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THE QUATERNARY EVOLUTION OF THE BRITISH SOUTH PENNINES FROM URANIUM SERIES AND PALAEOMAGNETIC DATA

by

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(9 figures and 1 table)

ABSTRACT.- At the southern extremity of the Pennine Range in central England, Carboniferous Limestone is exposed and forms in part an uneven plateau deeply dissected by gorge-like river valleys (Dales).

Analyses of uranium and thorium isotopes in calcite samples from thick flowstones within a high level relict cave remnant (Elder Bush Cave) indicated that the formations were beyond the range of the uranium-thorium dating technique (350 ka). $^{234}U/^{238}U$ isotope activity ratios approached unity, suggesting that the flowstones may have formed a considerable time before 350 ka. Palaeomagnetic samples taken from cores drilled through the flowstones showed the presence of both normally and reversely magnetized calcite. In some cases reversely magnetized layers overlie normally magnetized layers. This evidence, taken in conjunction with the uranium isotope data, is interpreted as indicating an Olduvai age (1.66-1.87 Ma) for some of the flowstone horizons. It is suggested that the cave became vadose by or soon after 2.0 Ma.

The position of the cave near the valley rim enables an estimate to be made of the maximum rate at which the present valley has been excavated. This is calculated to be 5.5 cm/ka. Remnants of old valley floors preserved within the existing valley suggest that downcutting has not been a continuous process. Flowstone from a cave on one of the lower valley floor remnants (Darfur Ridge Cave) has been dated to 284 +34/−27 ka allowing a maximum downcutting rate since that time of 11.2 cm/ka. The proximity of Elder Bush Cave to the valley crest suggests that its abandonment marked the onset of the incision of the present system of dales that characterize the English Peak District, presumably initiated by epeirogenic uplift or tilting.

RESUME.- Evolution quaternaire du sud des Pennines britanniques à partir des données des familles de l'uranium et du paléomagnétisme. Le Calcaire Carbonifère qui affleure à l'extrémité sud du massif des Pennines en Angleterre centrale forme en partie un plateau accidenté qui est profondément disséqué par des vallées en forme de gorges (*Dales*).

Des analyses des isotopes de l'uranium et du thorium, effectuées dans des échantillons de calcite d'épais planchers stalagmitiques situés dans une grotte de haut niveau (Elder Bush Cave), indiquent que ces formations dépassent la limite de datation de la méthode uranium-thorium (350 ka). Les rapports d'activité $^{234}U/^{238}U$ approchent l'unité, ce qui suggère que les planchers pourraient s'être formés bien avant 350 ka. L'étude du paléomagnétisme d'échantillons provenant de carottes forées à travers les planchers stalagmitiques montre la

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présence de calcite à magnétisme normal et inverse. Dans certains cas, les niveaux à magnétisme inverse surmontent les couches à magnétisme normal. On interprète cette évidence, en conjonction avec les données isotopiques de l'uranium, comme l'indication d'un âge Olduvai (1,66-1,87 Ma) pour certaines couches du plancher stalagmitique. Les auteurs suggèrent que la grotte est devenue vadose vers 2 Ma ou peu après.

La position de la grotte sur le bord de la vallée permet de faire une estimation du taux maximum auquel la vallée actuelle s'est creusée. Le calcul fournit une valeur de 5,5 cm/ka. Les témoins du fond de l'ancienne vallée préservés dans la salle existante suggèrent que l'enfoncement n'a pas été un processus continu. Un plancher stalagmitique d'une grotte située à un niveau inférieur (Darfur Ridge Cave) a été daté à 284 +34/−27 ka, ce qui permet le calcul d'un taux maximum d'enfoncement depuis cette époque de 11.2 cm/ka. La proximité de l'Elder Bush Cave de la crête de la vallée suggère que son abandon a marqué le début de l'incision qui caractérise le système en gorges du Peak District, probablement engendré par un soulèvement ou un basculement épéirogénique.

I.- INTRODUCTION

The antiquity of landscape features has been the subject of much speculation for over a century. As the science of geomorphology has developed, more understanding of form and process has been achieved, but generally techniques for establishing a chronological framework for the observed landforms have been lacking. In Britain during the immediate pre- and post- war years, many «erosion surfaces» were recognised, or at least proposed, (Hollingworth, 1938 ; Wooldridge, 1950 ; Sissons, 1954) and some were attributed to sub-aerial erosion, often thought to have occurred during the Tertiary, whilst others were deemed to have a marine origin. In this paper, U-Series and palaeomagnetic techniques are used to establish the chronology of major valley incision into one such «erosion surface».

II.- REGIONAL SETTING

The English Peak District is an upland area (275 – 475 metres a.s.l.) situated at the southern end of the Pennine Hills that form a north - south range down the centre of northern England. Here, the Pennine anticline has in part been eroded to reveal limestones belonging to the Dinantian Series of the Lower Carboniferous. To the west, north and east the limestones are unconformably overlain by the impermeable mudstones, sandstones and shales of the Millstone Grit Series of Namurian age.

Much of the limestone, especially in the south, has a gently undulating topography and the term «plateau» has frequently been used to describe the southern part of the limestone outcrop. Many authors have identified a «1 000 foot» (330 m) erosion surface, not only on the limestone but also on adjacent grits. The age and origin of this feature has been the subject of much speculation (King, 1966 ; Linton, 1956, 1964). In the north, the plateau is less well defined and summits here rise above 400 metres O.D. The plateau surface is deeply dissected by valleys (Dales) that have been cut by rivers flowing south or south east to the River Trent (fig. 1) and by a complex network of shallower dry valleys.

