream and (historically) a water supply for the village. Large parts of the cave complex were formed by dissolution solution along principal joint sets. This includes the 'Great Cave' and a vadose canyon more than 1km long and 20m high in places. The roof of the mine is stained black with soot deposits of carbon form smoke associated with medieval rope making and cottages. A public house stood at the entrance in 1794 but has since been demolished. The underground mine is complex and chambers reach approximately 70m long, 50m feet wide and 35m high.

Location 17. Cave Dale gorge

Cave Dale, located at the eastern part of Castleton village, is a classic dry valley. It is a picturesque gorge which has been incised through the limestone and it grades into the head of the Hope Valley. This was incised by run-off across frozen ground in largely post-Wolstonian times. The gorge provides an opportunity to examine in cross section the back-reef facies, which are well exposed. A small quarry at the entrance to Cave Dale and a number of abandoned adits in the sides of the gorge have been left by 17th and 18th Century miners who attempted to explore the valley sides for galena, glauconite, hydrocarbons, sphalerite, baryte, fluorite and smithsonite. In the entrance to Cave Dale mammalian fauna and flint of 'Neolithic', 'Bronze' and 'Iron' ages have been discovered. Less than 20m below the floor of Cave Dale are the cave systems forming part of the Peak Cavern complex. The entrance to Cave Dale shows fore-reef limestones dipping northwards at about 25^{o}. About 100m there is a change in stratigraphy and facies and the prominent crags are composed of horizontally bedded fossiliferous limestone forming the centre of the reef. On the northern side of the dale, near to Peveril Castle, the crags are poorly fossilifeorus and both reef and fore-reef facies interdigitate and contain reef tufa and geopetal fabrics. Back-reef facies are exposed on inaccessible parts of the valley. Cave Dale narrows and steepens where it is crossed by 'New Rake', which contains less than 0.5m of calcite, exploratory adits and minor workings. Small amounts of water flowing down the valley sink at this point to re-emerge in Peak cavern below. The upper section of Cave Dale takes on the appearance of a typical dry valley cut through the Bee Low Limestone (Upper Asbian). Variations in the dip of the Cave Dale (thalweg) may be related to the incision of Hope Valley in the Pliestocene forming a 'knick point' (Figure 13).

Figure 13. (Left) The entrance to Cave Dale, a dry valley near the centre of Castleton. (Right) The upper part of Cave Dale with olive basalt lava exposed on the left (south) side of the gorge.

Location 18. Cave Dale basalt lava flow

An isolated occurrence of lava outcrops at the southern end of Cave Dale. The flow is marked by a conspicuous ridge containing outcrops of multiple flows of fine-grained, vesicular, olive-basalt with occasional zeolites around the periphery of some of the cavities (Walters & Ineson 1981, Shirley & Horsfield 1940). The lava is poorly columnar jointed in places and basalt pillars stand proud, caused by differential weathering, some have a coating of chalcedony. Individual flows may be distinguished consisting of either massive basalt or vesicular basalt (some of the vesicles are filled with calcite or chlorite, producing an amygdaloidal texture). The flow reaches a maximum thickness of approximately 20m above the limestone and can be traced for approximately 200m along the upper part of the dale before it disappears below the stone. The lava is confined to the reef-belt, dying out in the back-reef facies. A small landslide has developed on the north facing lava slope. Underground evidence from caves and mines suggest the lava thins rapidly westwards. Great thicknesses of volcanic rock have also been found in boreholes drilled to the east of the village (Rodgers 1977). These rocks are known by local miners as '*toadstone'*. This is believed to be derived from German miners meaning '*todt stein*' or unproductive stone. But other interpretation suggest '*t'owd*' means '*the old*' (…..miners my have describes this as '*t'owd stone again*').

