Cave Science

The Transactions of the British Cave Research Association

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Volume 20 Number 2 November 1993

Forest of Dean inception horizons

Molluscs in Caves

Syngenetic Karst in South Africa

Human Impact on Karst

Caves in Tibet

Caves of Doshan

Cave Science

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Cover photo: View taken in 1909 looking north-eastwards in Ifton Quarry. The Drybrook Limestone contains neptunian infill of Namurian age in dissolutional fissures and cavities, most obviously within a palaeodoline in the centre of the view. [Geological Survey and Museum photograph A798].

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The Forest of Dean Caves and Karst: Inception Horizons and Iron-ore Deposits

D. J. LOWE

Abstract: Recent exploration of major active cave systems in the west of the Forest of Dean, United Kingdom, has drawn attention to and raised the level of scientific interest in this little known 'karst' area. The form and extent of the caves and the underground drainage system to which they belong conform well to a predictive model based on geological considerations pivotal to the Inception Horizon Hypothesis of cave origin and development. Elsewhere in the Forest of Dean area, palaeokarstic features, including palaeo-caverns, containing neptunian infill illustrate a long history of speleogenesis affecting Dinantian carbonate rocks. Consideration of these features and the geological structure in general, within the process and timescale framework offered by the Inception Horizon Hypothesis, allows theoretical reappraisal of the origin and nature of the once extensive iron-ore deposits of the area. Elements of the deduced model may be applicable to iron-ore and other mineral deposits elsewhere.

INTRODUCTION AND BACKGROUND

In describing the geology and underground drainage of the Forest of Dean, lying mainly between the valleys of the rivers Severn and Wye, in the borderlands of western England and Wales (Figure 1), Lowe (1989) paid relatively great attention to the Slaughter Resurgence, a rising on the east side of the River Wye (Figure 2). Richardson (1924, 1930) provided early accounts of 'swallow holes' near Joyford (Figure 2) and discussed the resurgence for water sinking here and in adjacent areas. Around the turn of the Century, an artificial flood pulse was released into the Joyford swallets and an angler at the Slaughter was surprised by a 'boiling up' of dirty water in the Wye. Later, the Joyford stream was reddened with ochre and discoloured water was reported at the Slaughter. Cause and effect were not connected on the earlier occasion (Richardson,1930); nor did Richardson question why the 'boiling up' was in the bed of the Wye, when resurgent water generally emerges from holes higher in the river bank. Richardson (1924, 1930) also discussed Hoarthorns Wood Swallet (Figure 2), and mentioned another tracing experiment. 'Green colouring matter' placed in the sink on Good Friday in 1914 was reportedly pumped from colliery workings in the Westphalian Coal Measures in the centre of the Forest of Dean Basin on Easter Monday. Credibility was attached to this result and pipelines built to carry surface water beyond the sink were maintained for many years. The veracity of the trace was rarely questioned.

Early cave exploration in the area was limited to examination of relict cave fragments rather than active sinks. Archaeological caves were examined by the University of Bristol Spelaeological Society. Dry open caves throughout the Forest of Dean were explored by cavers from Monmouth School, led by the late Cecil Cullingford, and active sites were examined first by the Hereford Caving Club and then by the Gloucester Speleological Society and the Royal Forest of Dean Caving Club. Water tracing (Table 1) carried out by Gloucester and Royal Forest of Dean cavers produced positive traces from the Joyford sinks and Symonds Yat Swallet (Figure 2) to the Slaughter Resurgence, and from Coldwell Swallet to Coldwell Rising (Figure 2). An attempt to trace the water from Redhouse Swallet (Figure 2) gave negative results at the Slaughter Resurgence and Coldwell Rising. In the early Nineteen-seventies many tracing experiments were carried out by Solari (1974), using optical brightening agent. These provided positive traces from Bent Hazel Swallet, Sopers Pot, Tip Sink Joyford,

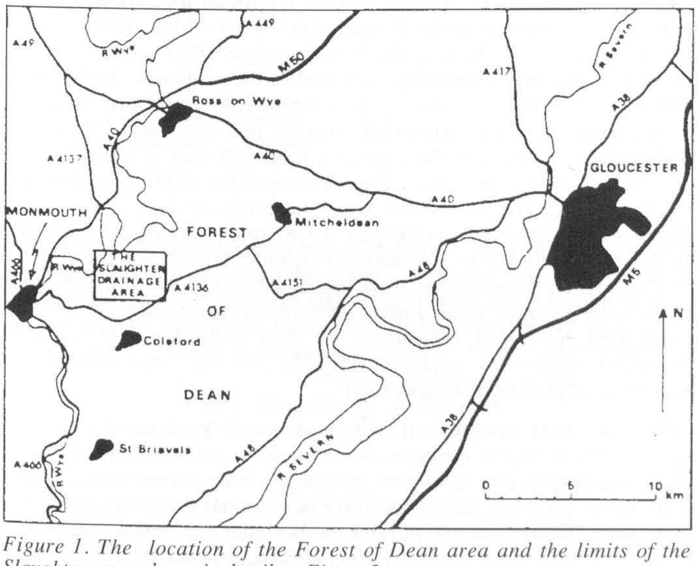


Figure 1. The location of the Forest of Dean area and the limits of the Slaughter area, shown in detail on Figure 2.

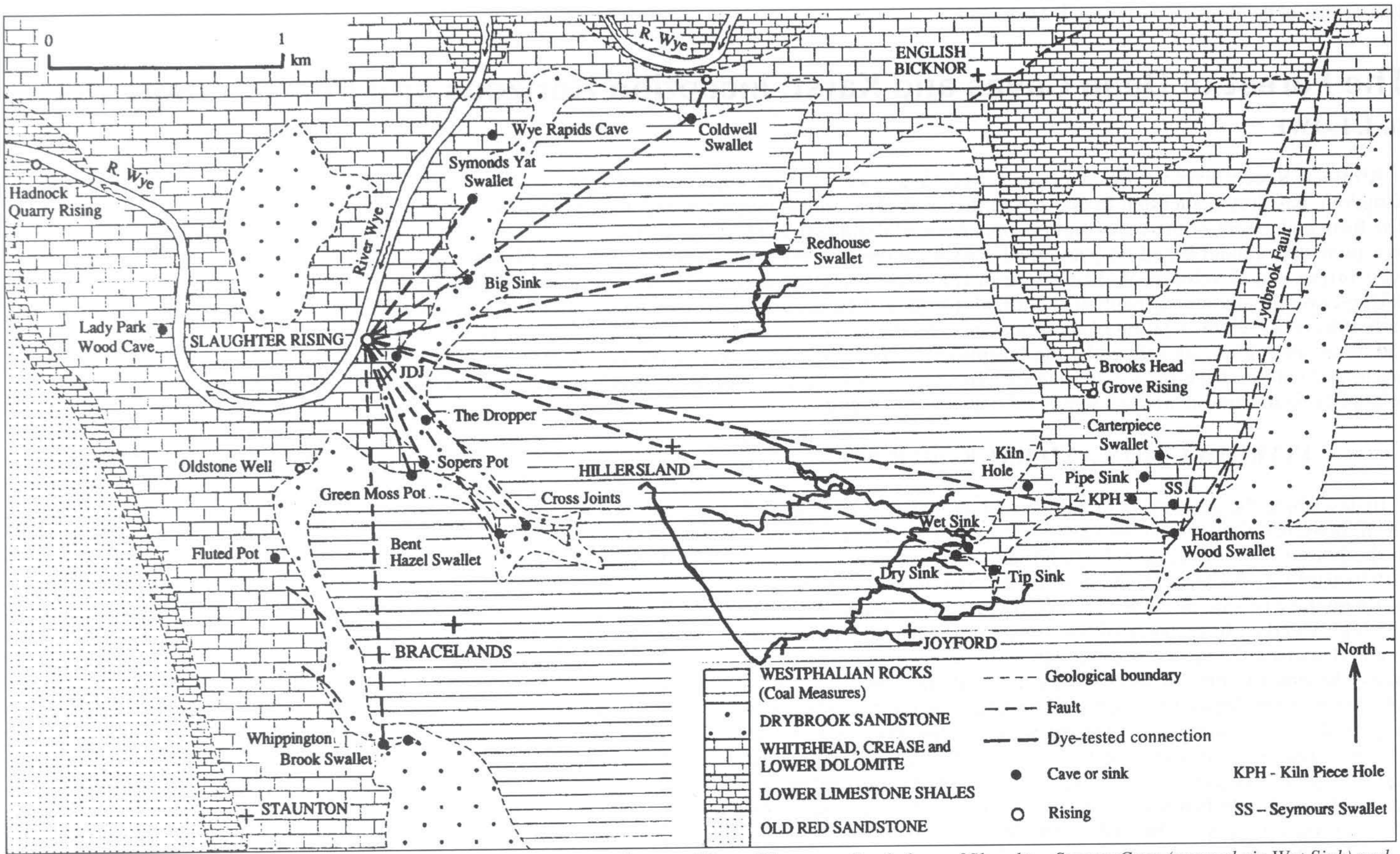
Sink	National Grid Reference	Horizontal distance Km	(miles)	Vertical distance m	(feet)	Approximate time (days)	Method(s) used
Sopers Pot	SO 5580 1408	0.54	(0.33)	40	(131)	c. 1 day	Optical brightening agent with cotton wool detectors
Green Moss Pot	SO 5575 1405	0.70	(0.40)	76	(250)	< 3 days	Optical brightening agent with cotton wool, cotton and calico detectors
Symonds Yat Swallet	SO 5602 1522	0.87	(0.54)	86	(282)	c. 1 day	Rhodamine B and conductivity
Cross Joints Swallet	SO 5622 1385	1.00	(0.62)	78	(256)	< 2 days	Optical brightening agent with cotton wool, linen and calico detectors
Bent Hazel Swallet	SO 5611 1384	0.92	(0.57)	86	(282)	< 3 days	Optical brightening agent with cotton wool detectors
Whippington Brook Swallet	SO 5563 1290	1.67	(1.03)	93	(305)	unknown	Optical brightening agent with cotton wool detectors
Coldwell Swallet *	SO 5696 1554	1.78	(1.10)	86	(282)	< 6 days	Fluorescein with activated charcoal detectors
Redhouse Swallet	SO 5734 1499	1.84	(1.14)	110	(360)	unknown	Optical brightening agent with cotton wool detectors
Dry Sink Joyford	SO 5812 1373	2.69	(1.67)	119	(390)	unknown	Fluorescein (observed)
Tip Sink Joyford	SO 5826 1368	2.87	(1.78)	119	(390)	unknown	Optical brightening agent with cotton wool detectors
Hoarthorns Wood Swallet	SO 5905 1376	3.59	(2.23)	123	(404)	< 3 days	Fluorescein with activated charcoal detectors

