Movement of the Mam Tor landslide, Derbyshire, UK

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Abstract

The Mam Tor landslide is a kilometre-long feature in shales and sandstones. The initial slope failure occurred over 4000 years ago as a rotational landslide that developed into a large debris flow at its toe. A road built across it nearly 200 years ago, and now closed, provides graphic evidence of continued movement of the slide mass; this has now been monitored for eight years. Current mean annual movement is up to 0.25 m; this increases greatly when winter rainfalls exceed thresholds of both 210 mm/month and 750 mm in the preceding six months. The most rapid movement is now taking place in a central zone of slide blocks that rest on a steep slip surface located at or close to the buried ground surface just downslope of the initial failure toe. Both the main upper mass of landslide blocks and the debris toe move more slowly over basal shears at lower angles of dip. Deep drainage of the central part of the landslide would be the most effective means of stabilization, but may not totally eliminate movement.

Keywords: geological hazards, hydrogeological controls, landslides, monitoring, slope stability

Introduction

Mam Tor is a prominent hill of Carboniferous sandstones and shales standing at the head of the Hope Valley, just west of Castleton, on the border of the White Peak and Dark Peak sectors of the Derbyshire Pennines (Fig. 1). A large landslide on its eastern face is conspicuously active (Fig. 2); Mam Tor is known locally as Shivering Mountain, though this may derive from shiver, an old dialect name for shale. Unfortunately the slide was crossed by a trunk road, which has now been closed due to the continual ground disturbance. Movements of the slide along the line of the road have been recorded for 90 years, and have now been monitored in detail for eight years.

Geology of Mam Tor

The summit and upper slopes of Mam Tor are formed in the distal turbidite sequence of shales, siltstones and fine-grained, sole-marked sandstones that constitute the Mam Tor Beds. The lithologies alternate in beds about 1 metre thick, and the sandstone units are densely fractured. They overlie the dark pyritic shales and mudstones, with thin siltstones, known as the Edale Shales (Stevenson & Gaunt 1971). Both these units are of Namurian age, and dip roughly to the north at 5–15°.

Underlying Dinantian limestones form the high ground south of Mam Tor. Their northern limit is an apron reef with a steep depositional dip in fore reef boulder beds, exposed as the face of Treak Cliff. The northern tip of the limestone outcrop is crossed by the Odin mineral vein, which was worked for about 700 years until underground mining finally ceased in 1869; the workings extend mainly westwards beneath the shale cap (Ford & Rieuwerts 1976). The landslide does not reach down to the stable limestone.

The Namurian clastics exhibit overlap onto the reef limestones. They dip away from the limestone, and differential compaction has caused their dips to steepen adjacent to the reef margin. The Mam Tor Beds exposed in the landslide head scar dip north at about 5°. Steeper dips in the Edale Shales are seen in boreholes through the landslide (Skempton *et al.* 1989) and above the Odin mine; these are probably due to differential compaction over the steep profile of the underlying reef limestone.

A minor fault cuts through the landslide zone (Fig. 3). It separates Mam Tor Beds from Edale Shales in the southern edge of the slide scar, below which it is obscured beneath slipped debris. Downthrow to the northwest appears to be about 20 m in the face, and diminishes to the northeast. The fault is also recognizable by the offset of the Odin vein in the inner reaches of the mine.

Pleistocene events in Hope Valley

Though the entire Derbyshire Peak District was covered by ice in the Anglian stage, and probably again in the Wolstonian, there are few surviving features of glacial origin. Hope Valley was probably beneath a zone of inactive ice sheltered by high ground to the north. A few striated erratics in traces of till exposed in the Hope cement works quarry (Ford 1986) are all that survive from the early glaciation of the valley. It is conceivable that these early ice covers included eastward flow along the Rushup Valley and down into the Hope Valley, but no firm evidence remains. Any ice flow deflected northwards by the spur of reef limestone would have scoured the face of Mam Tor, and glacial oversteepening of it may have contributed to the initial instability.

Fluvial processes further deepened Hope Valley, and steepened the face of Mam Tor, during the Hoxnian and

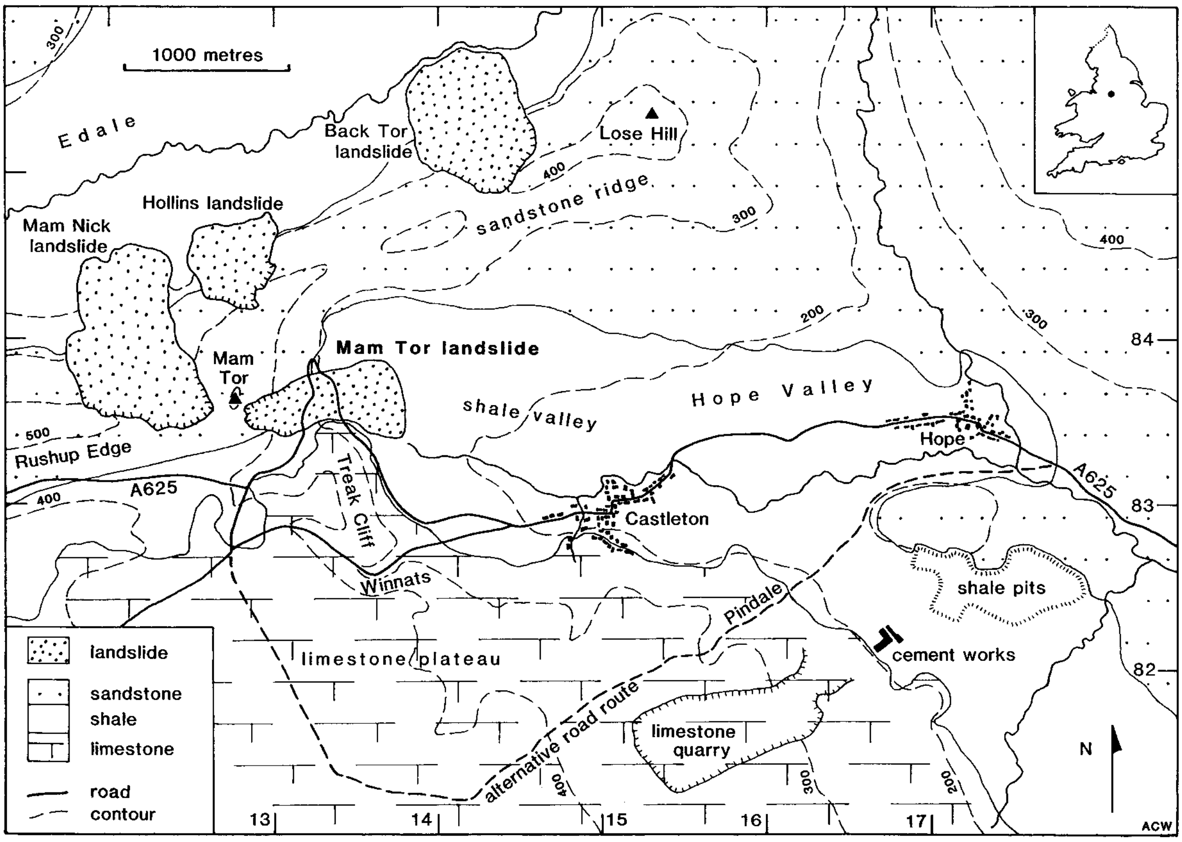

Fig. 1. Outline map of the area around Mam Tor, at the head of Hope Valley. The proposed road up Pindale avoids the problem sites of the Mam Tor landslide and the villages of Hope and Castleton, but its construction is now unlikely. Sandstones are the Mam Tor Beds and some higher strata; shales are the Edale Shales; limestones are the various reef and lagoonal carbonates of the Carboniferous Dinantian.

Ipswichian interglacials. Periglacial activity throughout the Devensian produced solifluction sheets that still floor the Hope Valley. The head is a rubbly clay soil containing sandstone fragments; it has been recognized in borehole cores from beneath the downslope part of the landslide debris (Skempton *et al.* 1989), where it is up to 2.7 m thick. Subsequent weathering has included degradation of the shales by leaching of disseminated

Fig. 2. The Mam Tor landslide viewed from the sandstone ridge to its north in 1998. The head scar is only seen in profile on the right, with the Iron Age fort ramparts visible just below the skyline. The road descends over the slipped blocks of the landslide mass, before turning back across the lower debris flow. Treak Cliff is the steep slope in reef limestone extending from the far side of the landslide to the shadowed breach of the Winnats Pass.