One of the rivers, the Manifold, has incised a deep valley across the limestone outcrop close to its south-western margin (fig. 1), and gorges have formed where the more resistant reef limestones have been encountered. These reefs contain many dissected fragments of old phreatic caves that once carried water to and beneath the River Manifold in former times when it flowed at higher levels than today. An extensive network of phreatic caves exists today beneath the present valley floor and the river frequently disappears underground during the summer months. Remnants of former valley floors can be identified within the existing valley (fig. 2) and on the basis of these Warwick (1953) suggested that the valley had been deepened in six successive stages.

III.- METHODS

In order to investigate the chronology of the development of the Manifold Valley, speleothems were collected from twelve fossil cave remnants and dated by the uranium - thorium method. The uranium and thorium isotopes were chemically separated by standard techniques described in Lally (1982) and Rowe (1986), electroplated onto stainless steel planchets and counted by alpha spectrometry. Much of the calcite examined was detritally contaminated or too young to be of significance, but two caves, Elder Bush and Darfur Ridge, contained flowstone of sufficient quality and age to be of use in reconstructing the history of valley incision.

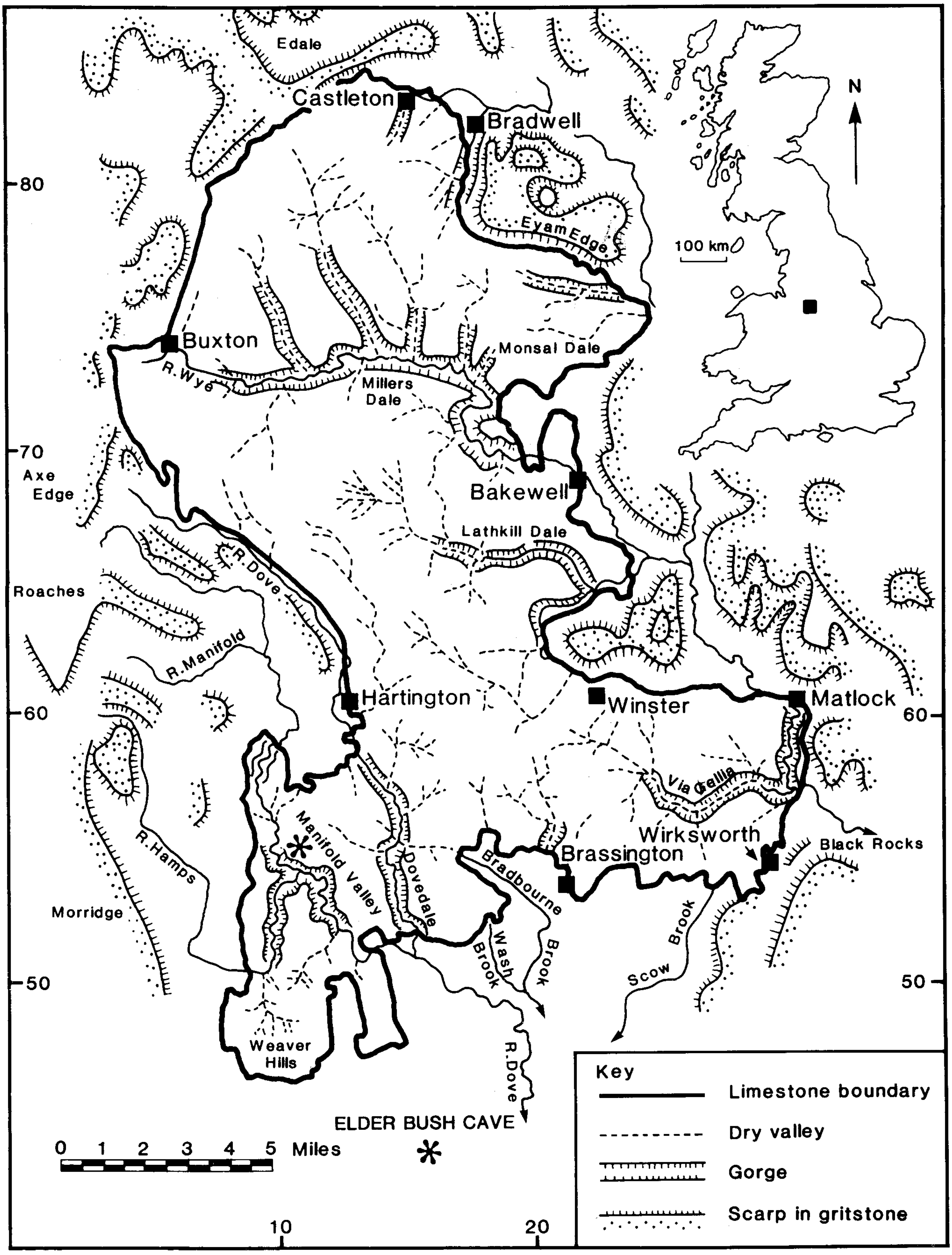

Fig. 1.- Simplified geomorphological map of the White Peak (after Ford, 1977).