* Depending upon stage, part of the water sinking at Coldwell Swallet follows an essentially down-dip route to the Slaughter Resurgence and part follows a shorter, probably fracture-guided, route to Coldwell Rising [SO 5701 1570], a connection which has been confirmed by at least three positive dye traces.

Table 1. Synthesis of water tracing results from tests carried out by various caving clubs and individuals in the Slaughter Resurgence catchment of the Forest of Dean.

Redhouse Swallet and Whippington Brook Swallet (Figure 2) to the Slaughter Resurgence. Repeat tests at Coldwell Swallet and Hoarthorns Wood Swallet gave dubious results which were considered negative. Later tests by the Cave Projects Group, using optical brightening agent and fluorescein, provided positive traces from Cross Joints Swallet, Green Moss Pot and Hoarthorns Wood Swallet to the Slaughter. Water from Coldwell Swallet was traced to the Slaughter Resurgence and Coldwell Rising. This conclusive illustration of alternative underground drainage routes from a single sink pointed the way to significant extensions of Coldwell Swallet.

During the Nineteen-seventies, a quantitative assessment of swallet water known to drain to the Slaughter was instigated by Worthington (unpublished). Estimated flow measurements indicated that far less water appeared to resurge than was known to enter the sinks. Concurrently a theoretical model for the broad skeleton of 'The Slaughter Master Cave' was developed (Lowe, c.1975, unpublished). Based upon the geological structure of the area, the model predicted the existence of several independent, sub-parallel main drains, each carrying water from individual sinks or sets of sinks. Then-current wisdom of speleogenesis included no obvious constraining mechanism to account for the proposed system's morphology. Several years later, the Inception Horizon Hypothesis (Lowe, 1992) provided potential, though untested, explanations of the system, as discussed in section 4.



Geological map showing sinks which drain to the Slaughter Resurgence, Forest of Dean. The generalised plans of Slaughter Stream Cave (entered via Wet Sink) and Redhouse Swallet are superimposed.

Excavation of Wet Sink at Joyford was not possible until the mid-Nineteen-eighties, following which determined work opened the Slaughter Stream Cave, exploration of which is described elsewhere (eg Clark, 1991a, b; Sibly, 1991). Water from Redhouse Swallet also rises at the Slaughter, and Solari (1974) noted that this site is almost unique in the area, being at the termination of a true blind valley. No bedrock was exposed in the sink depression, but in 1990 subsidence revealed bedrock beneath the silt and the area was stabilised to ensure that the hole would not be lost to future floods. Accounts of the discovery of cave passages below are given elsewhere (eg Taylor, 1991, 1992, 1993).

Part of Lowe's (1989) review of the Forest of Dean discussed iron-ore mines, once active in the area. Evidence presented by Solari and Lowe (1974) and Lowe (1974), indicating that ore was emplaced within pre-existing cavities, was briefly reiterated, but full consideration of links between *palaeokarstification* (section 2), ore deposition and speleogenesis was not attempted. The Inception Horizon Hypothesis of carbonate cave origin (Lowe, 1992), allows linkage of the effects of ancient speleogenesis, and associated relict features such as iron-ore deposits, with more recent speleogenesis and modern cave systems. Some of these links are examined in this paper.

THE CONCEPTS OF KARST AND PALAEOKARSTIFICATION

The terms *karst* and *karstification* have been absorbed into the English language and are used commonly and informally by those who study the landscapes developed upon and within carbonate rocks. Both terms are used in contexts extending far beyond that of their first usage by western scientists in the mid-Nineteenth Century (cf Sweeting, 1972; Jakucs, 1977). Pedantically, a limitation of the formal meaning of *karst* to **'a landscape formed upon and within carbonate rock sequences by the dissolutional effect of carbonic acid'** can be argued (Lowe, 1992, p.9). Such a landscape exhibits distinctive surface landforms (*karst* landforms) resulting from interaction between a restricted set of erosional processes (*karst* processes), the mechanisms of which are constantly evolving, and carbonate bedrock. If this narrow view is accepted, the term and its derivatives must be used with care. More realistically, every scientist involved in *karst*-related research has a personal view of the meaning and limitations of the term.

Relatively recently it became acceptable to apply *karst* terminology to features resembling true *karst* but formed by different processes (eg physical dissolution of evaporites by fresh water) or upon different rock types, such as evaporite or quartzite. Several classifications have been proposed, based on a variety of parameters. Some workers have appended appropriate prefixes, generating terms such as *gypsum karst*, but this has been far from universal. A classification based on phase equilibria, proposed and then modified by Cigna (1978, 1985), restricted *karst (sensu stricto)* to pure limestone areas. Cigna introduced categories to encompass *'karstic phenomena'* developed by a variety of processes within or upon a spectrum of materials, including pure and mixed carbonate rock, evaporite, quartzite, volcanic rock and ice. In a different context, *karst* has been used to describe landform assemblages founded upon a variety of rock types (but mainly carbonates) due partly to modification by non-dissolution processes. Terms such as *glacio-karst* have been introduced and gained wide acceptance.