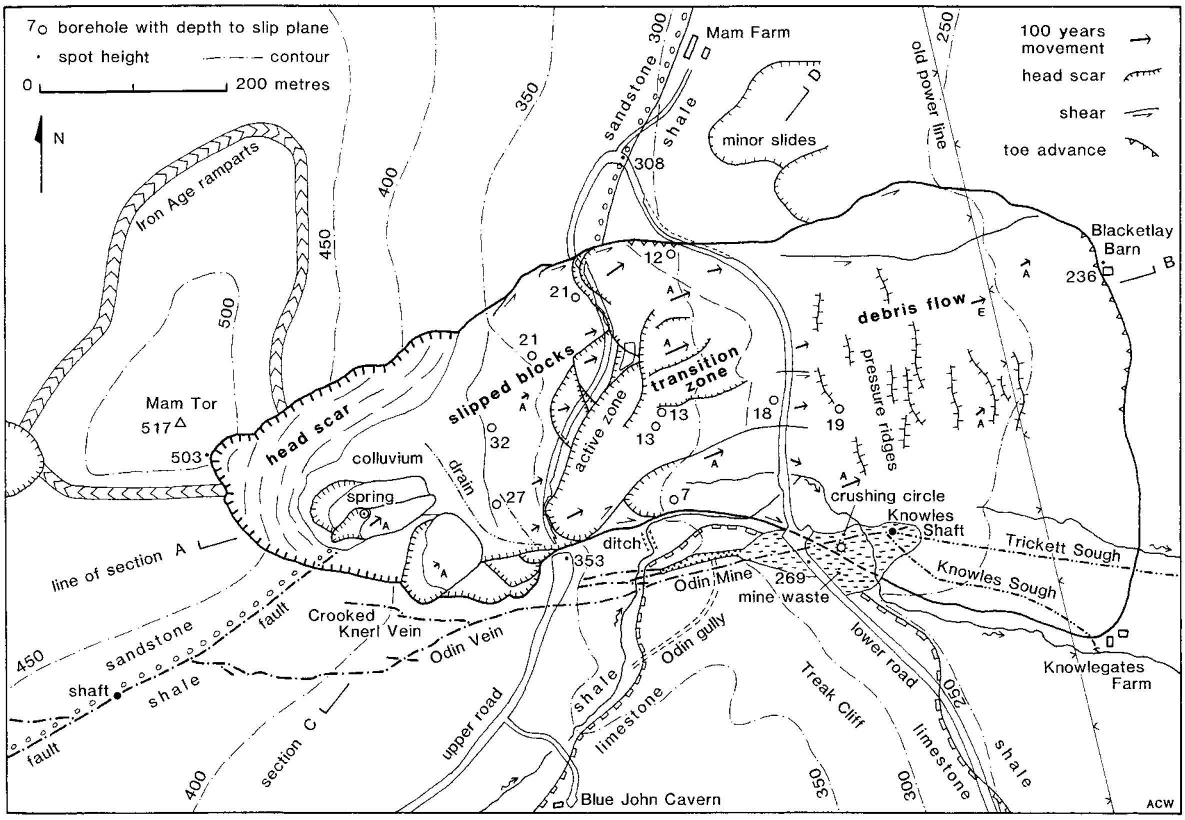

Fig. 3. Map of the Mam Tor landslide and adjacent features. The road is shown in the position occupied in 1996. Arrows showing movement of the landslide material are drawn to a length that represents about 100 years of movement at the map scale; those labelled A are adapted from Al Dabbagh (1985), and the one labelled E is interpreted from displacement of the electric power line. Figures by the boreholes indicate depths in metres to the slip surface (from DCC logs). Cross sections A–B and C–D form Fig. 4. The pressure ridges are largely after Brown (1966). The main line of the Odin mineral vein is plotted in workings at a level about 50 m below that of the open cut (Ford & Rieuwerts 1976) and therefore appears further south due to the steep southerly dip of the vein.

pyrite and diagenetic carbonate cement, exacerbated by acid produced from oxidation of the pyrite; these processes have reduced the strength of the near-surface shale (Vear & Curtis 1981; Steward & Cripps 1983).

The Mam Tor landslide is one of many on the steep hillsides flanking Edale and Hope Valley. More than fifteen slides have been mapped (Stevenson & Gaunt 1971), all where the Namurian succession has predominantly sandstone units overlying predominantly shale units. Largest of these is the Mam Nick landslide (Fig. 1), immediately west of Mam Tor (Doornkamp 1990); this appears to be now almost stable, but small movements disturbed the minor road across it at the same time as the Mam Tor slide moved in February 1977.

The Mam Tor landslide

The active landslide on Mam Tor extends 1000 m from the top of the head scar to the toe of the debris flow (Figs 3 & 4); there is a fall of 270 m between these points. The head scar is 70 m high, and is largely bare shale and sandstone except for its apron of talus and colluvium that extends onto the landslide.

The slide mass consists of three zones that are structurally distinct:

(1) The upper part of the slide material is a series of rock slices or blocks that were produced by the non-circular rotational failure of the original slope; most of these slices above the upper road show little sign of current movement.
(2) The central part of slide is a transition zone, forming most of the ground between the two segments of road; it lies between the upper landslide blocks and the lower debris flow. It is composed of an unstable complex of blocks and slices, some of which can be identified by ground breaks along their margins; they overlie the steepest part of the landslide's basal shear, which was the hillside immediately downslope of the initial failure (Fig. 4). The upper road lies along the highest

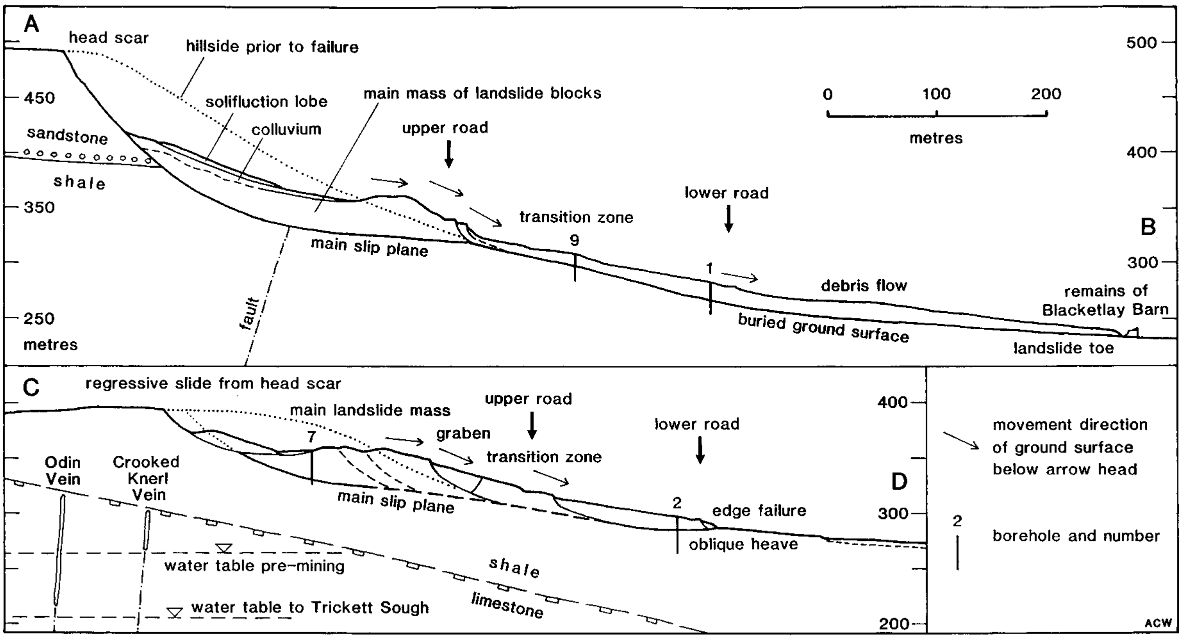

Fig. 4. Cross sections through the Mam Tor landslide along the lines indicated on Fig. 3. Perched water tables within the landslide mass are not marked on the sections, as they lie very close to the ground surface.

section of the transition zone, which is currently the most active part of the whole slide.

(3) Disintegration of the lower part of the slipped material has created a debris flow that now forms half the total length of the slide. This is described as a flow because it moves as a plastic deformable mass, but it may also be regarded as a debris flow slide because it has a well-defined basal shear surface.

The overall landslide mass reaches a maximum thickness of 30–40 m and tapers to all margins (Skempton *et al.* 1989). Its thinner debris toe spreads to a width of 450 m, while the head scar is only 300 m across; the landslide contains about 3.2 M m^3 of slipped material. The slope of the original hillside that failed is estimated as 30–35°, and the mean slope on the slipped material is about 12° (Fig. 4).