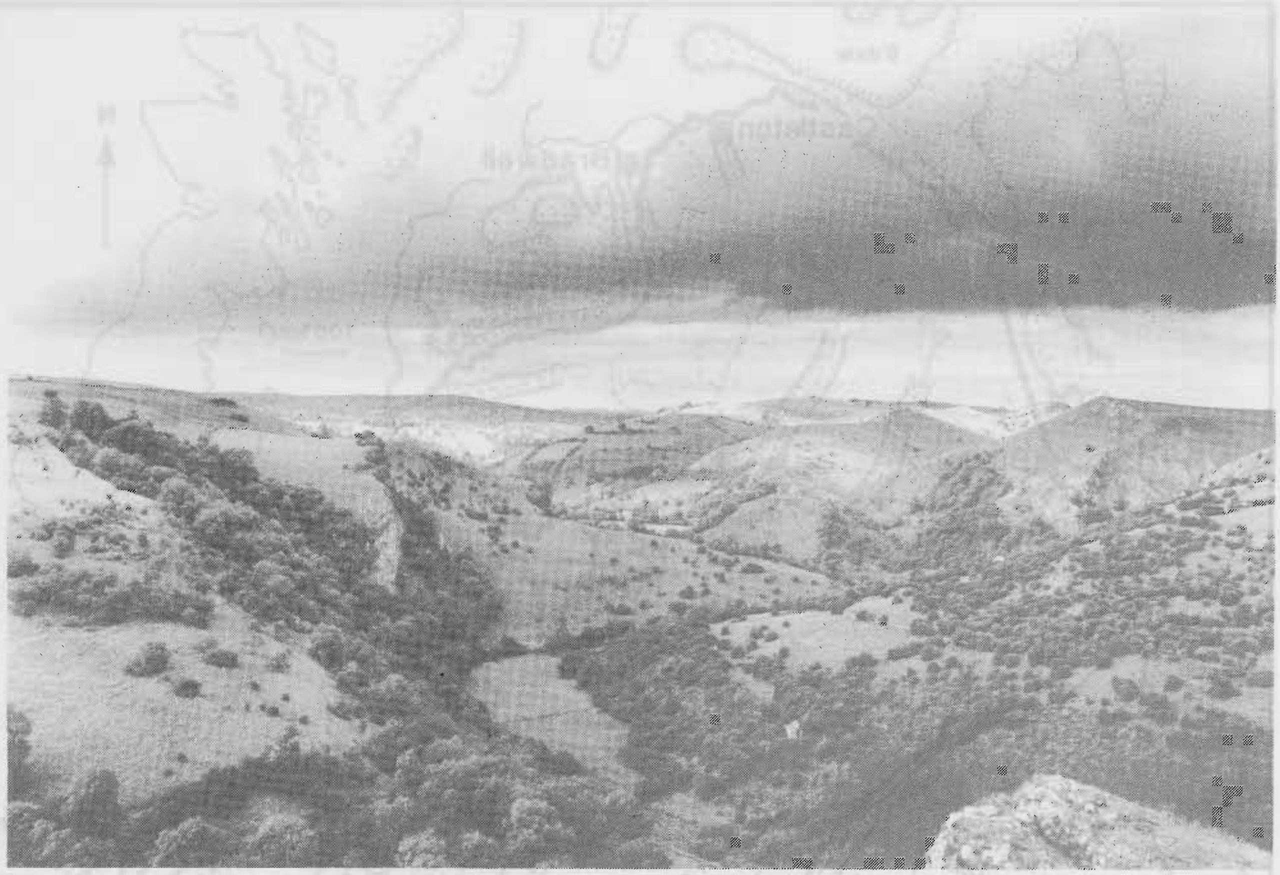

Fig. 2.- The Manifold Valley. View is north from a point near Elder Bush Cave.