It is no longer feasible to limit use of the term *karst* to the narrow effects of carbonic acid upon pure carbonates as suggested above or as implicit in Cigna's (1978) *'karst, sensu stricto'*. It is now accepted that a *karst* landscape developed on a carbonate succession is due not only to dissolution by meteoric carbonic acid, but also to processes involving other solvents. Carbonic acid is generated biogenically in the soil; complex soil acids may be active; strong acids form due to oxidation and reduction (with or without microbial mediation) within the rock mass; mixing of fresh and saline water in the littoral zone may have great significance; fresh water might physically dissolve segregated and interstitial evaporites within the sequence. These and other processes acting alone or in combination contribute to *karst* development. If non-dissolutional erosion and non-carbonate rock substrates are included in the equation, it is clear that, if unqualified, the term *karst* no longer has the narrow meaning implicit within its original use. Qualified variations of the term, or use of specific, defined terms such as those of Cigna (1978, 1985), are less misleading and generally acceptable. For instance, *quartzite-karst* (or the Cigna sub-class which encompasses it) is useful shorthand for *'a landscape or landscape features formed upon quartzite sequences* [by the action of specified processes], *resembling the suite of landforms produced upon carbonate rock sequences by the dissolutional effects of carbonic acid* [and/or other solvents]'.

The seemingly simple and commonly used word *karst* and, by implication, its many derivatives, must be written and read with caution. Simplistically the term *palaeokarst* may be viewed as 'old *karst*', but if *karst* has such a spectrum of potential meanings, so must *palaeokarst*. Awareness that *karst* may no longer be viewed narrowly, allows pragmatic definition of *palaeokarst* as, **'features within the**

Regional Stage	Approximate duration	Approximate limits
	------------------------	326 my
Brigantian	?4 my	
	------------------------	?330 my
Asbian	?5 my	
	------------------------	335 my
Holkerian		
Arundian	15 my	
Chadian		
	------------------------	350 my
Ivorian		
Hastarian	10 my	
	------------------------	360 my

Table 2. Age limits and duration in millions of years (my) of British Dinantian Regional Stages. Note that some authors now prefer the use of the single Regional Stage Courceyan in place of Ivorian and Hastarian.

Chronostratigraphy	Potential lithostratigraphy	Forest of Dean lithostratigraphy
?Stephanian Westphalian D and part Westphalian C	Upper Coal Measures	Some Upper Coal Measures
part Westphalian C plus Westphalian B	Middle Coal Measures	Nothing preserved
Westphalian A	Lower Coal Measures	?nothing preserved
Yeadonian to Pendleian (Namurian)	Millstone Grit	Nothing preserved except for fissure fills discussed in this paper
Brigantian and Asbian	Carboniferous Limestone 'Series' - part	Nothing preserved
Holkerian	As above	*Drybrook Sandstone*
Arundian to Courceyan	As above	*Carboniferous Limestone Series*

Table 3. Comparison of lithostratigraphical units represented in the Forest of Dean with a theoretical complete Carboniferous sequence – terms used by Sibly are shown in italics.

System	Stages	Dominant regime
Triassic	uncertain/ diachronous	deposition
major unconformity of regional extent		~~~~~~~~~~~~~~~~~~
Permian	all	?non-deposition and erosion
Carboniferous	Stephanian and Westphalian	local non-deposition and erosion
	local unconformity	~~~~~~~~~~~~~~~~~~
	Namurian	erosion and deposition
major unconformity of regional extent		~~~~~~~~~~~~~~~~~~
	Viséan and Tournaisian	deposition ~~~~~~~~ deposition ~~~~~~~~ deposition (*local unconformities*)

Table 4. Generalised representation of the late Palaeozoic to early Mesozoic depositional/erosional regimes deduced in the Ifton and southern Forest of Dean area (cf tables 3 and 5).

stratigraphic column which resulted from the effects of the broad suite of *karst* processes; commonly encompassing rock or mineral materials younger than the underlying host rock, deposited within a variety of erosional voids within the host rock'. There is an important distinction between underlying host rock (which underwent *karstification*) and that which overlies and may enclose the *palaeokarstic* features, though if the features are cave-like, they may lie within rather than upon the underlying beds. The suite of erosional and depositional *palaeokarst* forms varies from the microscopic to those many metres in amplitude, but it is vital to recognise that activity which removed many metres of rock during hundreds of thousands of years, may be recorded in the stratigraphic column by zones only millimetres thick.

Much has been written concerning *palaeokarst*, mostly in recent years, and papers by T D Ford (1976, 1984) and Simms (1990) are of particular interest in the British context. Several thought-provoking chapters, including one by Smart and others (1988) dealing mainly with depositional (neptunian) aspects of *palaeokarst*, comprise a single volume, *'Paleokarst'* [sic], edited by James and Choquette (1988). Observations in Australia, described in many papers by Osborne (eg 1983, 1986, 1993), have provided unequivocal evidence of links between *palaeokarst* and subsequent speleogenesis.

Timescales of *palaeokarstification*, a topic of great interest and importance, are not examined in detail here. Various chapters in *'Paleokarst'* indicate that such features exist in rock sequences of all ages, back into Precambrian time. Some gaps in the stratigraphic column marked by *palaeokarstic* surfaces are very great, both in terms of the potential thicknesses of missing rock and the length of time represented by the gap. Some *palaeokarstification* episodes might have been much shorter and significant surface and underground *karst* features can develop in less than 10000 years (eg the time since the end of the last major glaciation in Britain). Very important to this paper is recognition that during early Carboniferous times, when the Dinantian carbonate sequences of the Forest of Dean were deposited, several significant non-depositional and/or erosional episodes provided ample scope for the development of surface and underground *karst* features. Table 2 shows the duration of the Regional Stages of the British Dinantian. Tables 4 and 5 give an overview of the main non-depositional phases, marked by unconformities, some of which exhibit marked *palaeokarstic* features as described below.

Processes considered above may broadly be described as producing penecontemporaneous or syngenetic *palaeokarst* – acting upon rocks which were effectively 'new' – commonly with deposition of similar rocks resuming after *karstification*. Another broad type of *palaeokarst* is recognised, which can be termed subsequent *palaeokarst*. Subsequent *palaeokarst* is common and examples include *karst* features superimposed on Dinantian carbonates during Triassic times. Subsequent *palaeokarst* is generally more striking than penecontemporaneous, and due to tectonism between deposition and *karstification*, the features may cut across sequences rather than being specific to a single horizon. Subsequent *palaeokarst*, which might potentially be reburied by later rock deposits but might also remain exposed and difficult to differentiate from modern *karst*, was termed *'buried karst'* by T D Ford (1976).

PALAEOKARST IN THE FOREST OF DEAN AREA

3.1 Early views, including those of T F Sibly and E E L Dixon

The Forest of Dean has attracted field scientists since the early days of geological awareness. It provides a compact, discrete, study area illustrating many geological relationships linked to stratigraphy, *karstification*, speleogenesis and mineralization. It was chosen by Thomas Sopwith (1803-1879) for illustration by a three-dimensional structural model. Turner and Dearman (1981, p.24) report that *"... he* [Sopwith] *had modelled the complex structures of the Forest of Dean coalfield with the structure and workings in three coal seams accurately portrayed"*. Though accurate and instructive, Sopwith's models were based upon limited understanding of local stratigraphy, particularly the beds beneath the Coal Measures. During the late Nineteenth and the first half of the Twentieth centuries, eminent geologists such as Sibly, Dixon, Trotter, Rose and Dunham provided clearer views of the stratigraphy and structure. The question of the age and mechanism of emplacement of haematitic iron-ore deposits, once worked extensively from mines within the Dinantian succession, has remained controversial. A broad ore genesis model, modified from ideas put forward tentatively by Solari and Lowe (Solari and Lowe, 1974; Lowe, 1974) is considered in this paper.