Location 19. Dirtlow Rake

Dirtlow Rake forms one of the most principal epigenetic mineral veins in Derbyshire. It is a north-west trending replacement deposit with a downthrow to the south of about 70m and considerable lateral movements in places (observed as mineralised slickensides of the footwall and hanging wall). The entire length of the rake contains three complex, parallel, distinct veins. Where the vein crosses reef-complexes and natural caves, fluorite lenses are well developed, sometimes associated with chert. The rake has been mined by both surface and underground extractions (for example at Ashton's, Hollandtwine and the Hazard mines). Towards Pindale (a gorge to the east of Castleton village) evidence of historical workings exist and the surface outcrop of the vein has been completely extracted to leave a deep, steeply inclined gorge. A small open-pit mining operation presents an ideal opportunity to inspect the mineral vein in cross section which is seen to dip at about 70^{o} to the south. The open pit is situated where Dirtlow Rake crosses pre-Namurian solution collapse structures (Butcher & Hedges 1987). The main economic and productive part of the vein is along the wall rocks which contain large masses of radiating columnar jointed calcite and veins of fluorite, baryte and galena. The limestone host rock has been altered and tectonised and in places silicification is common extending over 400m parallel to the vein on the south side. To the east Dirtlow Rake and associated scrins are marked by numerous shafts, lines of spoil heaps and narrow 'gorges' representing worked-out sections of the vein. Several hundred thousand tonnes of fluorite have been mined from Dirtlow Rake. Lead is no longer exploited and the fluorite, baryte and calcite historically discarded as 'gangue' or waste, now form important commodities. Fluorite is needed as a raw material in the chemical industry as well as being required for the fluoridation of water and in toothpaste. Baryte in used as a filler in paper and as an additive to drilling mud in the North Sea hydrocarbon industry to help control high gas pressures (Figure 14).

Figure 14. (Left) Open pit workings at Dirtlow Rake. (Right) Narrow 'gorge' caused by the historical, complete extraction of minerals in Dirtlow Rake.

Location 20. Treak Cliff Cavern

Treak Cliff Cavern contains the only known workable deposits of 'Blue John' fluorite in a 'pipe' vein, following the inclination of the bedding in the limestone. The vein may be followed up the steeply dipping rocks forming the Treak Cliff reef escarpment. Records for mining date back to at least 1757 and the mine has worked since then on a discontinuous basis. The Old Tor Mine, which is situated on Treak Cliff, was once a major producer of 'Blue John'. Mining resumed after the World War I in 1926, to provide fluorite as a fluxing material in electrical furnaces. At this time miners discovered old shafts leading to a spectacular cave networks containing stalactites and stalagmites lined with 'Blue John' fluorspar. The cave was opened to the public in 1935 when electricity had been installed. Outward dips of between 25 to 30^{o} can be seen on the fore-reef limestones at Treak Cliff. The limestone is highly fossiliferous and contains abundant well preserved fossils including; brachiopods, polyzoa, rare corals, sponges, nautilus, lamellibranchs, gastropods, ostracods, bryozoans, goniatites, crinoids, stromatolitic algae and some trilobites. Near the foot of Treak Cliff is a large, distinct, circular depression. Often mistaken for a karst doline or old mine workings, but it is actually a Nazi bomb crater formed in 1941.