Recorded history of the landslide

Mine workings on the Odin vein had no known influence on the landslide until either 1709 or 1711, when the Odin stream was diverted away from the gorge where the mine entrances lay (Fig. 3); the water was turned into a cut ditch which debouches onto the southern edge of the lower slide (Ford & Rieuwerts 1976). This input of water would have had a small negative effect on the slide stability, but there are no movement records from these times. The Knowles Shaft was sunk through the toe of the slide debris in the early 1820s; it now has standing water above a blockage about 5 m down, and it appears that the top of the shaft has been sheared out of line by the continued slide movement. In 1712, the Knowlegates Sough was driven into the limestone, and this lowered the water table by about 30 m. In 1822, the Trickett Sough lowered the water table by another 40 m, to an altitude of around 195 m under the toe of the slide. Both these drainage measures would have had positive impact upon the slide stability, by very small and unmeasured amounts. The main working of the mine ceased in 1869, but the limestone is still freely drained to the 195 m sough level (Ford & Rieuwerts 1976).

The old packhorse route across the Derbyshire Pennines descended the periglacial limestone gorge of the Winnats into the Hope Valley. Too steep for heavy horse-drawn wagons, this route was replaced by a better graded turnpike road, at a date variously ascribed to either 1802 or 1810. The new road took the easiest line, dictated purely by topography, and therefore crossed the landslide twice. Consequently, it is often regarded as a classic case of ‘where not to build a road’, mitigated by the facts that there was no reasonable alternative route and that geotechnical engineering was barely appreciated in that era. Immediately south of the landslide, the new road crossed the main transport level out of Odin mine on a substantial masonry arch only a short way behind the mine portal; this remains stable.

Disturbance and repair of the new road across the landslide was probably a regular occurrence throughout the nineteenth century, but no records are known. Derbyshire County Council kept notes on movements

Table 1. *Recorded displacements to the road across the Mam Tor landslide within the period 1903 to 1998*

Winter	Recorded movements of road surface	Rainfall (mm)	
		1 month	6 month
1910	Cracks alongside road in December	**253**	**752**
1912	Road cracked and twisted in January	**227**	**726**
1915	Subsidence 2.5 m in January	**215**	**800**
1919	Subsidence 0.3 m in December–January	**228**	**868**
1920	Steady movement in December–January	**226**	**758**
1930	Serious slip in December–January	**246**	**987**
1931	Slip with 60 m crack in January–February	*174*	**877**
1937	Displacement 1.2 m in February	**227**	**1049**
1939	Subsidence 0.25 m, 100 m crack in January	**223**	**931**
1942	Subsidence 0.1 m, 30 m crack in October 1942	*184*	*687*
1946	Extensive slip in February	**243**	**791**
1947	New movements in November 1946	**234**	**834**
1948	Subsidence along 200 m of road in February	**309**	**775**
1950	Slip in December 1949	*181*	*683*
1952	Large slip in January	**289**	**906**
1955	Large movement, requiring repairs	**219**	**1092**
1966	Slip, displacement 1.5 m, in December–February	**324**	**1086**
1977	Subsidence 0.4 m, breaks road in February	**264**	**904**
1978	Continued winter movement of damaged road	**218**	**801**
1983	Winter movement of up to 0.7 m	*196*	**869**
1984	Notable subsidence observed but not measured	**237**	**980**
1987	Notable subsidence observed but not measured	**261**	**789**
1988	Notable subsidence observed but not measured	**234**	**800**
1994	Winter movement of 0.6 m	**270**	**802**
1995	Winter movement of 0.6 m	**257**	**1056**
	Mean rainfalls	138	743

The 1-month rainfall for each slide event is that of either the calendar month for which movement was reported, or the previous month, whichever was the higher; for events after 1980, recorded only by the annual monitoring, the cited figure is for the wettest month from November to February inclusive. Figures in bold are rainfalls above the threshold levels, as defined in the text; those in italics are below. The cited movement for 1983 is the mean value for two stations in the most active central portion of the slide (Al Dabbagh 1985).

on the road from 1907 until its final closure in 1979 (Table 1). Increasing traffic demanded engineering remediation, which was carried out as and when necessary, prompted by greater movements of the slide. The main remedial works date from 1912, 1933, 1946 and 1952 (these and the subsequent stabilization measures are discussed below). Late in the 1930s, the road was given its first blacktop surface. There was a further phase of reconstruction in 1966 after serious dislocation of the road in the previous winter (Brown 1966).

Renewed movements of the landslide in February 1977 created major breaks across the upper road, which was therefore closed to traffic. In June of that year, the county surveyor reported on a variety of options for re-opening the trans-Pennine road (DCC 1977); these included repairing and stabilizing the existing road, or diverting the road completely away from the landslide. A series of boreholes provided internal data on the slide for a stability analysis by consultants (Skempton *et al.* 1989). The county surveyor then recommended, in September 1978, that the Council Highways Committee approve the landslide drainage and road repairs in accordance with Skempton's report (DCC 1978). However, the substantial costs of remediation represented a high proportion of the cost of a replacement road on the Pindale route, which had the clear advantage of also bypassing the villages of Hope and Castleton (Fig. 1). Though the Pindale option was therefore favoured, it was delayed by budget constraints, and was subsequently abandoned, when it was realized that traffic patterns had successfully adapted to the loss of the Mam Tor road.

By August 1977 the road had been temporarily patched, so that it was reopened to light traffic on a single lane controlled by signals. Renewed movements in the winter of 1978 required further repair works. The slide movements in the following winter were smaller, but the road was closed again in January 1979; it was never reopened. The upper road has been permanently abandoned except as a bridleway, while the lower road is maintained in a distorted state to provide access to Mam Farm. The slide has therefore continued to move unchecked. Around 1990, a rather inappropriate programme of minor landscaping works obscured some

(a)

(b)

Fig. 5. The breaks in the upper road surface where it crosses onto the active landslide from the southwest. Photographs were taken in (a) 1977, soon after the road was closed to traffic, and (b) 1998. The earth bank across the road below the fence was placed over the landslide's marginal scar in 1990, and has subsequently broken.

geological features, and the new earth bunds were soon destroyed by continued movement of the slide. Blacketlay Barn was largely destroyed in 1983 when the northern sector of the slide toe advanced into it. An overhead power line was placed across the slide toe in the 1940s, and 40 years later was rerouted to the east to avoid the continued movement; surviving bases of the original poles west of Blacketlay Barn are now about 6 m out of line across the northern part of the slide debris.

Observed movements of the landslide

The road across the Mam Tor landslide was closed in February 1977 after the main mass of slide material moved during a month of very high rainfall. The head scar of the zone of active movement almost followed the line of the upper road; it occupied a position similar to that of the main cracks recorded in 1912 (Brown 1966), and has remained as the most active zone of movement ever since. There were three areas where the slide movement and road damage were most conspicuous. Near the upper southern end of the upper road, the entire width of the carriageway was broken as a crescentic sector of the road surface dropped away steeply to the east (Fig. 5) Near the lower northern end of the upper road, the northern boundary of the active zone created a lateral offset in the road alignment, with little vertical component of displacement. The same northern boundary of the moving material displaced the northern end of the lower road; Armco crash barriers that were partly on stable ground were torn from their ground

Fig. 6. The northern margin of the landslide where the slide debris is heaved obliquely up the rising slip surface to create a fresh and rising step in the ground surface. The photograph was taken looking down the slide in early 1977, when the movement rate was at a maximum; the scar is now less active and is largely grassed over.

supports; immediately west of the road, a bank of ground rose over a fresh earth scar where the rim of the slide debris was heaved obliquely up a slip plane which rises to intersect the ground surface (Fig. 6).

The main landslide movement occurred within about two days, and the landslide was observed immediately after this. At each of the above three sites, the total slide displacement was in the order of 500 mm, with the vectors as described above. There had been precursory movements over the preceding few weeks; these had required that breaks in the road surface were patched by manual application of asphalt at increasingly frequent intervals, until road closure was enforced by the major movement. Landslide movements at a reduced scale were observed to continue for a few weeks, into March; they then appeared to cease before the summer, though no measurements were taken at that time. Total displacements over the winter were in the order of 600 mm. Renewed movements were seen to take place over many of the succeeding winters, but there was then no systematic documentation of the landslide.