Sibly (1912) provided a lithostratigraphical division of the rocks of the Forest of Dean which formed the kernel of terminology in use today. Most crucial was recognition that the Drybrook Sandstone, a clastic unit overlying his *'Carboniferous Limestone Series'*, is not the local equivalent of the *'Millstone Grit'*. The *'Millstone Grit'* was, even then, recognised as *'Upper Carboniferous'* (Silesian) and Sibly demonstrated that Drybrook Sandstone deposition commenced in mid-Dinantian (*'Lower Carboniferous'*) times. Moreover, the beds are conformable with the underlying carbonates, being a sandy facies, unrelated to the true Millstone Grit, equivalent in age to limestone formations in adjacent areas. Later Sibly (1918) described a major unconformity between *'Lower Carboniferous'* beds, including the Drybrook Sandstone, and the overlying Upper Coal Measures. Table 3

View taken in 1909 looking towards the west in Ifton Quarry. The Drybrook Limestone is overlain by 'Millstone Grit' strata which are in turn overlain by Triassic rocks. The 'Millstone Grit' fills dissolutional hollows and fissures in the Drybrook Limestone, such as the one to the right of the figure and the large one within the protruding shoulder right of centre. [Geological Survey and Museum photograph A796].

Neptunian infill of Namurian age within a ?palaeo-doline formed in the Holkerian Drybrook Limestone, exposed at Ifton Quarry in 1909. [Geological Survey and Museum photograph A799].

indicates the extent of the gap in the Forest of Dean succession when compared to a potential full sequence. It is important to realise that a full lithostratigraphical sub-division of the *'Carboniferous Limestone Series'* was not then established and, particularly, the relationship of the Drybrook Limestone to the Upper and Lower Drybrook Sandstone was not appreciated.

The obvious unconformity between the Dinantian rocks and the overlying Coal Measures was termed the *'Intra-Carboniferous Unconformity'*. Later another unconformity was noted within the *'Carboniferous Limestone Series'* (Trotter, 1942). This break in deposition, locally accompanied by erosion, separates the Crease Limestone and overlying Whitehead Limestone (Table 5) and was termed the *'Mid-Avonian Break'* (Welch and Trotter, 1960, p.64). Subsequently, Lowe (1989, p.107) postulated a non-sequence between the Lower Dolomite and the Crease Limestone. The nature and importance of this non-sequence and the *'Mid-Avonian Break'* are discussed later in this paper.

Dixon (1910) described two broad types of unconformity in areas of carbonate sequences overlain by clastic rocks. In one the underlying carbonates, regardless of structural attitude, have been planed by marine erosion or peneplanation prior to deposition of the overlying beds and, according to Dixon (1910, p.478), *". . . any limestones which occur below the unconformity appear to be devoid of pipes or swallow holes contemporaneous in origin with the plane of the unconformity."*. Dixon cited the junction between Triassic or Jurassic rocks overlying Carboniferous Limestone, *'at most places'* as a typical example, and believed that such unconformities were a sign of *'mature erosion'*. The second type of unconformity is one in which the underlying carbonates were not maturely eroded. Commonly the junction is complicated by swallow holes and pipes formed contemporaneously with the unconformity and filled with rock material resembling that of the overlying formations. These effects are locally more, or less, well developed and Dixon (1910) described slight piping (at West Williamston in Pembrokeshire), advanced *'solution-erosion'* (at Ifton, Monmouthshire) and extreme cases of huge breccia-filled cavities in the Carboniferous Limestone of Pembroke. In the latter case Dixon claimed some overlap with his first unconformity type, since the limestone surface was a base-levelled plane before deposition of overlying Triassic strata. He believed that the infilled cavities pre-dated peneplanation and that no swallow holes were produced during base-levelling. Thus, this particular example is a combination of both unconformity types. Clastic/carbonate unconformities probably lie upon a continuum, rather than representing two discrete types, since unrecognised contemporaneous *palaeokarstic* features possibly exist beneath any erosion surface. Dixon's example of a type-one situation with Triassic beds overlying *un-karstified* Dinantian rocks cannot fully be supported in areas such as the Mendip Hills and the southern Forest of Dean.

Advanced *'solution-erosion'* at Ifton was described in detail by Dixon (1921), the work complementing that of Sibly (1912, 1918) discussed above. Dixon describes exposures of *palaeokarst,* within Dinantian rocks, which are set apart from most other recorded *palaeokarstic* features on the sub-Triassic unconformity by the nature of the dissolutional features and their neptunian infill. Extensive subaerial and underground *karst* features, including channels, fissures and dissolutional cavities containing clastic deposits of pre-Triassic age were formerly exposed in clear quarry sections, beneath Triassic rocks. Dixon (1921) discussed the age and correlatives of these deposits, showing them to have closer affinity with the (Namurian) Basal Grit of South Wales than with Upper Coal Measures sandstones or the Drybrook Sandstone. Thus, he demonstrated significant erosion between deposition of the Holkerian Drybrook Limestone Formation (Table 5) and the onset of mainly deltaic deposition during the Namurian. Further erosion then occurred between deposition of the Namurian rocks and the overlying Triassic beds.

Dixon's (1921) attribution of a Namurian age to the neptunian deposits was supported by later workers. Welch and Trotter (1961, p.84) stated, *"The deposits consist of hard, partly quartzitic sandstone and soft shale filling steep sided channels and underground cavities eroded in the Carboniferous Limestone"*. From the current viewpoint it is not the existence of this *palaeokarst* that provides the greatest interest, but the recognition that the *palaeokarst* suite includes palaeo-cavities. Photographs taken at Ifton in 1909 are archived at the Keyworth office of the British Geological Survey and, though these are monochromatic, enough detail is discernible to confirm that Dixon's interpretation was realistic (see photos accompanying this paper). The features were not a merely local phenomenon. Welch and Trotter (1960) report 16 grit/shale-filled fissures at the Ifton quarries in 1938, and grit-filled pipes, one containing shales with *Spirorbis,* in old limestone quarries near Dewstow and Portskewett, east of Ifton. It may also be noted that Trotter (1942, Plate IV B) illustrates but fails to describe in detail a (? dissolutional) pipe, within the Lower Dolomite at Ruardean, infilled by Upper Coal Measures sediment. Thus, *palaeokarstic* features may occur more widely in the area than published descriptions indicate.

What can be distilled from the work of Sibly, Dixon and other Geological Survey officers (as reported by Welch and Trotter, 1961) may be viewed thus:

1. In the southern Forest of Dean the period between deposition of the Drybrook Limestone and the diachronous marginal facies of the overlying Triassic rocks was one of net erosion.
2. After the deposition of the Drybrook Sandstone, but before local onset of Millstone Grit facies deposition during the Namurian, erosion included surface and sub-surface *karstification* of the Dinantian carbonate sequence.
3. *Karstification*, including local establishment of an underground drainage system, occurred during a span which falls within two stages (Asbian and Brigantian) and might be considerably shorter than this c.10 million year interval (Table 2).
4. Following infilling of *karst* voids in Namurian times, variable conditions of local deposition, non-deposition and erosion persisted into the Triassic.
5. On the available evidence it is uncertain how much additional *karstification* occurred during the Namurian-Triassic interregnum. Evidence from adjacent areas indicates that where Dinantian rocks were exhumed from beneath later cover, there was at least one more *karstification* episode prior to the onset of Triassic sedimentation (see the discussion of iron-ore deposition below, and Simms, 1990).

3.2 The iron-ore mines of the Forest of Dean

The Forest of Dean area has a complex history of deposition, non-deposition, erosion and *karstification*. Neptunian dykes and cavity fills (Smart and others, 1988) of Namurian age, within Dinantian host rocks (Dixon, 1921), provide valuable examples of how ancient *karst* features may survive later processes, remaining potentially available for involvement in later *karstification*. Of equal or greater importance within the main Forest of Dean Basin are haematitic iron-ore deposits, many of which were emplaced within pre-existing, *karstic,* cavities during Triassic times (Solari and Lowe, 1974; Lowe, 1974; Lowe, 1989; Simms, 1990).

Fierce controversy has centred on the age and chemical mechanism of haematite emplacement. Early discussion was reviewed by Trotter (1942) who also stated his own views. Since much ore lies within mid Dinantian rocks, deposition was no earlier than late Dinantian. However, similar ores are reported within Coal Measures beds (Trotter, 1942, p.75), implying that emplacement was post-Westphalian. Possibly the ore derives from oxidation of iron compounds within Upper Carboniferous rocks in pre-Triassic times, the process also contributing to the reddening of later, Triassic, deposits. Alternatively the ore may derive from Triassic rocks which had gained iron compounds from breakdown of Westphalian rocks. The former option indicates ore deposition within or stretching through the late Westphalian-early Triassic interregnum; the latter places the depositional phase later than the mid Triassic. A compromise (Simms, 1990) is that ore emplaced in Triassic times was derived contemporaneously by oxidation of iron compounds within a Silesian rock dominated hinterland.