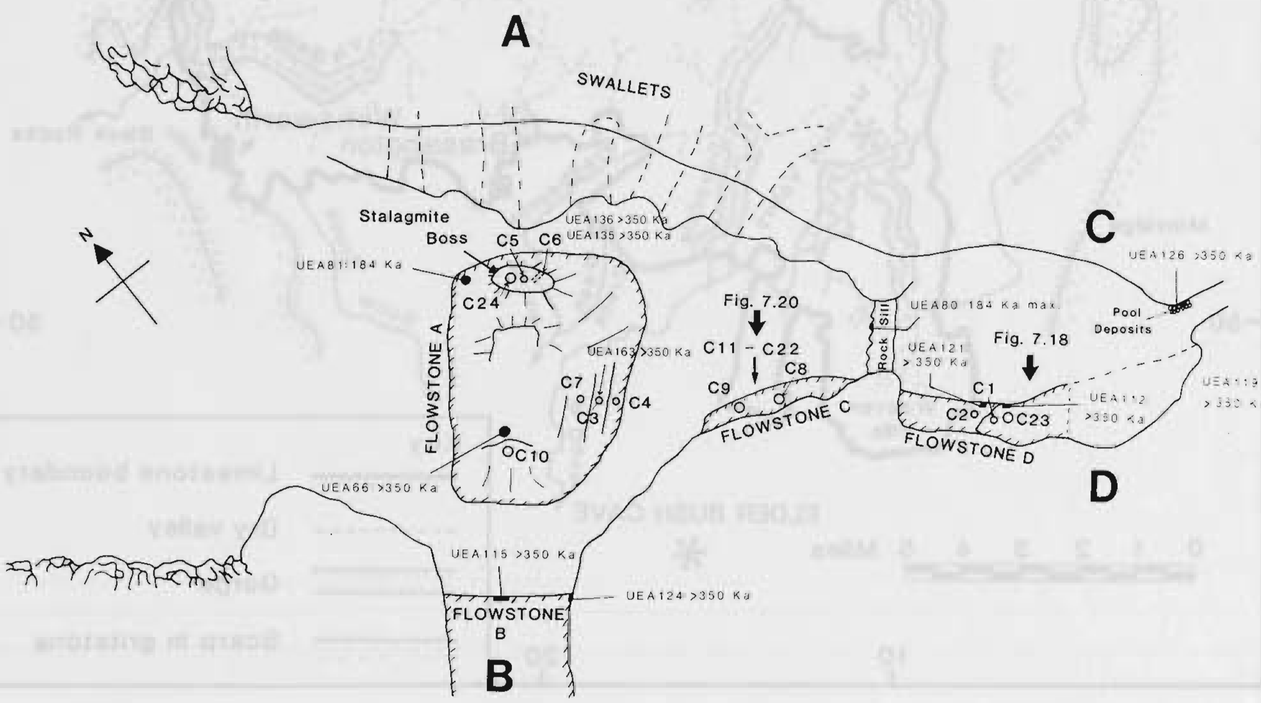

Fig. 3.- Sketch plan of Elder Bush Cave entrance chamber showing main flowstone formations and locations from which cores and hand specimens were recovered.

Elder Bush Cave is a truncated high level phreatic tube situated close to the valley rim at 275 metres O.D. Four substantial flowstones., A, B, C and D (of which A and C are about one metre thick), are preserved in this cave (fig. 3) as well as numerous smaller formations. One flowstone (A) has cracked and foundered and a substantial stalagmite boss subsequently grew on its upper surface (fig. 4), after an interval represented by a mud - filled cavity in the stalagmite base. Uranium - thorium dating of hand specimens taken from flowstones A, B and D showed them to be older than the limit of the technique (350 ka) (table 1). $^{234}U/^{238}U$ ratios in samples UEA66 and UEA115 from flowstones A and B were close to unity, suggesting that the samples were probably considerably older than 350 ka. To try and estimate their likely age more closely, a palaeomagnetic investigation was undertaken.

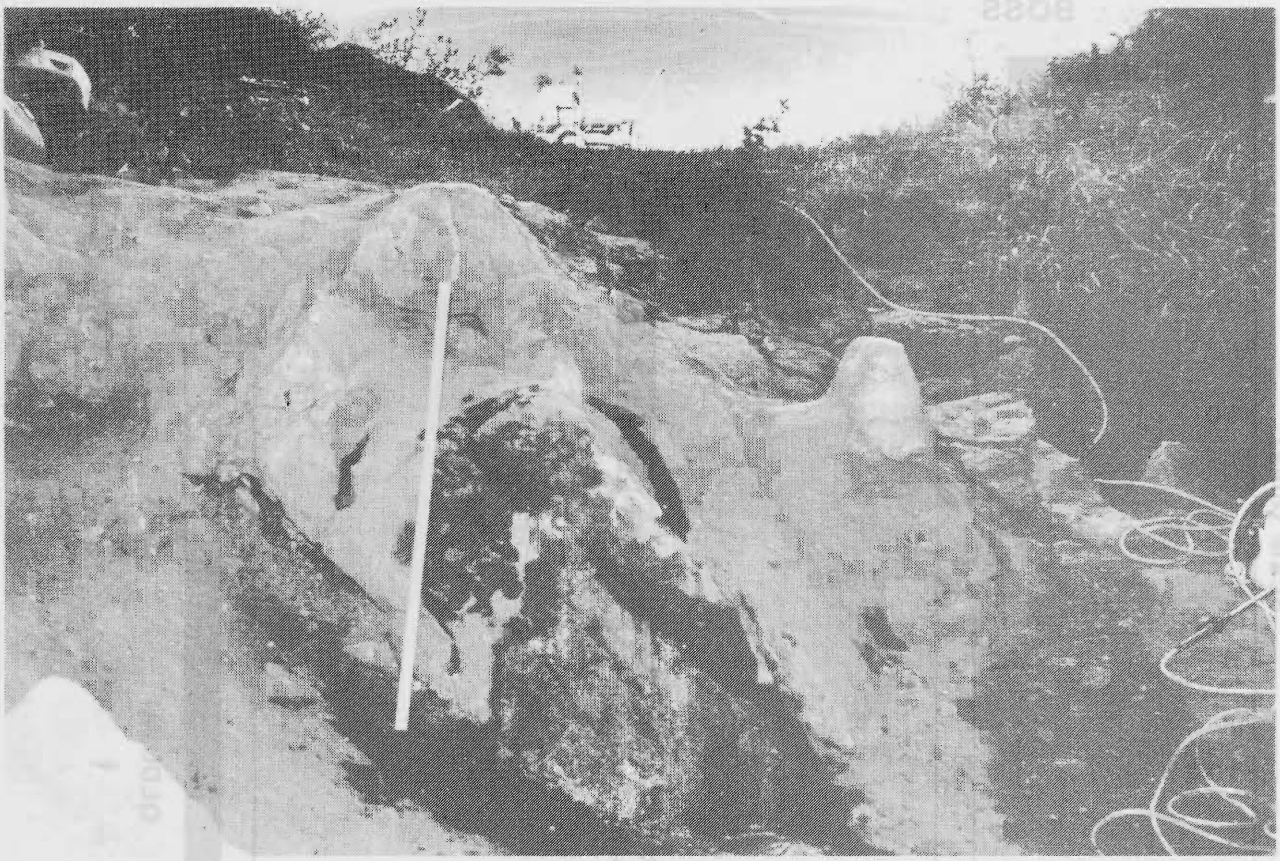

Fig. 4.- Flowstone A, Elder Bush Cave. Stalagmite Boss is right of centre.