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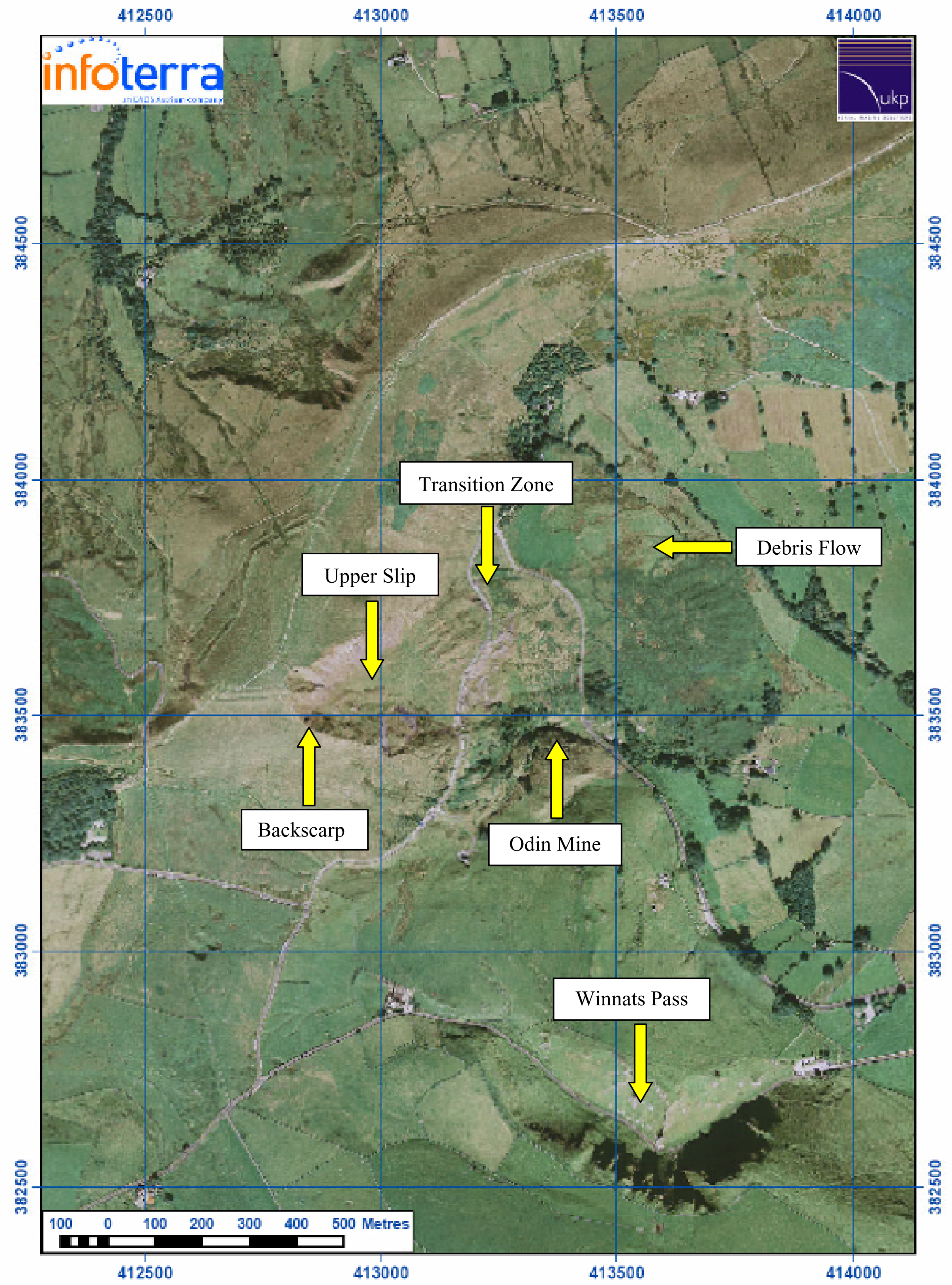
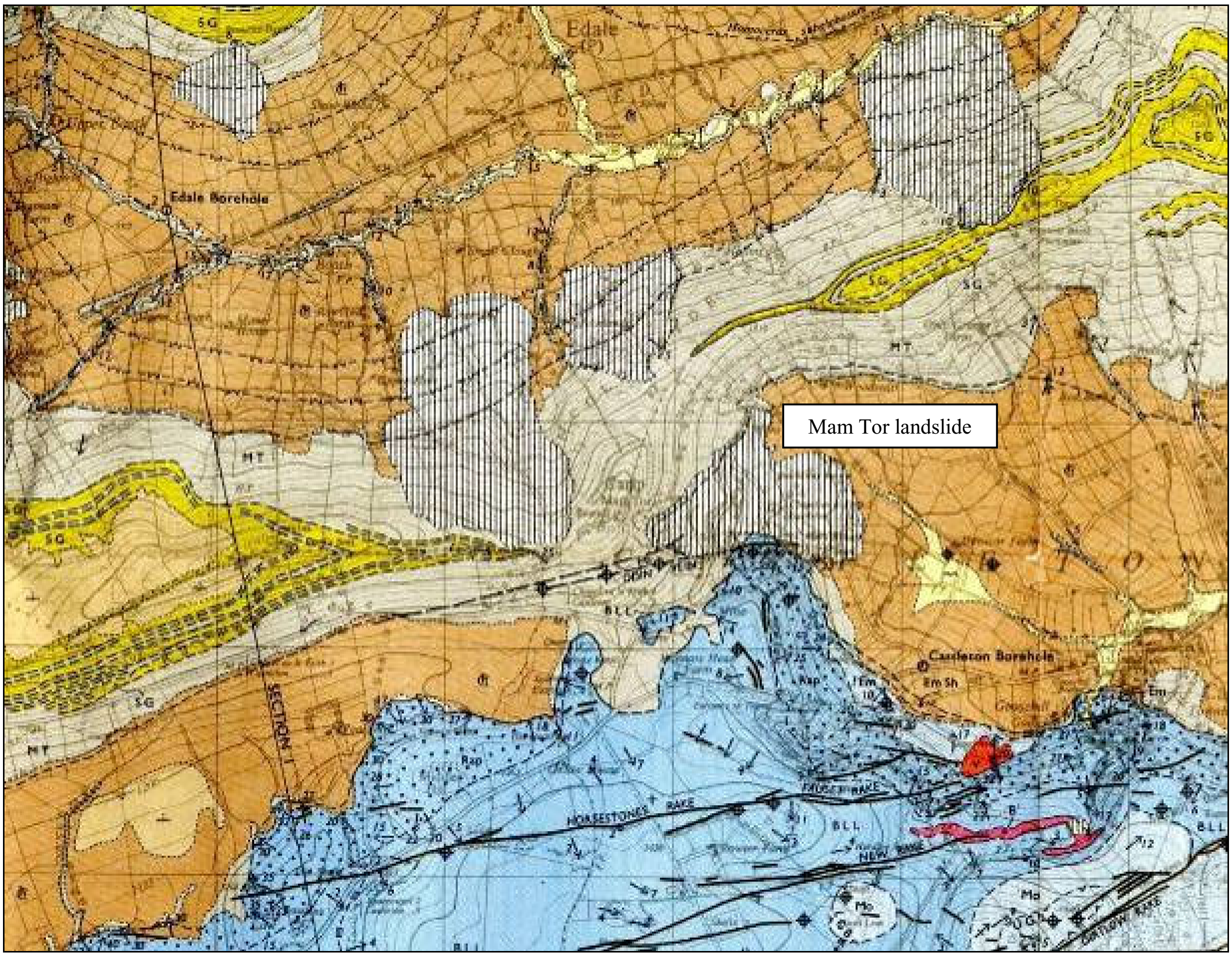
APPENDIX I.