It is proposed here that at least some of the open cavities which pre-dated ore inundation were much older than mid Triassic. There is ample evidence that *karstification,* including speleogenesis, took place during the late Dinantian to Namurian interval. Considering the local absence of Namurian, early Westphalian, Permian and early Triassic

Regional Stage	Lithostratigraphy	Thickness
Holkerian	Upper Drybrook Sandstone (part)	120 - 150m
	Drybrook Limestone	0 - 140m
	Lower Drybrook Sandstone	36 - 90m
Arundian	Whitehead Limestone	15 - 45m
~~	? gap	
Chadian	Crease Limestone	10 - 30m
~~	? gap	
Ivorian and Hastarian	Lower Dolomite	70 - 120m
	Lower Limestone Shales	55 - 70m

Table 5. Chrono- and lithostratigraphy of the Forest of Dean Dinantian. Supposed non-sequences are indicated by the symbol ~~~~~~~~~~~~~~.

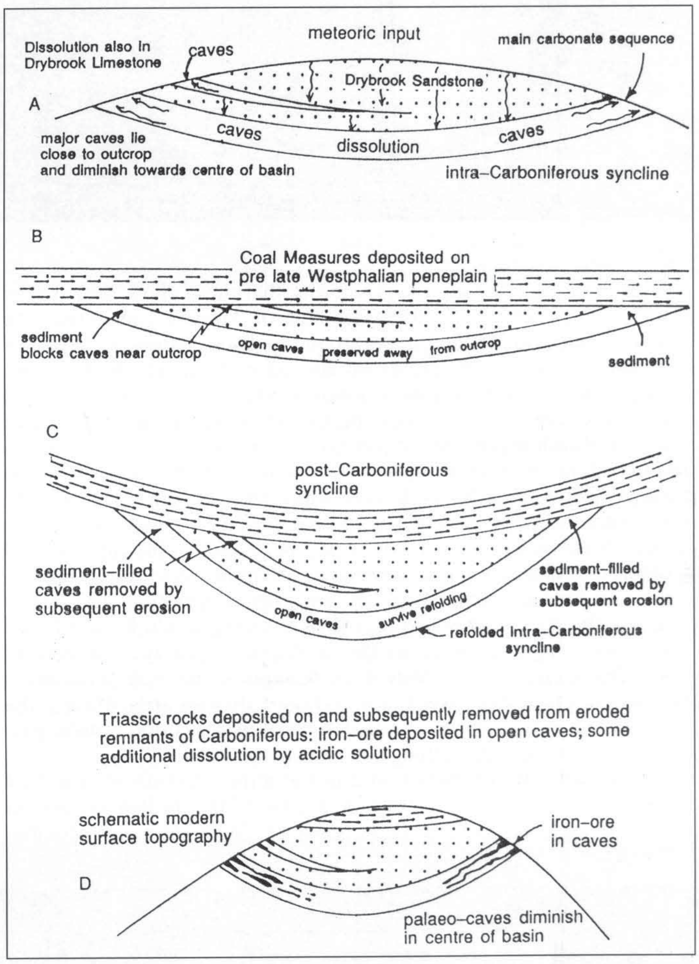


Figure 3. Schematic two-dimensional view of a possible explanation of ancient karstification in the Forest of Dean and the subsequent preservation and involvement of palaeo-caverns in iron-ore deposition.

rocks (Table 3) it is also reasonable to assume further *karstification* prior to late Triassic ore emplacement - if Simms (1990) is correct in identifying this as the date of ore genesis. Objection might be raised that *karstification* could proceed only where the carbonate sequence was exhumed from beneath younger beds, but this need not be true of early speleogenesis or of some other *karst* processes (eg Lowe, 1992).

Figure 3 is a diagrammatic, view of possible stages of iron-ore emplacement within palaeo-cavities in the Forest of Dean. The vertical scale is exaggerated and the detailed geological relationships and 3-dimensional complexity are ignored in attempting to emphasise the important events. Caves were developed in each named carbonate unit, but the unconformities above and below the Crease Limestone are the horizons of greatest interest. Early workers noted the upper unconformity (the *'Mid-Avonian Break'*), but the lower hiatus, deduced by Lowe (1989), is of equal or greater importance in this context. The significance of beds adjacent to the unconformities is discussed in section 4.

Not all *palaeokarstic* cavities pre-dating haematite deposition were infilled by iron-ore. Locally, as in Westbury Brook Mine (Solari and Lowe, 1974; Lowe, 1989) substantial clay deposits coincide with a supposed upper limit of ore emplacement. If ore emplacement took

The Lidstone bed exposed in the inclined roof of Honeycomb Rift, Westbury Brook Iron-ore Mine. The Lidstone is the lowest bed of the Whitehead Limestone and commonly forms the roof of the iron-ore workings. In the case of Honeycomb Rift the bed forms the roof of a natural cavity with no indications of previous ore infill. [D M Judson]

place during the Triassic, the possibility that these clays, and similar deposits elsewhere in the area, are also of Triassic age, remaining unconsolidated due to their underground location. Extensive, complex dissolutional cavities are preserved above this level (see photograph). It might be doubted that these cavities are natural, lying within a worked ore-field, but, in describing the first explorations of the mine since its abandonment, Solari (*in* Solari and Lowe, 1974, p.71) was adamant that the miners never entered the higher areas. Whereas passages below the mud level, from which large quantities of ore were won, were liberally supplied with clog marks, the mud floors at a higher level were pristine. It could be argued that this lack of footprints reflects a water-table rise or flood event since mining ceased, or since an earlier, near surface, mining operation. The former idea is a theoretical impossibility; such flooding would have affected lower workings, as well as those above. Equally, the second possibility is unlikely. It is unrealistic to suppose that rich ore deposits below the clay level were not pursued downwards during the hypothetical early venture, or that so profound a flood would pass unremarked in the local mining folklore.

Relict voids are not only found in the mines, though seen to best effect in the context of the vast ramification of the infilled system. At two stratigraphical levels in cliffs above the Wye are many bedding-guided dissolutional cavities, some originally partly filled by iron-ore, but picked clean by the early miners. Some were free of ore, but all are now blocked by clastic material (possibly related to earlier river levels), calcite speleothem or breakdown. Most lie along two putative inception horizons (discussed in section 4) at the upper and lower boundaries of the Crease Limestone, with sub-elliptical cross-sections (locally much modified by breakdown) and major axes parallel to the bedding. A level driven from the Whippington Brook valley towards Staunton, designed to de-water the Robin Hood Mine, failed in its aim, but crossing ground adjacent to the Whitehead Limestone/Crease Limestone junction the adit proved many bedding-guided dissolutional cavities, some of large size. The far reaches of the tunnel are no longer accessible due to major roof collapse; cavities still visible are devoid of ore but contain red mud fill, not unlike that preserved in Westbury Brook Mine. None of the abandoned caves is known to carry water, other than localised drips, even in the wettest conditions, though Solari (*in* Solari and Lowe, 1974) reported encountering an active stream passage (**not** water flowing in a mine level) when he dived beyond flooded workings near Columbus Pit in Wigpool Mine. The discovery of a natural underground lake by miners beneath Wigpool, reported in the press early this century, is now a part of local folklore. However, details of its location are lacking and the lake, which might not have been encountered from the main Wigpool

Part of a meandering dissolutional tube passage pre-dating and intersected by the Tertiary downcutting of the River Wye. This cave segment, one of many to be found in the gorge south of Symonds Yat, lies at the level of a supposed inception horizon at the base of the Crease Limestone on the west bank of the river. [Geological Survey and Museum photograph A6787].