Magnetostratigraphy is a useful tool for correlating and dating Quaternary deposits and Noel *et al.* (1984) have pointed out its potential for investigating cave sediments. Latham has investigated the palaeomagnetism of speleothems (Latham, 1981 ; Latham *et al.,* 1979 ; Latham *et al.,* 1982) and his work has shown that many speleothems have a measurable natural remnant magnetism (NRM).

Oriented core samples were recovered from flowstones A, C and D and the stalagmite boss. The cores were sawn into 2 cm sample cubes and their NRM measured on a cryogenic magnetometer after removing any viscous remnant magnetism (VRM) in an alternating field. Pilot studies indicated the presence of a residual, highly stable, primary remanence, and 20 mT was chosen as the optimum peak cleaning field. A fuller account of these measurements will be published elsewhere.

IV.- RESULTS

Figure 5 is a composite diagram summarising the palaeomagnetic and uranium-series results from Elder Bush Cave, while figure 6 displays detailed sample data obtained for flowstone C. Figure 7 shows the Earth's magnetic polarity timescale for the past five million years. Many of the speleothem samples analysed are reversely magnetized and in some cases these overlie others which possess normal magnetization. The frequent presence of hiatuses in some of the cores indicates that a great deal of the record is probably missing, and interpretation is therefore rather more complex than a simple comparison with the polarity timescale.

Uranium - thorium dating of speleothem samples from Darfur Ridge Cave, situated at shallow depth beneath an old valley floor remnant, showed that one flowstone associated with an old gravel infill possessed an age of 284 +34/−27 ka.

V.- DISCUSSION

$^{234}U/^{238}U$ ratios from the stalagmite boss (UEA135, UEA136, table 1) suggest that the magnetic transition from reversed to normal, seen near the top of the boss represents the Matuyama - Brunhes boundary (0.73 Ma), rather than an older transition such as the lower boundary of the Jaramillo event (0.97 Ma). If the latter were the case, the cave dripwaters would have possessed an initial $^{234}U/^{238}U$ ratio of 2.63. This is considered very unlikely because (i) such high values rarely occur in the literature and (ii) it is six standard deviations higher than the mean initial ratio determined from all well dated speleothems younger than 350 ka in the Manifold valley (mean = 1.680, $1\sigma = 0.149$, n = 6). An age of 0.73 Ma for this magnetic transition would suggest the much more likely value of 1.57 for the initial $^{234}U/^{238}U$ ratio. The reversely magnetized calcite in the stalagmite boss is therefore most likely to be post-Jaramillo in age and the normal event near the