Monitoring surveys on the landslide road

Regular monitoring of the Mam Tor landslide was started in 1990. A chain of 46 survey stations was established along the upper road so that it completely

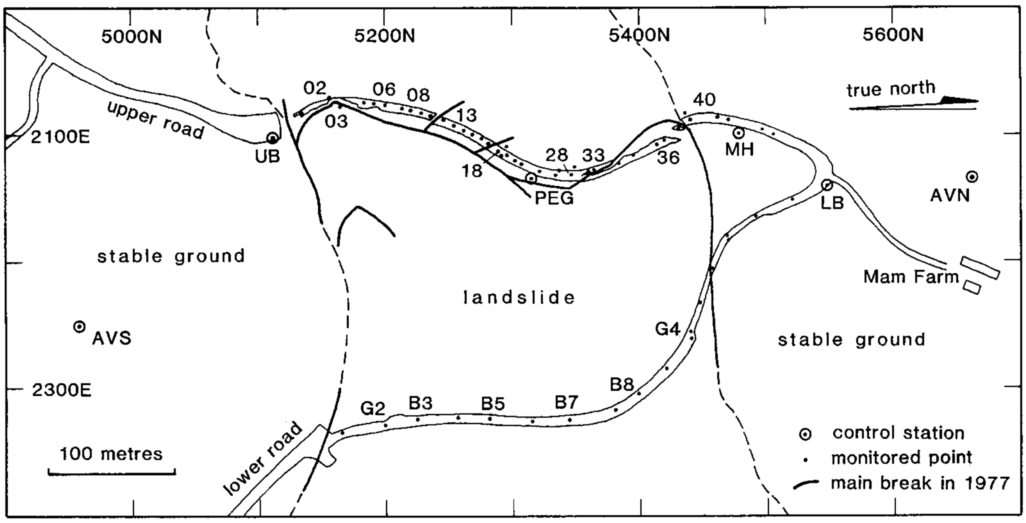

Fig. 7. Positions of the surveyed monitoring points and the fresh head scars that have been active since the 1977 road closure. The superimposed grid is the arbitrary frame created for the surveys, whose grid north is 3° east of true north. Only those monitored points that are referred to in the text are numbered.

crossed the landslide between base stations on stable ground to both north and south (Fig. 7). The site was then re-surveyed each year by groups of students from Nottingham Trent University as class exercises in the final year of their diploma courses in Engineering Surveying; this continued until the last of the projects in 1998.

The main survey control was established by closed loop traverses using a variety of optical and electronic theodolites with add-on EDM, and also electronic total station instruments including the Nikon DTM-A20 and Geodimiter 504. Level control was similarly observed in closed loops, using automatic and tilting optical levels and a Leica NA3003 digital level. The baseline between the AVN and AVS control stations (Fig. 7) was checked in 1994 using two Leica System 200 GPS receivers. The monitoring points were all levelled in closed loops, and were co-ordinated (and levelled by trigonometric heighting) by radial observations from control stations. All points were sighted at least twice; further repeated sightings, by multiple groups of students using a variety of survey techniques, produced an unusually high degree of checking. Gross errors were easily recognized; questionable data were then either recalculated or eliminated.

The academic timetable dictated that surveying was in the late spring of each year. Smaller groups of the same students on their final year projects carried out additional surveys in the autumn months of some years, in order to provide data on winter and summer movements of the landslide. In 1994, 1995 and 1998, further project groups surveyed a chain of 20 stations along the lower road, also completely across the landslide (Fig. 7).

The survey station data tabulated and presented in this paper has been abstracted from the far greater databases prepared by the survey teams and presented in their unpublished project theses (of which the most useful are by Poole & Powell (1994); Core (1995); Reed (1996) and Ivens (1997)). (The full matrix of coordinates from this period of surveying is recorded in the University Department, and is available on application by anyone with an ongoing monitoring programme.) After elimination of dubious data, it is considered that the computed station coordinates presented here are accurate to ± 5 mm. Due to reduced student numbers and a consequent shortage of data replication, the station coordinates for 1998 are better regarded as ± 10 mm.

Two other sets of monitoring data by repeated surveys have been recorded on the Mam Tor landslide since the road closure in 1977. Sheffield University monitored 21 stations scattered across the landslide in October 1981, October 1982 and May 1983 (Al Dabbagh 1985). Manchester University installed 16 new monitoring stations and included measurement to some of the Nottingham Trent stations in surveys in May 1996 and April 1997 (Arkwright 1997), and intends to continue with annual re-surveys.

Structure of the landslide

The Mam Tor landslide has a complex structure which can be divided into 16 component elements (labelled A–T) on the basis of the surface geomorphology (Fig. 8); interpretation of the subsurface structure relies on the ten boreholes cored as part of the 1977 investigations (Skempton *et al.* 1989) and on the movement vectors of the different elements recognized by the surveyed monitoring.

The exposed head scar continues to degrade, supplying the colluvium of element C, which extends over the upper edge of the landslide mass. Elements D and E are small solifluction flows within the colluvium. There are no large failures in the sandstone head scar, but regressive failure of the shale head scar, south of the fault, has created the subsidiary rotational slide blocks F and G, of which only the former is currently active.

The upper part of the slide mass is a complex of slipped blocks or slices (elements H, J and K, and a part of H covered by the colluvium of element C). These were created when the original landslide mass broke up as it moved over its non-circular slip plane. Boreholes 6, 7 and 8 (Fig. 8) revealed that their internal structure is largely intact, except that they have rotated backwards during movement down the curved slip surface. Elements J and K are recognized by their fresh head scars; they are probably close to the size of the many blocks which constitute element H. Individual blocks within element H probably account for the larger lumps in the very irregular terrain (Fig. 9), but they cannot currently be distinguished by fresh surface scars. Much of element H rests on a slip surface dipping at about 6°, and is consequently moving slowly. Backward rotation causes sagging of its back end against the head scar, to create a zone of depressions and poorly drained ground. Its front end is breaking up where it moves into a zone with a steeper basal slip surface. Element K is such a breakaway block, moving nearly twice as fast on a steeper basal slip surface, and element J is a graben sinking behind it.

Elements L and M are moving much more rapidly, above a more steeply inclined slip surface. The steeper movement may indicate that this active slip zone is located immediately downslope of where the original slip plane returned to daylight (Fig. 4). The slide blocks are therefore slumping down the pre-slip hillside, and are progressively breaking up as they do so. Variation in the dip of the movement vector at monitoring point 03 (Fig. 7) may indicate a measure of breakup between multiple shear planes at the head of element L. Together with element N, this central part of the slide represents a

key	landslide element	movement mm/year	dip of basal shear
A	Head scar in Mam Tor Sandstone, north of fault	0	~50
B	Head scar in Edale Shale, south of fault	0	~35
C	Scree, colluvium and fans below head scar; partly covering upper end of slide complex H	-	-
D	Solifluction lobe within scree and fans	?	~25
E	Subsidiary solifluction lobe within D	high	~25
F	Regressive slide block from shale head scar	low	~30
G	Group of four minor regressive slides	very low	?
H	Main complex of multiple slide blocks; component sections not currently definable	107	6
J	Graben block descending between H and K	154	23
K	Subsidiary block active on front of H	177	20
L	Main active frontal block	234	29
M	Northern active frontal block	248	21
N	Central zone of active multiple blocks; individual boundaries not clearly definable	high	10
P	Southern edge degenerated into active debris flow; boundary to T not clearly definable	93	8
R	Main active toe debris flow; boundary to T not clearly definable	149	~5
T	Less active southern part of toe debris flow	very low	~4

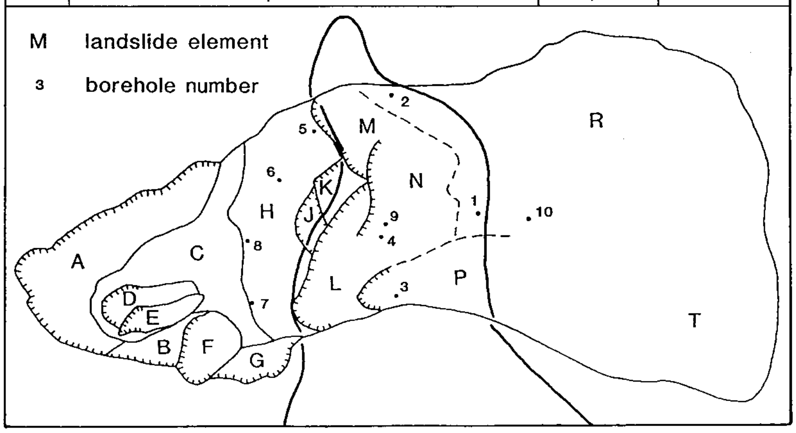

Fig. 8. The main elements of the Mam Tor landslide. The 16 identified elements are identified by the same letters on the map and in the table. Their movement rates are the mean annual rates achieved over one wet year and three dry years. The dip of their basal shear is the angular vector of their monitored movement, as shear surfaces are not exposed; cited figures are mean values for the sector, so are less than the dip at the respective head scar. Movement rates on elements E, F and N are interpreted from only two years' data by Al Dabbagh (1985). Borehole numbers are those assigned by Skempton *et al.* (1989).

transition from the slide blocks above to the debris flow below; cores from boreholes 2, 4 and 9 (Fig. 8) contained little intact rock.