The 'left-hand' (southern) entrance to an ox-bow of dissolutional cave passage at the base of the Crease Limestone. The cave, truncated during the incision of the River Wye in Tertiary times, lies on the west bank of the river. [Geological Survey and Museum photograph A6790].

workings, was not rediscovered during Solari's extensive exploration of the area.

Immature caves are known adjacent to the Crease Limestone boundaries (Lowe, 1989) and, locally, cave streams have invaded pre-existing voids. Large chambers (reminiscent of some iron-ore mine chambers) entered by streams in Symonds Yat and Cross Joints swallets (Lowe, 1989) may be relict features, since it appears unlikely that the immature stream passages and the chambers formed within similar timescales by similar processes. If the chambers are *palaeokarstic* and belong to the major network of pre-mineralization dissolutional voids, other segments could form part of the modern drainage system. Shatter Passage, adjacent to the chamber in Symonds Yat Swallet, is incongruously large but now largely infilled and blocked. Excavation at Whippington Brook Swallet penetrated voids whose walls appeared to be ancient passages, infilled by re-cemented carbonate breccia, boulders and clay. This poorly documented occurrence (Solari and Lowe, 1974) may be one of few recorded British examples of palaeo-cavities infilled by (at least partially) lithified rather than unconsolidated neptunian material.

Relict passages in the Wye cliffs south of Symonds Yat lie well above present base level, which lowered dramatically as the Wye incised in response to Miocene *('Alpine Orogeny')* uplift. A lack of vadose trenches below the truncated passages suggests that underground drainage diversion to deeper conduits accompanied the rapid surface downcutting, or that the relict system was abandoned before Miocene times. Local cavers report that farther south, around Ban y Gor, cave remnants currently being investigated on both sides of the river were once continuous across what is now the gorge of the Wye, thus pre-dating the Tertiary incision of the valley (John Elliott, Gloucester Speleological Society, written communication, 1994).

Modern underground drainage enters each of the carbonate units at outcrop and active cave passages have been explored within the Whitehead Limestone, Crease Limestone and Lower Dolomite. Much of the sinking water resurges by, or possibly beneath, the Wye, at or

The 'right-hand' (northern) entrance to the ox-bow cave fragment shown right. [Geological Survey and Museum photograph A6789].

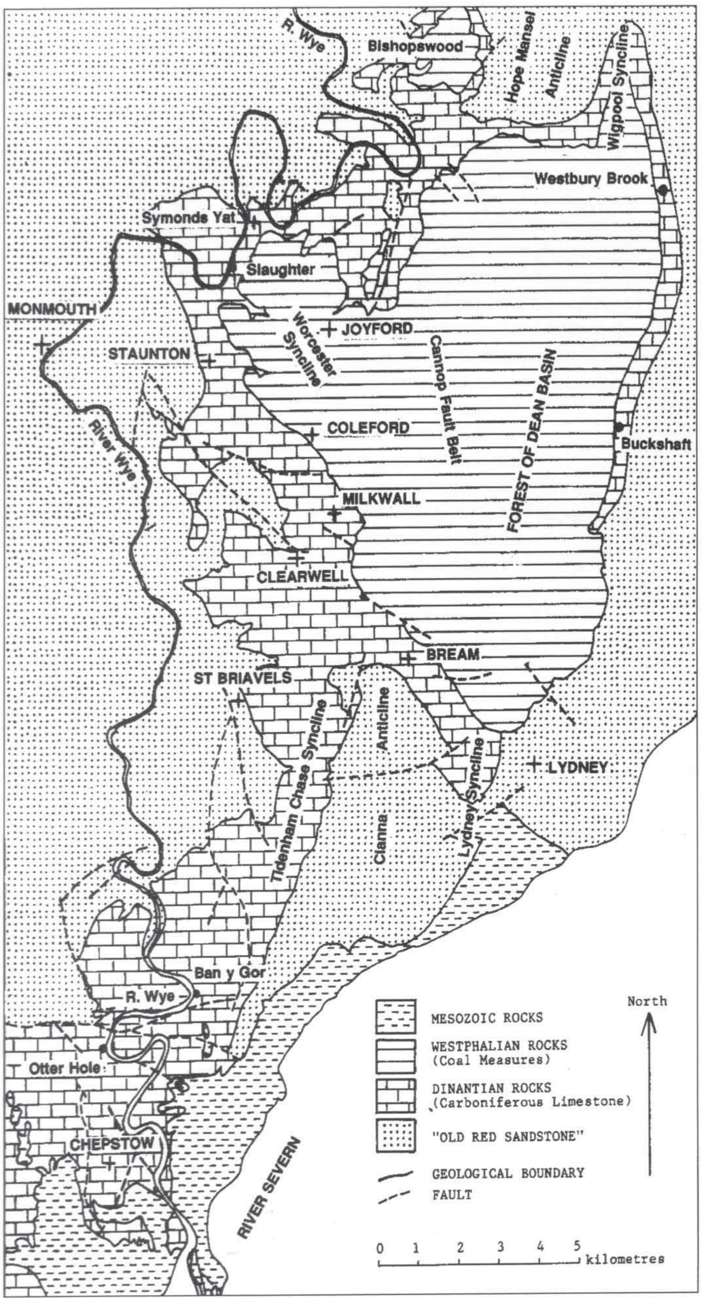


Figure 4. Generalised geological map of the Forest of Dean, showing locations of areas and structural features mentioned in the text.

adjacent to the Slaughter Resurgence (Lowe, 1989). Within the catchment limited cave development is also known within the Lower Limestone Shales. Several springs drain this formation and it is unknown whether any water passes up-sequence to join the major underground flow to the Slaughter. The stratigraphical level of the Resurgence is below the basal Crease Limestone inception horizon (section 4). Another major inception level, as deduced in Otter Hole and the Slaughter Stream Cave (section 4.2), is probably present below. However, significant cave development in the Lower Dolomite is recorded only within jointed/faulted synclinal folds (section 4.1) and this horizon may be less favourable to dissolutional speleogenesis in untectonised conditions than those in the Crease Limestone. To date little *palaeokarstification* is implicated in this deeper element of the Forest of Dean speleogenesis.

3.3 Other thoughts on ore deposition

The Forest of Dean iron-ore is not unique in showing a potential genetic link to pre-existing voids. Examples of extensive ore deposits related to palaeo-caverns in North American Palaeozoic rocks are common (eg De Voto, 1988; Sangster, 1988). Olson (1984) and D C Ford (1986, and in Ford and Williams, 1989) have disputed the development of palaeo-cavities occupied by lead/zinc ores in Precambrian dolostone at Nanisivik on Baffin Island. Ford's view of paragenetic enlargement of a pre-existing *"common cave system of primary tubes and strike passages"* (Ford and Williams, 1989, p.293) by hot fluids may be more reasonable than Olson's view of ore infilling a large, *'Mammoth Cave type'*, passage. Which is correct is less important in the present context than the recognition, by both authors, of open caves within the Precambrian dolostone prior to ore deposition. In eastern Europe iron minerals infilling *karst* cavities are described within a general consideration of *palaeokarst* by Činčura (1993). Less attention has been paid to such potential links in the British context, where mineralization has generally been assumed to involve rock replacement, commonly along fracture zones, by ascending or descending fluids. Such processes are relevant in non-carbonate situations and probably 'overlap' with those discussed here in areas where *palaeokarstic* voids exist. Minerals may enter the rock mass by non-*palaeokarstic* routes, but will certainly fill any voids encountered. Mineralization, previously not deduced to relate to *palaeokarst,* may thus owe its local economic viability to voids hosting ore-bodies of a size which could not have been attained by direct, concurrent rock replacement.