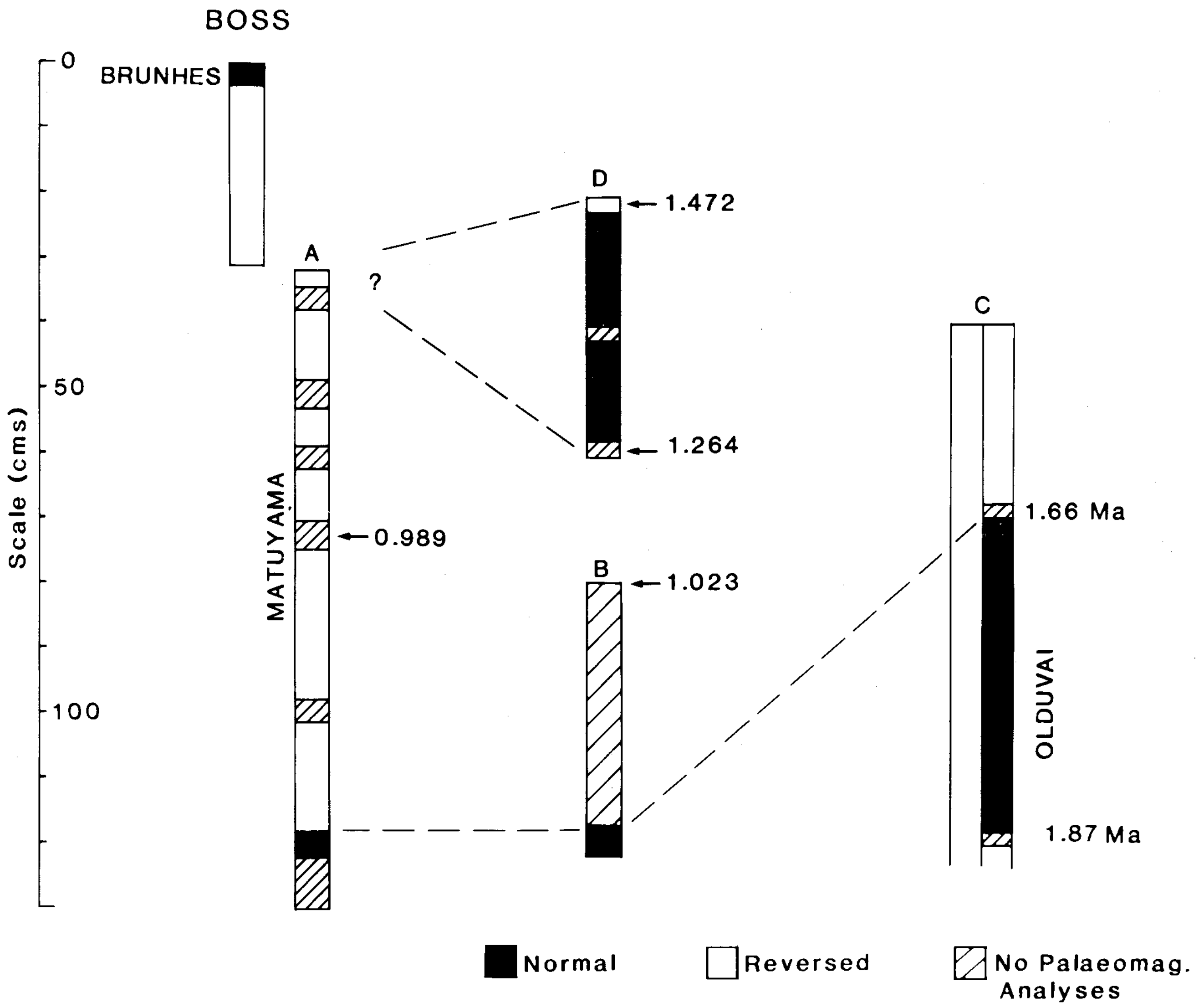

Fig. 5.- Summary of palaeomagnetic and uranium isotope results from Elder Bush Cave flowstones showing suggested correlations.

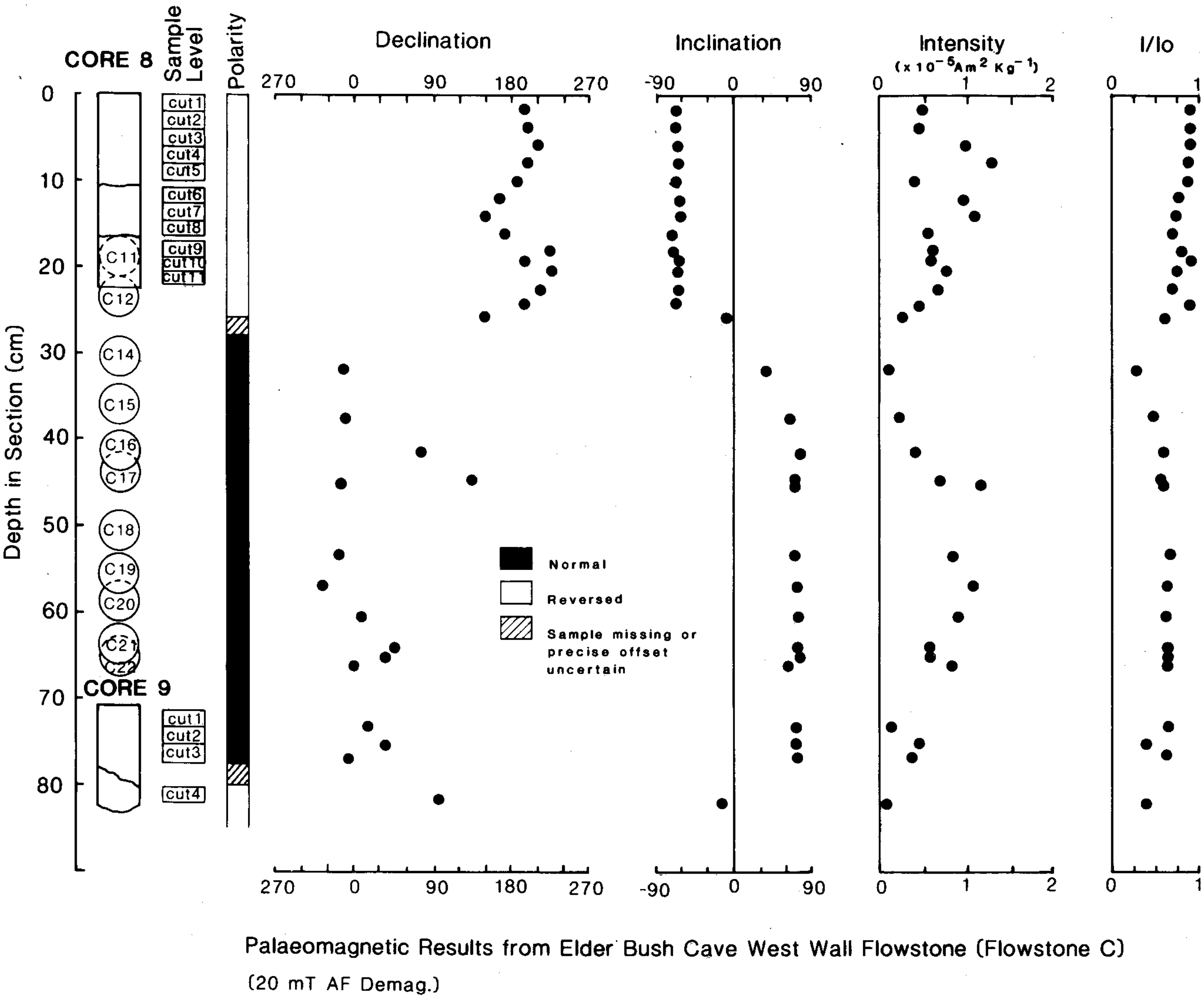

Fig. 6.- Palaeomagnetic data from flowstone C samples.

base of the underlying flowstone must be at least as old as the Jaramillo (0.91-0.97 Ma). However, uranium isotopic evidence suggests that it probably relates to an earlier event. The samples of finite age (< 350 ka) in the cave have calculated $(^{234}U/^{238}U)_0$ ratios of 1.820 (UEA80), 1.840 (UEA81) and 1.690 (UEA123), and the equivalent ratios for UEA135 and UEA136 from the stalagmite boss (730 ka) could not have been less than 1.57 as stated above. If ratios of this order have existed in calcite-forming dripwaters throughout the cave's history, then the proximity of the measured 234-U/238-U to equilibrium in samples UEA66 and UEA163 (see table 1) suggests the reversely magnetized part of the flowstone is much older than the post-Jaramillo part of the Matuyama Epoch (0.91 – 0.73 Ma). This being so, then the normally magnetized episode observed near its base must relate to the Olduvai event (1.66 – 1.87 Ma). The Jaramillo event is therefore not represented in the sequence (although it may be present in flowstone D). The field relationship between flowstones A and C suggests that they may once have been part of the same formation and it therefore seems probable that the normally magnetized layer observed near the base of flowstone C also relates to the Olduvai event but this has yet to be confirmed by analysis of $^{234}U/^{238}U$ ratios. There is some evidence of reversely magnetized calcite at the base of this formation and if so, its probable age is about 1.87 Ma (fig. 7).