Further displacement of the slide material has broken it into a debris flow that forms an extensive toe of the slide; the active part is element R, which continues to move over a basal shear surface dipping at about 5°. The plastic nature of the debris flow is demonstrated by the distortion of the lower road; though badly twisted and moved considerably out of line (Fig. 10), it has no major breaks in the blacktop, except along the marginal shears. In contrast, the upper road has developed large steps where it crosses the boundaries of independently moving slide blocks.

The main mass of the landslide is moving to the northeast. This is a direction in between those of the ground slope and the stratal dip, and therefore appears to be influenced by both aspects. Close to borehole 2 (Fig. 8), this movement heaves the rim of the slide mass obliquely upwards where the main shear surface curves up to daylight (Fig. 6). The southern part of the slide mass is away from the main movement. Element P is a thin sheet of debris with slow movement to the east. Element T is an almost stationary part of the debris

Fig. 9. The upper road across the landslide is broken by the head scars of element M as this cuts into the stepped and hummocked ground created by the multiple slide blocks which form element H, as seen in 1998.

flow, partly in the lee of the limestone bluff of Treak Cliff. Since 1977 there has been no noticeable movement of the landslide toe at Knowlegates Farm (Fig. 3), while Blacketlay Barn (Fig. 3) has been destroyed by the toe advance in the same period.

The minor landslides downslope of Mam Farm appear to be shallow failures developed entirely within the weathered zone of the Edale Shales and their head cover.

Patterns of movement of the landslide

From the matrix of accumulated survey data, both temporal and spatial patterns can be recognized within the movement of the Mam Tor landslide. Absolute rates of movement for seven points on the landslide are summarized for wet winters (as defined below), dry winters and their long-term mean in Table 2; the recorded data are representative of movements across the landslide. Plan movements of eight of the monitored points along the upper road show considerable contrasts due to their locations on separate blocks within the landslide complex (Figs 7 and 11), which are clearly identifiable from the surface breaks between them. The same data show contrasts in the rates of movement during the wet winters of 1994 and 1995 with those in the five drier winters between 1992 and 1998. Both aspects are discussed below. Horizontal components of movement are indicated by arrows drawn to scale length on Fig. 3; some of these arrows have been scaled from interpolations of data by Al Dabbagh (1985), and the length of one arrow has been derived from the position of a 50 years old power wire pole that is now out of line with poles on the stable slope below Mam Farm. Displacement data for points omitted from Figs 3 & 11 show similar patterns to those on the same landslide blocks.

Fig. 10. Severe distortion without major fracturing of the lower road across the debris flow elements of the landslide in 1998.

Vertical components of movement also distinguish the different parts of the landslide, as are represented by the ten monitored points in Fig. 12. The same figure also correlates landslide displacement with rainfall, as further discussed below. Vertical and horizontal components of displacement are related where the slide blocks move over clearly defined slip surfaces (Fig. 13). The unwavering dip of the movement vectors for points 36 and G2 imply that these lie above single, but different, slip

Table 2. *Summary of absolute movements of the different elements within the Mam Tor landslide*

Monitored point	Landslide element	Annual movement (mm)		
		Mean	Wet year	Dry year
Main complex of multiple slide blocks				
06	H	118	324	30
13	J	154	424	35
18	K	177	454	49
Active frontal blocks				
03	L	234	567	37
36	M	248	658	56
Toe debris flow				
B7	R	149	324	90
G2	P	93	200	62

Data are for representative monitored points, on landslide elements as identified in Fig. 11. Mean movements are over 4-year periods of one wet year and three dry years; these have been calculated from seven sets of data through two wet and five dry winters on the main part of the landslide and its active frontal blocks along the upper road, and from four sets of data through one wet and three dry years on the debris flow underlying the lower road. For the main and frontal slide blocks, the wet and dry years' movements are the extremes from the period 1991 to 1998; for the debris flow, the wet year movement is that for 1995, and the dry year rate is the mean of the years 1995–1998.

surfaces. The conspicuous variation in the vector dip for point 03 is due to its location over a complex of shear planes in the head scar of an active element of the landslide. For the same reason, points 18 and 28 may be interpreted as lying above multiple active slip surfaces, but some of the relative movements are smaller and are close to the limit of survey accuracy. Point B7 may be expected to move more erratically where it is located on the deformable debris flow, but further years of survey data are required to confirm this.

Correlation of rainfall and slide movement

The growing records of road damage on Mam Tor since 1909 have long demonstrated that slide movements occur during unusually wet winter months following wetter years, with most movements in January or February. Rainfall stations at Mam Nick and Edale Mill are both less than 2 km from Mam Tor, but their records are short, and data starting in the last century are available from the station at Buxton Town Hall. Mean rainfalls at all three stations are within 1% of each other, and the long sequence of Buxton data has been taken as representative of the rainfall on the landslide for the purposes of statistical analysis; at both Mam Tor and Buxton the rainfall is largely orographic due to the prevailing westerly winds.

The recorded list of slide movements has been correlated with preceding rainfall over periods of 1, 3, 6 and 12 months since 1903. Landslide events correlate most closely with a combined record of the preceding 1 and 6 months rainfalls. This is demonstrated in Fig. 14, where the 1-month figures refer to rainfall in the wettest of the calendar months between November and February inclusive. The 6-month figures are the higher of those for the inclusive periods of July–December or August–January (but denotes only the former if a slide movement was recorded for December). Each record is dated by the winter of its occurrence, and each winter is dated by the year of its January; an annual record

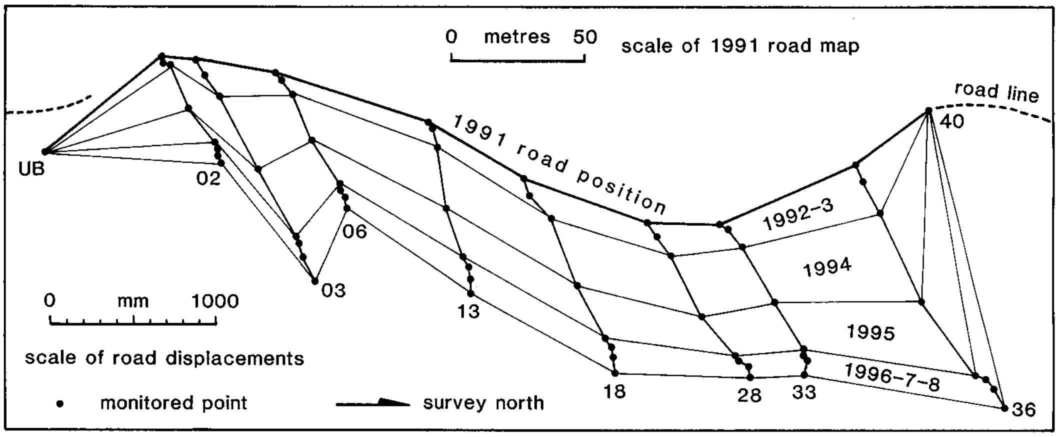

Fig. 11. Progressive plan displacement of selected monitoring points along the upper road. The 1991 position of the road is drawn to scale, and the vectors to subsequent positions are drawn at a scale 62.5 times greater. The winters of 1994 and 1995 had rainfalls that passed the threshold levels to trigger enhanced movement of the landslide; the other five years had no months with more than 210 mm of rainfall. All survey stations lie along the centre line of the road, except #02 on the western edge and Upper Base on the eastern edge of the old turning circle.