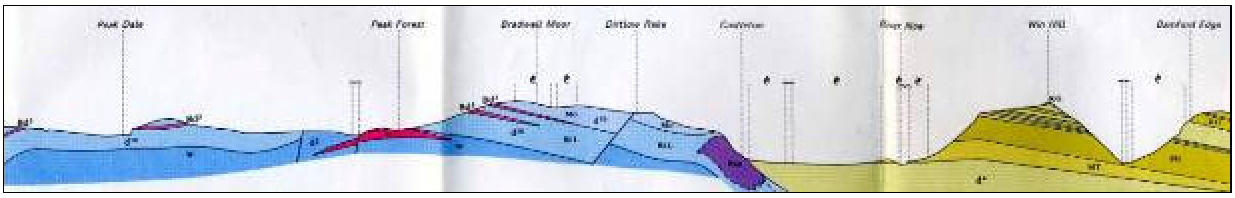
Aerial photograph showing the main features of the mam tor landslide (reproduced with kind permission form dr martin insley & infoterra ltd).

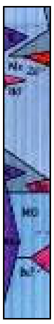


APPENDIX II.

1:50,0000 scale, sold and drift edition geological map and cross section of the area around the Mam Tor landslide and Castleton, Derbyshire (reproduced with kind permission of the British Geological Survey).