Since speleothem is only able to form in the vadose zone, the evidence suggests that Elder Bush Cave was drained, probably by the downcutting of the Manifold Valley, by or soon after 2.0 Ma. Similarly it is likely that Darfur Ridge Cave was drained by about 300 ka.

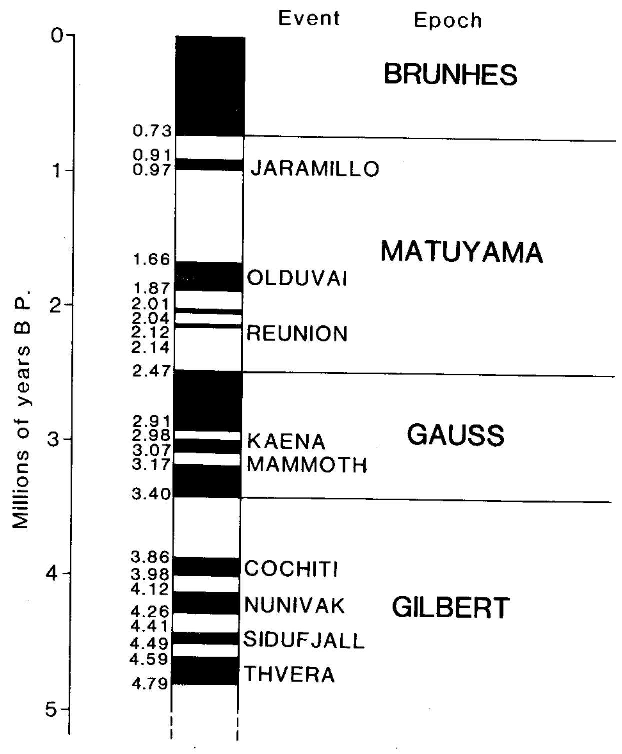

Fig. 7.- Magnetic polarity timescale for the last five million years (from Harland *et al.*, 1982).

VI.- CONCLUSIONS

Elder Bush Cave stands today about 110 metres above the present river bed and the maximum value for the average rate of valley downcutting over the past two million years can therefore be calculated at 5.5 cm ka^{-1}. If the dated speleothems grew immediately after the drainage of both Elder Bush and Darfur Ridge Caves, the mean valley incision rate between the two would be approximately 4.1 cm ka^{-1}. The maximum average incision rate from Darfur Ridge Cave to the present valley floor was 11.2 cm ka^{-1}. These findings are summarized in figure 8. The incision rates are comparable with cave passage entrenchment rates found by Gascoyne *et al.* (1983) in the northern Pennines (2.2 – 8.3 cm ka^{-1}) and with valley incision rates in the Magnesian Limestone of the East Midlands (6.6 cm ka^{-1}) (Rowe, 1986).

On the western side of the Manifold Valley, opposite Elder Bush Cave, the limestone plateau is well represented. The land surface has little relief and slopes with a gradient of only 1 in 25 upwards from the marked break of slope at the valley rim at about 275 metres O.D. (fig. 9). This surface is cut on basinal limestones rather than the resistant reef knolls that dominate much of the Manifold Valley in this locality, and may represent the remains of a land surface that existed at the time Elder Bush Cave was active. Sharp and spectacular breaks of slope occur widely along the rim of the Manifold Valley and that of its tributary, the Hamps, at about 275 - 290 metres O.D., and also along the nearby Dove Dale, Lathkill Dale and Upper Wye valleys, at 265 - 300 metres O.D. These breaks of slope appear to mark the commencement of the latest phase of incision into a pre-existing land surface of comparitively low relief. The