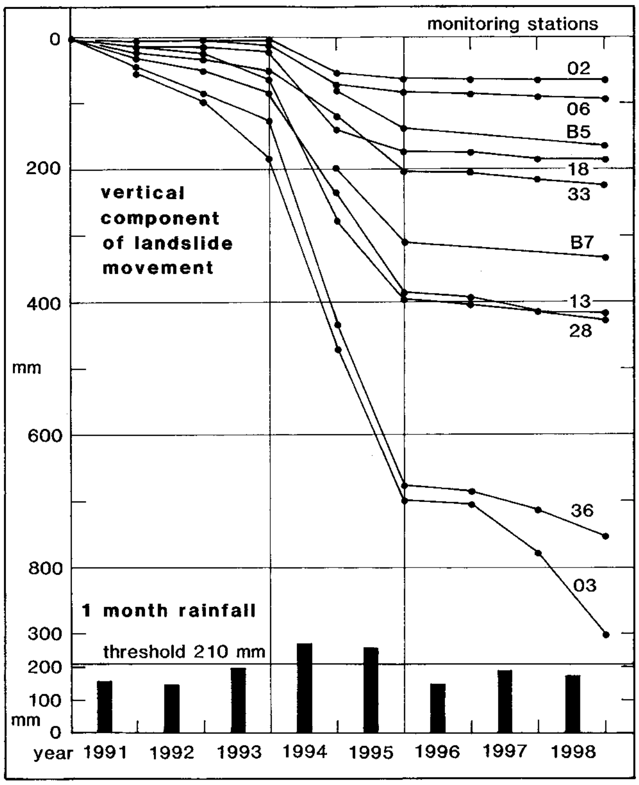

Fig. 12. The vertical components of movement at ten monitored points on the landslide, correlated with the highest winter month's rainfall in eight successive winters. Movement is not proportional to rainfall; it increased greatly when the threshold level of 210 mm in a month was exceeded in the winters of 1994 and 1995, compared with the drier winters both before and after.

therefore includes any landslide events of the previous year's November or December. Similarly, the 6-month rainfall figure starts in the July or August of the previous calendar year; it starts in June where it denotes the rainfall preceding a very wet November. Rainfall data have been included in Table 1 for the occasions when significant landslide movement has been recorded, and each event is dated on the same basis. The 1-month figures refer to rainfall in the wetter of the two months including and preceding the recorded movement; this recognizes the immediately preceding rainfall, as the movement event is only recorded by the month, and could have been either early or late within that month.

Rainfall thresholds for enhanced movement

The correlated data indicate that increased movement of the landslide occurs when rainfall exceeds 210 mm in a calendar month between November and February inclusive, during a winter that follows a 6-month period with more than 750 mm of rainfall. The 210 mm threshold is a value 50% above the mean monthly rainfall for the four winter months, while the 750 mm threshold is close to the mean value for total rainfall in the autumn months of August to December plus the wetter of the adjacent July or January.

A 1-month rainfall of over 210 mm has occurred in 31 of the 96 recorded years, but eight of these events followed dry autumns with less than 750 mm in the

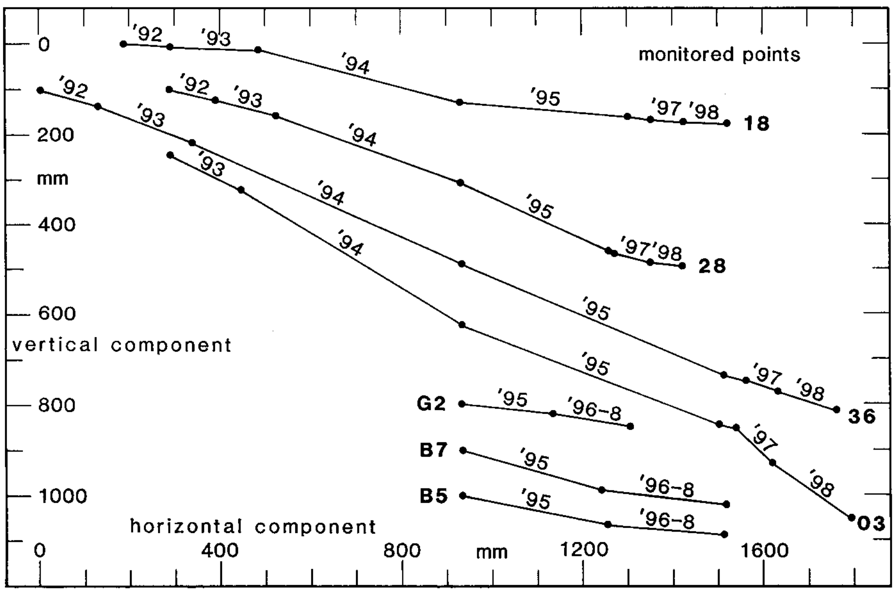

Fig. 13. Vertical vectors of movement at seven monitored points on the landslide. Segments of movement are labelled by the year of the January of each winter.

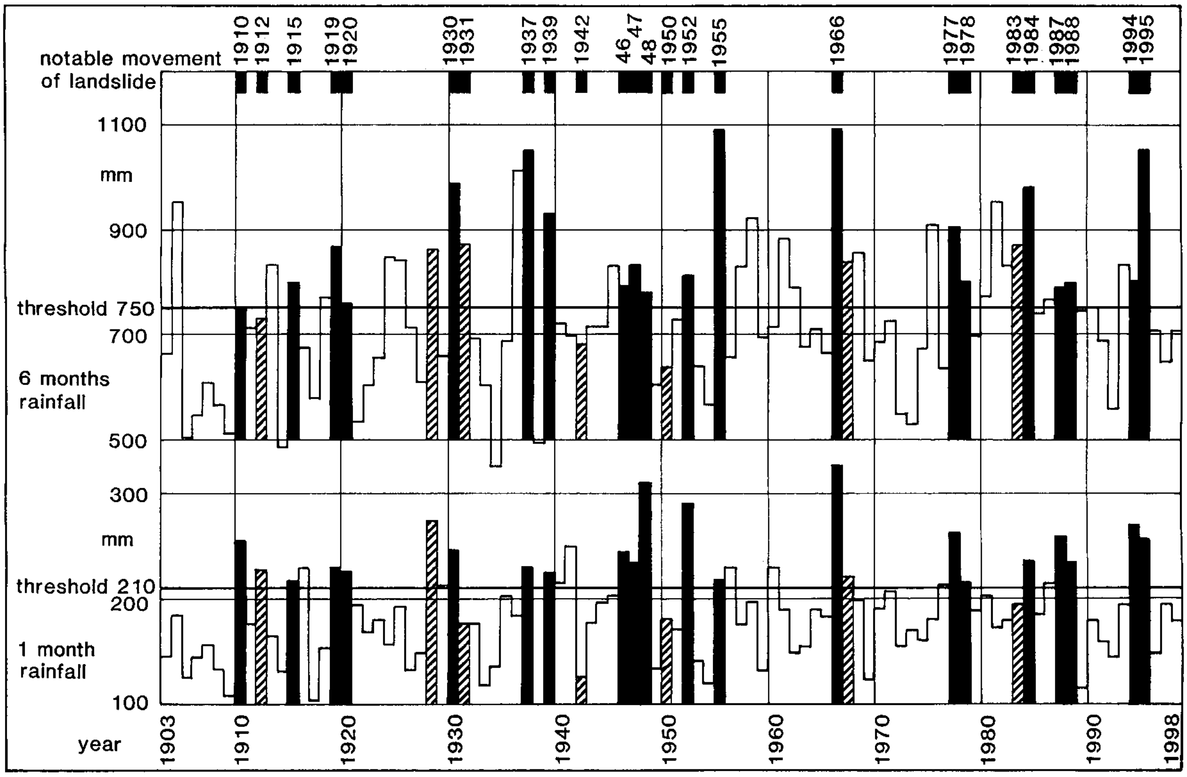

Fig. 14. Correlation of rainfall patterns and landslide movements 1903–1998. Each year refers to the winter at its start, and therefore includes any landslide movements that occurred in the November or December of the previous calendar year. The 1-month rainfall figure is that for the wettest calendar month in the winter of November to February. The 6-months rainfall refers to either the period July–December of the previous year, or the six months up to and including a notably wet winter month. Landslide events are those documented as significant (as listed in Table 1). Years with the rainfall bars in black are those where both threshold levels were exceeded and landslide movement therefore increased. Years with oblique ornament in the rainfall bars lacked the normal correlation between rainfall and landslide movement.

preceding six months. Accelerated movements of the landslide occurred as a consequence of 20 out of the 23 events when both rainfall thresholds were passed. Slide movements were also notable on four other occasions in marginally drier winters. The repeat period of significantly large slide movements is close to four years, and this is a function of the rainfall patterns.

There are seven years where landslide movements appear not to conform to these rainfall criteria. In the winters of 1928 and 1967, rainfall patterns exceeded the threshold values, but there are no records of significant movement. Data on the landslide may be incomplete for 1928. The maximum monthly rainfall of 219 mm in 1967 was close to the threshold, and activity could be expected to be reduced directly after the major movements and subsequent engineering works of 1966. Slide movements in 1912, 1931, 1942, 1950 and 1983 occurred when rainfalls were below one or both of the threshold values. The 1983 movements were recorded on the most active part of the slide between the roads, and the upper road experienced almost no displacement (Al Dabbagh 1985). Magnitudes of the 1912 and 1931 road cracks are not recorded, and the latter followed a period of seven consistently wet months. The 1950 event was of unrecorded scale in December 1949 when rainfall at Buxton was only 181 mm, but unusually localized rainstorms may have distorted the figures, as 230 mm of rainfall was recorded for the month in the Hope Valley (Skempton *et al.* 1989). The movement in October 1942 was an anomaly, though its recorded subsidence of 100 mm was little more than the vertical movement that occurs on parts of the slide in any year; it followed an erratic rainfall pattern through a generally wet summer when alternate wetting and shrinkage cracking may have weakened part of the slide mass. It appears that none of these anomalies was of great significance.