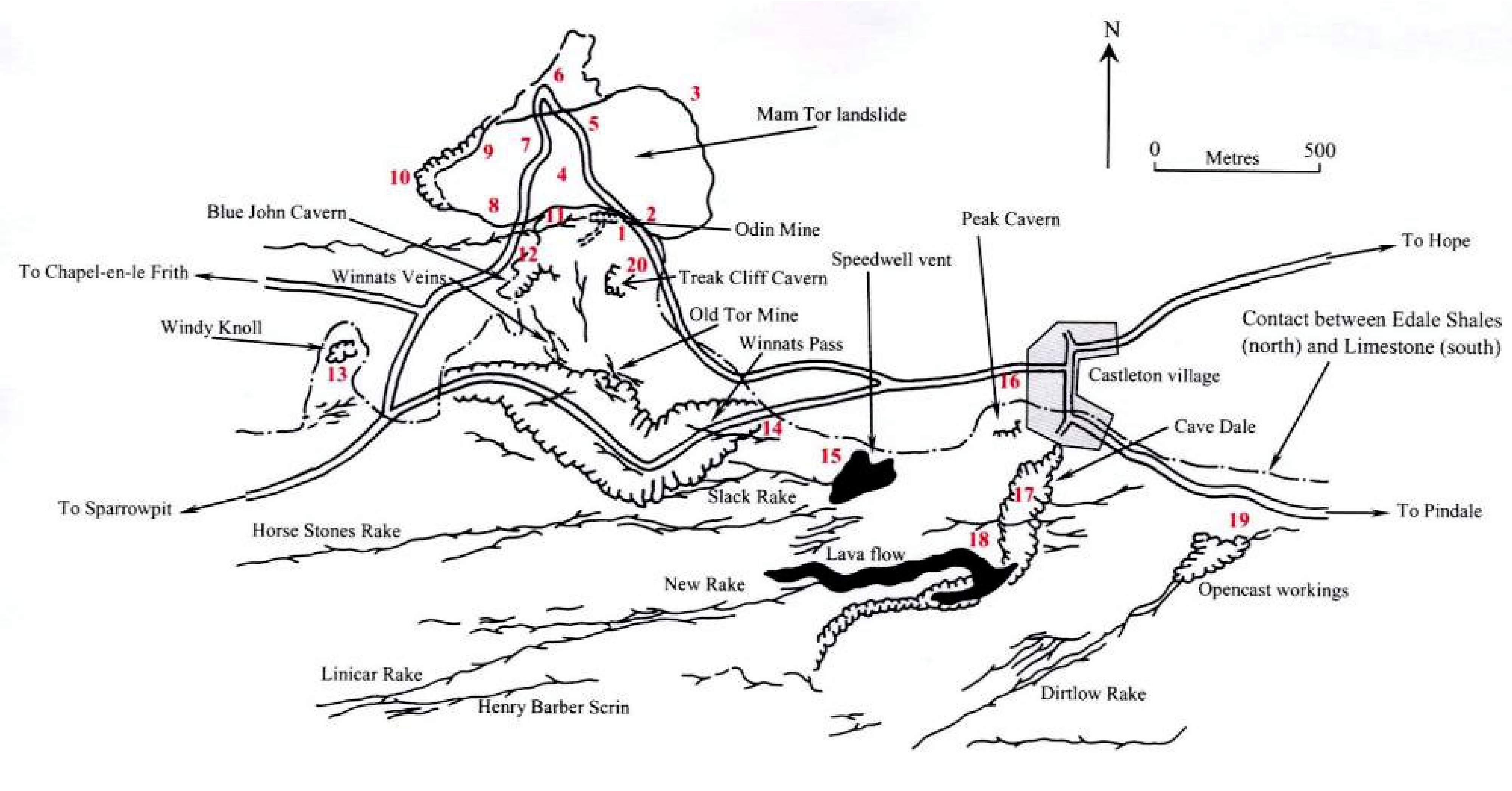




DINANTIAN (CARBONIFEROUS LIMESTONE SERIES)		Monsal Dale Group (with reef-knolls, tuff & lava) Bee Low Group (with tuff and lava)	NAMURIAN (MILLSTONE GRIT SERIES)		Kinderscout Grit Shale Grit Mam Tor Beds (above Edale Shales)

APPENDIX III

Schematic map to show the field visit locations around the Mam Tor landslide and Castleton.



APPENDIX IV.

Detailed schematic map to show the field visit locations around the Mam Tor landslide.