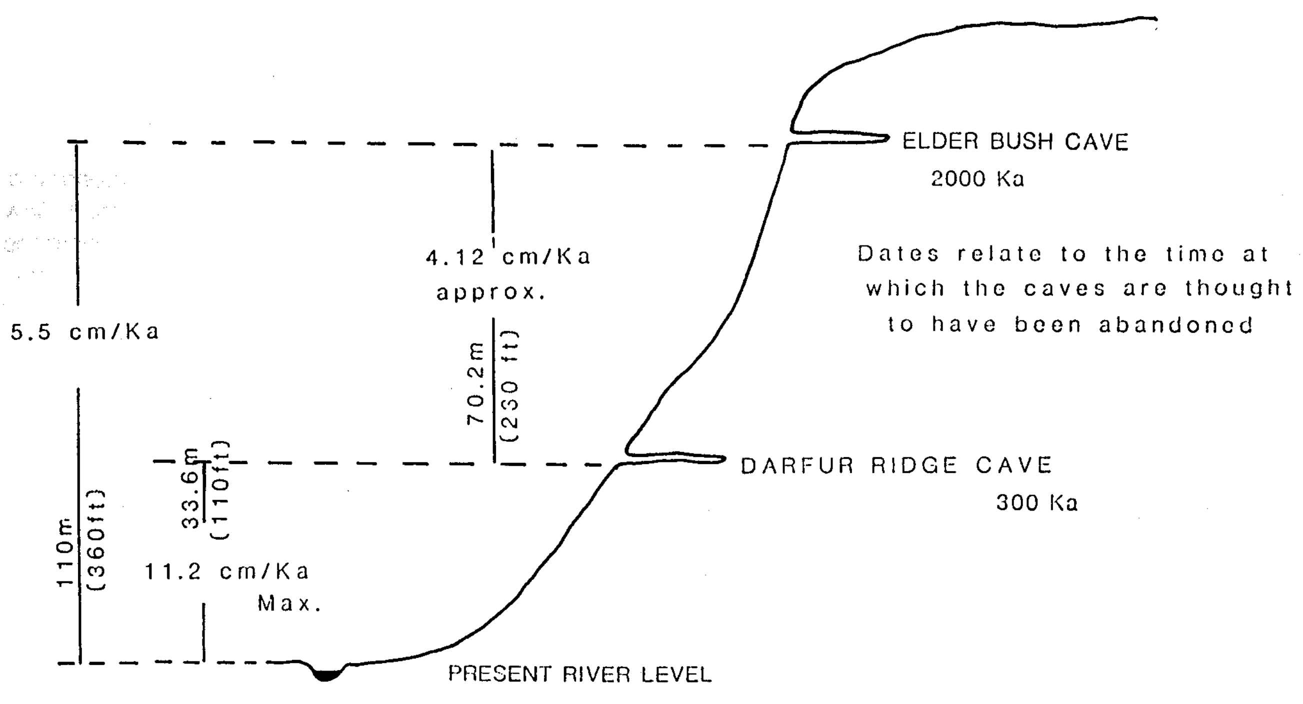

Fig. 8.- Schematic diagram illustrating the use of palaeomagnetic and uranium-series data in the calculation of the rate of incision of the Manifold Valley.

proximity of Elder Bush Cave to the break in slope together with the chronological data derived from the cave and outlined above, suggest that this phase may have begun around or just prior to 2.0 Ma, probably in response to a falling base level as the southern Pennines experienced renewed uplift.

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Table 1.- Uranium-series data for samples from Elder Bush Cave and Darfur Ridge Cave.

CAVE	SAMPLE N°	LAB. N°	U (ppm)	Chemical Yield (%) U	Chemical Yield (%) Th	234-U / 238-U	230-Th / 232-Th	230-Th / 234-U	AGE (Years B.P.)
ELDERBUSH (A : TOP)	UEA830109-1	UEA66	0.06	20	45	1.017 ± 0.053	55.6 ± 17.8	0.985 ± 0.051	> 350 ka
ELDERBUSH	UEA831027-6	UEA80	0.08	57	47	1.489 ± 0.036	3.8 ± 0.2	0.876 ± 0.027	184 200 + 14 000/ − 12 600
ELDERBUSH (A : DRAPE)	UEA831027-7	UEA81	0.21	77	15	1.501 ± 0.021	17.1 ± 1.5	0.876 ± 0.022	184 000 + 11 300/ − 10 400
ELDERBUSH (D : BASE)	UEA840524-5	UEA112	0.06	72	76	1.264 ± 0.030	4.4 ± 0.2	1.078 ± 0.033	> 350 ka
ELDERBUSH (B : TOP)	UEA840524-8	UEA115	0.08	53	65	1.023 ± 0.025	30.4 ± 3.3	1.088 ± 0.037	> 350 ka
ELDERBUSH	UEA840524-6	UEA119	0.05	67	81	1.167 ± 0.032	6.7 ± 0.4	1.021 ± 0.034	> 350 ka
ELDERBUSH (D : TOP)	UEA840524-3	UEA121	0.14	70	23	1.472 ± 0.029	6.6 ± 0.3	1.128 ± 0.042	> 350 ka
ELDERBUSH	UEA840524-1	UEA123	0.05	74	57	1.384 ± 0.038	4.6 ± 0.3	0.912 ± 0.033	208 900 + 21 800/ − 18 500
ELDERBUSH	UEA840523-2	UEA124	0.08	71	71	1.044 ± 0.030	12.2 ± 0.8	1.015 ± 0.031	> 350 ka
ELDERBUSH	UEA840524-7	UEA126	0.07	71	59	1.098 ± 0.025	7.5 ± 0.4	1.041 ± 0.033	> 350 ka
ELDERBUSH (BOSS : OUTER)	UEA840905-4	UEA135	0.07	60	74	1.132 ± 0.026	18.9 ± 1.7	1.028 ± 0.026	> 350 ka
ELDERBUSH (BOSS : INNER)	UEA840905-4	UEA136	0.10	58	80	1.074 ± 0.024	27.3 ± 2.2	1.017 ± 0.026	> 350 ka
ELDERBUSH (A : CENTRE)	CORE 3A	UEA163	0.11	55	37	0.989 + 0.023	91.0 ± 60.1	1.013 ± 0.033	> 350 ka
DARFUR RIDGE	UEA840921-5	UEA137	0.12	63	69	1.305 + 0.025	17.7 + 1.4	0.992 + 0.026	283 700 + 34 300/ − 26 800

Fig. 9.- View westward from Elder Bush Cave mouth. Manifold Valley (foreground) is incised into a sub-horizontal «surface».