The 1-month and 6-month rainfall thresholds correlate with the landslide movement for 89 out of the 96 years, and are more significant than 3-month or 12-month rainfall patterns. The landslide movements are dependent on increased porewater pressures, which are generated largely by direct rainfall infiltration. Abnormally high rainfall inside a single winter month is adequate to mobilize the landslide, as long as it does not follow a second half of a calendar year which is drier than normal, in which case groundwater levels are

Table 3. *Seasonal variation of absolute movement rates on the landslide*

Season	Period	Movement of the landslide	
		mm total	mm per month
Upper road in dry years			
Winter	November 1995–March 1996	37	9
Spring–summer	March–November 1996	23	3
Winter	November 1996–February 1997	40	13
Spring	February–April 1997	13	6
Lower road in wet year			
Winter	November 1994–February 1995	205	68
Spring	February–May 1995	92	30

Rates for the upper road are the means of data from eight monitoring points, and for the lower road are the means of data from four points.

initially low. It is significant that renewed slide movements are dependant on critical patterns of antecedent rainfall, as has been recognized on comparable large slides elsewhere (Bromhead *et al.* 1998). The limited data on groundwater levels in the landslide mass (Skempton *et al.* 1989) indicate a rapid response to rainfall; this also implies the importance of direct infiltration. Mean groundwater levels are about 8 m below ground level in the upper and central parts of the landslide, but lie only about 2 m deep in the debris flow.

Spring-fed groundwater appears to be of little relevance to the landslide. There is one small spring where the minor fault is cut by the head scar (Fig. 3), but the main flow of groundwater in the sandstones of the Mam Tor Beds is downdip to the north, away from the slide zone. Very small springs and seepages in the debris flow part of the slide contain a proportion of deep seated groundwater (Vear & Curtis 1981); these may affect the current stability of the debris flow portion of the landslide, but they lie downslope of the original failure. The karst water table in the limestone is below the level of the entire landslide, and there is no evidence of flow from the limestone into the shales.

In the winters when rainfall thresholds are not reached, there is only minimal movement of the slide mass. In the central most active part of the slide, movement in a dry year is around 60 mm. The same ground is displaced about 500 mm in a wet year. The rate of movement does not rise in direct proportion to the rainfall, but increases sharply once the threshold rainfalls are reached (Fig. 12). Mean long-term movement rates for each part of the slide may be taken as the movement over a four-year cycle of one wet year and three dry years. The mean rate for the main bulk of the slide is therefore about 150 mm/year, while the most active parts move at a mean rate of over 200 mm per year. The debris flow of the landslide also responds to the rainfall thresholds, but the lesser amount of data on this area suggests that movement is more readily maintained by low rainfalls through the drier winters.

Seasonal variations of movement

There is only a limited amount of data on seasonal variations of movement rates (Table 3); as the low rates measured over short periods during the dry years are close to the limits of the surveying accuracy, mean values from groups of data sets are cited. Rates of movement decline in a spring to about half the rates achieved in the preceding winter. It appears that rates further decline into the summer, and comparison of the 1996 and 1997 data for the upper road implies that movement slows to a stop in the later part of the summer. After the very wet winter of 1966, movement rates of 24 to 165 mm/month were recorded on parts of the slide (Brown 1966); these were measured late in the dry month of January when groundwater levels were still high after the exceptionally wet December, and represent the elevated rates that persist late in a wet winter. Observation of the road damage in 1977 revealed that movements approaching 400 mm could occur within about two days, but there are no more accurate data on these short peaks of movement rates.

Stability of the landslide mass

The stability of the Mam Tor landslide mass in its current state depends on the geometry of its basal slip surface, the shear strength of its component materials and the groundwater levels at various times of the year. None of these parameters is completely known, and any stability analysis can be only an approximation. Back analyses of various components of the slide are confirmed by factors of safety which range above and below unity when groundwater levels are at summer lows and winter highs respectively. This approach provides a reasonable assessment of the current stability of the slide mass (Skempton *et al.* 1989), which can be modified slightly in the light of the patterns of movement recognized from the survey monitoring.

The main mass of landslide blocks (element H on Fig. 8) is advancing slowly over a slip surface dipping at only 6° (Fig. 4). Its driving force is its upper end, where the slip surface is curved to a steeper dip; increases of head load by the scree, colluvium and regressive slides of elements C and F have a modest positive effect.

The central transition zone of the slide, elements M, N and L, is the least stable sector, as it rests largely on the steeper slip surface that was the groundslope below the original slide toe. It has the largest movement on the steepest angle. It is not being pushed by the main slide mass, element H, which is moving more slowly. Its movement away from the main mass, has created a graben (element J) in the tension zone, and permits unsupported slices to fall away from the front of the more stable ground (elements J and K).

At the toe of the slide, the debris flow is moving slowly on a gradient which decreases from about 10° to 4° down its length. It is being pushed by the faster moving transition zone, so that its upper part is crumpled into transverse pressure ridges that decline in number towards the toe. Its southeastern part, element T, lies away from the northeasterly driving force of the transition zone, and is now almost stationary. Its northern marginal zone is bounded by a shear (Fig. 3) and also appears to be nearly stationary, but its movement has not been monitored.

Much of the main landslide mass (element H) and most of the debris toe would be stable on their very gently dipping basal shears, if they existed in isolation. However, they remain unstable because of the interdependence of the individual elements within a complex slide mass such as this. The main driving force for the whole landslide is the transition zone of elements M, N and L, which move so readily during wetter winters. Following these intermittent events, stress redistribution may be expected to account for part of the landslide movement during the drier winters, though there is no evidence for this in the available data on the landslide's movement history.

The effects of increased residual strength in the shear zone due to increased strain rate were examined by Wedage *et al.* (1997); their rate-dependant model reveals a damping effect, with slow initial movement followed by ongoing creep. This was a theoretical finite element analysis based on the earlier, limited data on movement rates; it ignores the landslide's major internal shears. The new surveys provide minimal data on short-term movements, and more data on the interaction between the landslide blocks is required before the validity of the rate-dependent model can be established for the Mam Tor landslide.

The geometry of the initial slope failure is also open to interpretation. The original slip surface is identified in boreholes 6, 7 and 8 (Figs 3 & 8), but its depth is unknown upslope of these positions. Skempton *et al.* (1989) assumed a shallow profile in this sector. Optimum stability analysis (Reed 1996) suggests a slightly deeper profile, which is also commensurate with both the slope of the exposed head scar and the current movement vector of slide element H. This profile has been incorporated into the landslide long section (Fig. 4).

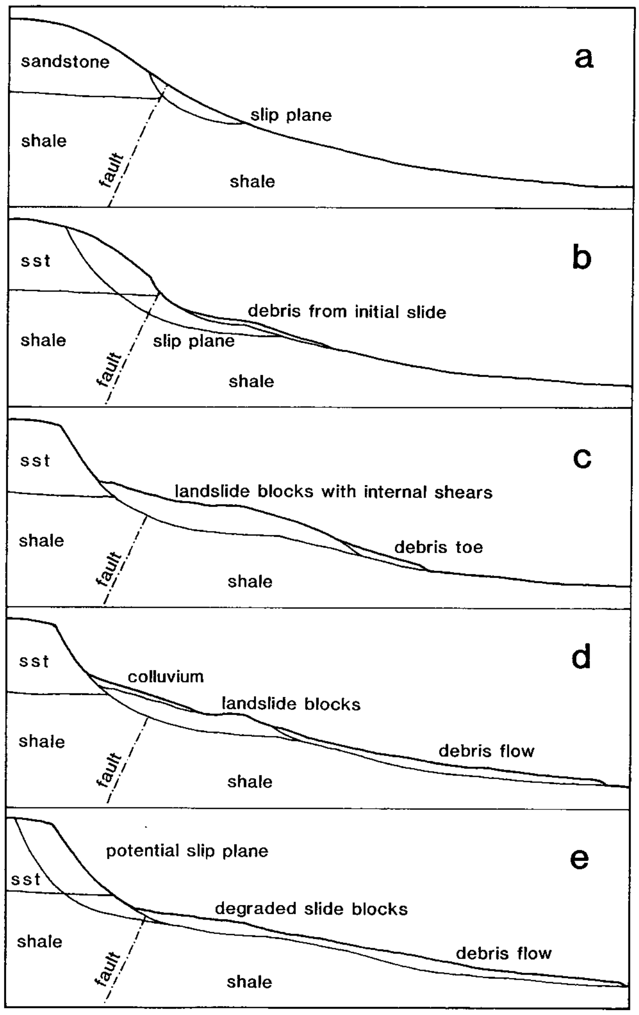

Fig. 15. Stages in the evolution of the Mam Tor landslide: (a) the original unstable slope, before any failure; (b) after a possible small initial failure of faulted shales, with a larger failure imminent; (c) just after the main rotational landslide, with an early stage of debris flow development, by 4600 years ago; (d) the present situation, after degradation of the frontal slide blocks and extension of the debris flow; (e) before a repeat failure of the head scarp following erosion and slumping of slide debris, in the distant future.