Examples of this link are immediately evident if the explanation of mineralization in the Forest of Dean is accepted. Iron-ore deposits at Llanharry, South Wales, are a close analogue. Gayer and Criddle (1970) provided an insight into replacement of carbonate by acidic, iron-rich solutions in this area, but did not pursue the potential involvement of palaeo-voids either as feeders or host cavities. The chemistry of ore deposition described by Gayer and Criddle (1970) and refined by Rankin and Criddle (1985) is probably more realistic than the simplistic reaction assumed here. Haematite deposits in North Wales, such as those now exhausted around Moel Hiraddug near Rhuddlan, were less extensive, but probably of similar origin:

> *"It* [iron ore] *is found in pockets or widened-out spaces in joints ranging about north-north-west. The pockets are irregular in shape, but generally bounded by curving vertical walls like those of a swallow-hole."*
> (Strahan, 1885, p.53)

> *"They* [iron, nickel and cobalt ores] *occur in an irregular chamber or cavity in the limestone, originally opened out, as may be inferred from its rounded walls, by the solvent action of carbonated water. . ."*
> (Strahan, 1885, p.54)

The origin of limestone-hosted iron-ore in Cumberland was controversial and Geological Survey officers presented two contrasting views. Dixon (1928) considered that the ores were of magmatic origin, but admitted that their geological relationships could indicate deposition by ascending magmatic water or descending meteoric water. He stated that the occurrence of haematite in carbonate outcrops close to iron-rich Permo-Triassic rocks was coincidental and, on this basis, suggested that theories of meteoric ore emplacement in North and South Wales and the Forest of Dean should be re-examined. In contrast, Smith (1928) considered that the Cumberland ores were of meteoric origin and post-dated other, magmatic, mineralization in the area. His arguments against Dixon's theory and in support of his own are convincing and include the almost incidental observation:

> *"It must be remembered that a drainage system was operative* ***in*** *the Carboniferous Limestone in early Permian times, and its effects may have had considerable effects upon the anomalous positions,* ***high or low in a bed*** *of limestone, of certain ore-bodies formed later on.* ***As in the Forest of Dean*** *also certain beds would be more susceptible to alteration than others."*
> (Smith, 1928, p.34. [present author's emboldening])

Smith's views show partial agreement with those developed in this paper. Despite contemporary awareness of *palaeokarsts* and palaeo-conduits being limited, his statement indicates a clear grasp of the potential involvement of underground drainage in the Cumberland iron-ore deposition, and also points to the importance of specific horizons to underground drainage in carbonate successions. Though made in the context of *'alteration'* rather than primary cavity inception by the assumed meteoric waters, his statement was prophetic and pre-dated the milestone works of W M Davis (1930) and Gardner (1935). Smith's linking of mineralization to pre-existing cavities possibly extended beyond the limits of meteoric deposition. Describing lead and zinc ores in the Carboniferous Limestone of North Wales, Smith (1921) mentioned natural cavities and *'swallow holes'* encountered by miners He did not suggest specifically that ore deposition was guided by pre-existing conduits, but perhaps suspected such a link. He, and later workers (eg Warren and others, 1984), described a small proportion of heavy metal ore bodies in North Wales as being unrelated to either regional fault/joint trends or to individual mapped fractures. Such aberrant, non-vein, bodies imply ore emplacement in pre-existing non-tectonic voids.

Similar possibilities can be deduced for ore bodies in areas such as the Derbyshire Peak District, the Yorkshire Dales and the more northerly Pennines (eg Mostaghel and Ford, 1986). It is accepted that mineralizing fluids ascend pre-existing fractures and follow them laterally for great distances, but the potential role of pre-existing natural cavities linked to such fractures has received little consideration. Many cave segments are described as 'vein-guided' (or 'vein- controlled'), but few workers have acknowledged the reciprocal, that 'veins' could be guided by pre-existing cavities. This reflects a generally narrow view of speleogenetic timescales and a reluctance to believe that caverns (*sensu* palaeo-voids) pre-dated ore deposition. Hence, for instance, smithsonite in Pikedaw Calamine Caverns (Gemmell and Myers, 1952) was labelled a Quaternary deposit by Dunham and Wilson (1985) and Arthurton and others (1988), who believed the cave to be a post-glacial feature. Work by T D Ford and others in Derbyshire is noteworthy in linking the form of some ore-bodies to pre-existing cavities. Many workers on ore genesis have ignored this link, implied by Smith (1921, 1928) and described by W M Davis in 1930.

THE POTENTIAL INCEPTION HORIZONS OF THE FOREST OF DEAN

Crucial links exist between ancient *palaeokarst* and more recent speleogenesis; many cavities identified among a suite of *palaeokarstic* features are guided by features still active in a guiding role. As discussed in section 3, almost all the *palaeokarst*-hosted iron-ore of the Forest of Dean was emplaced within narrow stratigraphical limits, and the special characteristics which were favourable prior to and during ore deposition, related here to inception horizons, remain operative.

4.1 The structural context of the Slaughter Drainage System

The Slaughter Resurgence catchment (Figures 1 and 2) lies on the edge of the Forest of Dean Basin, which owes its origin to at least two major tectonic episodes. North-westward of the main basin and separated from it by the Cannop Fault Belt, the axis of a relatively gentle fold system, the Worcester Syncline, passes through the resurgence (cf figures 2, 4 and 5). The rising lies where the River Wye, incising a gorge through the Dinantian succession south of Symonds Yat, has intersected active conduits within the core of the syncline. Underground drainage from a wide area east of the Wye (Figure 2), including allogenic inputs to at least eight major and innumerable minor sinks, is deduced to be channelled into the fold core, whence a main drain follows the fold axis to, and possibly beyond, the resurgence. Percolation water must enter the system via carbonate outcrops on both

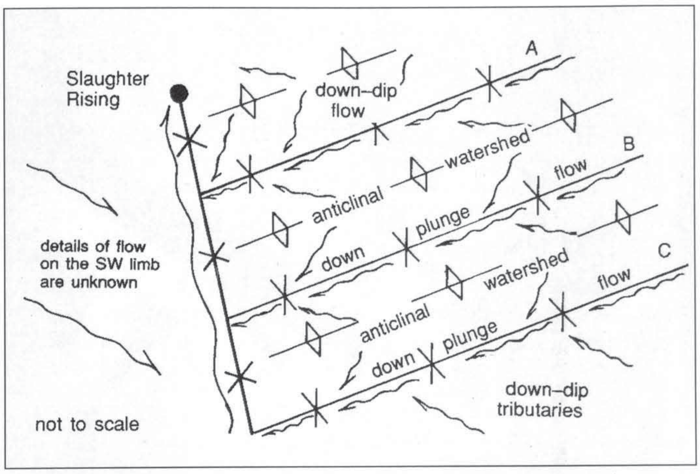
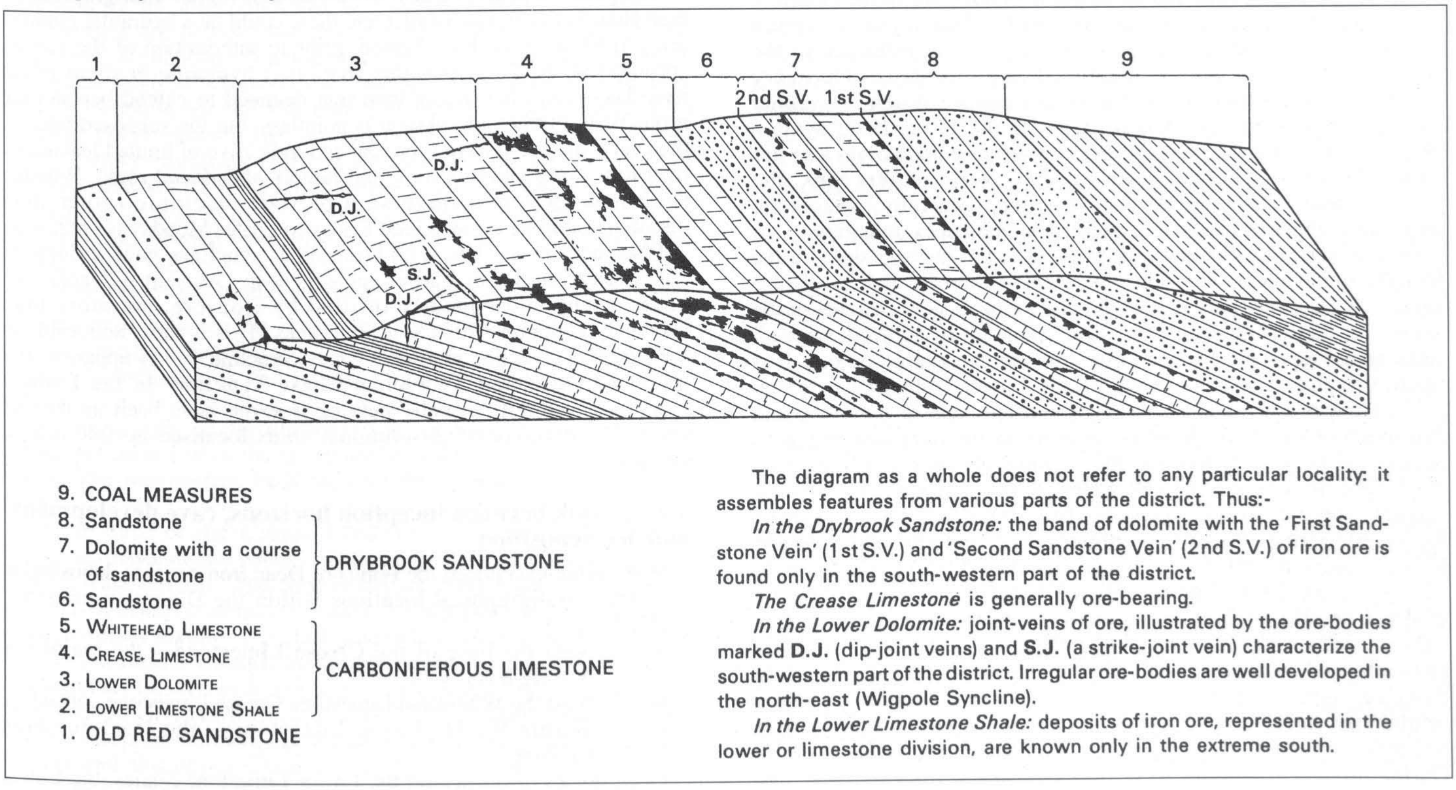