Initiation and history of the slope failure

The original slope which failed at Mam Tor was formed in the sequence of sandstones overlying shales where they were cut by a small fault. The Mam Tor Beds constitute a poor aquifer and have many small springs at

Fig. 16. Severe damage to the upper road on the southern part of the landslide, as it was in 1998. The road has slide element L falling away to its left, and steps down onto element J in the foreground. Intermittent remedial works have set the road further into the slope, creating the steep bank with trench drains on the right; the same works have placed fill to support the left of the road, but have therefore head loaded the active landslide element L.

their base on downdip slopes. The one small spring in the landslide head scar (Fig. 3) appears to emerge from the fault; its ochreous waters indicate removal of pyrite and carbonate (Vear & Curtis 1981) on a scale that may have created significant weakness within the fault breccia. The fault lay obliquely across the slope so that an unbuttressed wedge of shale stood in front of a mass of sandstone. A failure of this shale wedge (Fig. 15a) could have been a precursor to the main slide event (Fig. 15b).

The primary failure of the Mam Tor slope is interpreted as a rotational landslide (Fig. 15c). It is likely to have been a single large event, when a mass of rock moved rapidly over a shear zone in which strength was reduced to its residual value for the first time. The lower section of the slip surface dipped only gently and parts of it appear to have followed bedding planes in the weak Edale Shales; it emerged to daylight at a level close to that of the hairpin bend in the road. Displacement was towards the northeast, oblique to the surface slope, but deflected towards the direction of the shale dip. The steep upper part of the slip surface cut through the Mam Tor Beds. These sandstones were too strong to be sheared, and the slip surface would have been stepped on joints through the thin sandstone beds and then along the intervening shale beds.

From the initial rotational failure, the failed mass broke into a complex of blocks and slices as it was deformed by its movement over a non-circular basal slip plane. The toe of these landslide blocks advanced down the unfailed lower slope, breaking up to create a mass of debris (Fig. 15c). This material has continued to flow down the slope as it is recharged by faster movement and subsequent disintegration of the front of the landslide slices resting on the steepest part of the slip surface (Fig. 15d). Renewed failure of the head scar will only occur when the existing slide blocks have slumped and been eroded enough to reduce support at the foot of the shale slope where a new slip surface must emerge to daylight (Fig. 15e). The almost stable nature of these blocks (element H, resting on an almost level slip surface) implies that such a failure is not imminent. Major failure of the sandstone scar is unlikely because it would require significant dilation of the slope face to allow displacement over a slip surface stepped across the bedding and joints in the units of stronger rock.

Evidence for the age of the landslide comes from a tree root, radiocarbon dated to about 3200 years old, extracted from an older peaty soil beneath the landslide and recovered in borehole 10; this was used to extrapolate an age of about 4600 years for the initiation of the landslide, assuming more rapid movement in the early stages (Skempton *et al.* 1989). The crest of the head scar breaches the ramparts of an Iron Age hill fort (Coombs & Thompson 1979); their misalignment suggest that they post-date the slope failure, and they are about 2000 years old.

The sheltered eastern slope of Mam Tor would have collected wind-blown snow in nivation hollows during the late Devensian, and periglacial freeze–thaw over a deeper permafrost may have weakened the slope and enhanced any instability. The extrapolated age of 4600 years implies that Pleistocene events were too early to be of significance to the main slope failure, unless the early history of the landslide included a longer period of slow intermittent movement. Any instability due to glacial oversteepening of the slope is also unlikely if the failure developed entirely within the Holocene.

Three aspects of the geology appear to provide the factors that distinguish the failed Mam Tor slope from the adjacent stable slopes in the same rock sequence. Along the stable northern side of the Hope Valley the stratal dip is directly into the slope of the Lose Hill ridge, while there are three large slides along the northern slope of the ridge (Fig. 1) where the dip is gently out of the slope. Where the ground slope turns towards the dip direction round the head of the Valley, only the Mam Tor slope is broken by a fault. The sandstones in the Mam Tor Beds reach their maximum development in the eponymous hill, thereby preserving a steeper upper slope, which was undercut by erosion of the underlying shale. The concurrence of these three aspects favoured landslide development at this site.

The juxtaposition of the upper road and the active zone of subsidiary slide scars suggests the possibility that ground vibration from heavy lorries may have triggered

(a) (b)

Fig. 17. Displacement of the upper road where it crosses landslide element M. Photographs were taken in (a) 1977 and (b) 1998. Movement is downwards and to the right at a mean rate of 0.25 m per year.

some movements. There is however no positive evidence for this, and there has been no decline of the movements since the road was closed.

Stabilization of the landslide mass

Various remedial works aimed at stabilizing the road across the Mam Tor landslide have included small drainage schemes and some regrading of the surface profile. Many of the minor measures were completed, but a major drainage scheme only reached the planning stage before it was terminated for external reasons.

In 1933, shallow drains were installed in the marshy area behind the main slide mass (parts of which are again marshy today), above the upper road. These progressively lost efficiency due to siltation and their outlet was ultimately broken by head scars in zones of renewed movements; the remains of the drains now discharge onto the slide mass. Until they were broken these drains must have had positive impact on the slide stability. However, movement of the slide responds to direct short-term rainfall over its entire area. These drains are in the more stable part of the slide, where their benefit is minimal.

During the 1940s, the upper road was substantially realigned by cutting it further back into the hillside of landslide blocks; excavated material was dumped beside the lower section of road, and one segment of the upper road was abandoned on a shoulder. The upper road was also set back into the hillside on various other occasions, with the immediate aim of keeping it away from the active head scars above slide elements L and M (Figs 16 & 17). These realignments into the hillside had minimal positive impact on the overall stability of the landslide; some parts had an adverse impact by unloading the toe of element H. Furthermore, the importation of large amounts of crushed limestone and lead mine waste to add to the failing downslope flank of the road had negative impact on stability by loading the head of the least stable elements within the slide mass.

There is no convincing evidence that any of these modest remedial works had significant impact on the slide stability. The lack of major movements in the marginally wet winter of 1967 may be partly due to preceding remedial works in 1966, but there is no perceptible change in the threshold rainfall levels that have induced movements recorded through most of the century. For a major, but non-essential, road across such a slowly moving landslide, the philosophy of repeated repairs and minor remedial works appears to have been the most appropriate and economical for the Mam Tor site.

Proposals to stabilize the landslide were based on the analysis carried out after the destructive movements of 1977. They centred on drainage adits driven into the centre of the slide mass. Four adits were proposed on each of two levels, one below the upper road, and one just above the lower road; the adits were to be of 1 m diameter, installed by pipe-jacking, with slight positive gradients to permit free outward flow. Each adit was to extend far enough to reach the main slip surface, about 70 m in from daylight. The road was to be realigned back into the hill just above the hairpin bend to pass west of the very active subsidiary slip surface, and associated earthworks including filling in and draining some of the ponds on the slide mass. The total cost was going to be about £2M (over £4M at 1998 values), but the works were cancelled in favour of a replacement road up Pindale. The drainage works were intended to lower the water table by about 1.5 m; this should have kept the factor of safety above unity in even the wetter winters, and thereby eliminated the larger and more destructive movements.

Movement patterns identified by both this and the other monitoring surveys (Al Dabbagh 1985; Arkwright 1997) indicate that both the upper zone of landslide blocks and the lower debris flow are approaching stability. The central zone of the slide is however unstable, due to its steeper basal slip surface; its continuing movement pushes the head of the debris flow and also removes support from the uphill slide blocks. A catastrophic event in the future is unlikely, and could only affect the steep central zone of the landslide mass between the roads. Slow intermittent movement is likely to continue. The monitored patterns of enhanced movement through wetter winters imply that drainage of the central part of the slide would have been the most effective means of stabilization. However, the continued smaller displacements through dry winters imply that drainage works would not prevent all damage to the road; the decision not to carry out major remedial works appears to have been appropriate.

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