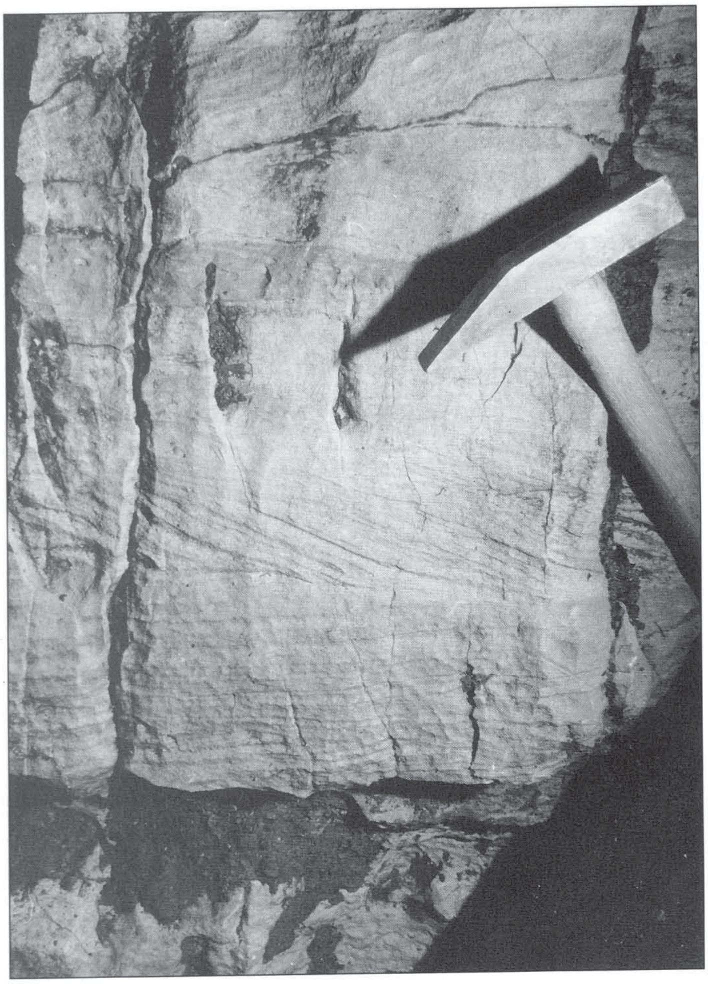
Figure 5. Schematic view of how underground drainage might follow synclinal flexures south-westward before following the Worcester Syncline northwards to the Slaughter Rising. The three minor flexures figured are deduced to guide the main drainage from Redhouse Swallet (A), Wet and Dry sinks (B) and Hoarthorns Wood Swallet (C) as shown on Figure 2. Another flexure to the north would be expected to guide drainage from sinks between Coldwell Swallet and the Slaughter Rising.

limbs of the Worcester Syncline, but most allogenic water known to rise at the Slaughter derives from sinks on the fold's eastern flank. In an unpublished study (c.1975) the present author deduced that, on the basis of the known geology and hydrology, it was unlikely that drainage from these sinks flowed directly towards the rising (cf the broken lines in Figure 2). Instead the drainage from the more remote sinks south-east of the Slaughter would flow south-westwards, following minor synclinal ripples on the eastern limb of the major syncline, before turning northward to follow the main fold towards the rising (figures 4 and 5). Although the guiding effect of minor synclines has been described (eg Waltham, 1974), an explanation of this type of constrained drainage in a carbonate sequence lacking significant aquicludes is lacking in traditional speleogenetic wisdom. Underground exposures indicate that thin 'marly' mudstones within the Whitehead Limestone have no appreciable influence upon local cave development. Shale (or similar) beds marking major cycle boundaries are absent from the sequence. The Inception Horizon Hypothesis suggests that only limited parts of a carbonate succession are favourable aquifers and such a bed is deduced to lie at, or just below, the Slaughter Resurgence, within the Lower Dolomite.

Exploration of the Slaughter Stream Cave (entered via Wet Sink, Figure 2) indicates that the c.1975 model is at least partly correct.

Figure 6. Block diagram illustrating the general form and distribution of the iron-ore deposits in the Dinantian rocks of the Forest of Dean (not to scale). After Sibly, 1927, Fig. 2. Reproduced with permission, British Geological Survey.





Cross bedded oolite close to the top of the Crease Limestone in the shaft of Sopers Pot. Similar rock is a favoured lithology for cavern development, just below a supposed inception horizon at or just below the Whitehead Limestone/Crease Limestone boundary. [D J Lowe].

Drainage from Wet Sink flows south-westwards at a constant horizon within the Lower Dolomite, remaining independent from water sinking at Hoarthorns Wood and Redhouse swallets. Passages at the south-western extremity of the system turn abruptly northwards, but drainage continues westwards in a flooded passage towards the axis of the Worcester Syncline. Reliable levelling data are not available and it is unknown whether the main drain beyond the present flooded limit, leading along the Worcester Syncline towards the rising will include unflooded passage. Joints and faults guide minor steps in the currently known major streamway and are assumed to link higher inception horizons with that in the Lower Dolomite, but the influence of the Worcester Syncline and its associated ripple folds is of primary importance to the form of the Slaughter drainage system. A similar situation has been reported in parts of the Otter Hole system (Westlake, Elliott and Tringham, 1989), where the main drain also lies within the Lower Dolomite (section 4.3). North of Wet Sink, the passages below Redhouse Swallet also trend generally towards the south-west (Figure 2), but await detailed geological examination.

On the basis of estimated quantities of water entering sinks in the Slaughter catchment, ignoring the potential increase due to diffuse input, it is clear that only part of the underground flow emerges at the rising. Yet there is no doubt that a single conduit is involved, since all sinks tested have given positive results via the visible output. It is likely that the main conduit within the Lower Dolomite inception horizon lies beneath the visible rising (on the bank of the Wye) and that much of the drainage either emerges in the river bed or passes beyond, to be assimilated into the regional groundwater body. The main conduit is assumed to be water-filled, accounting for upward leakage, under hydrostatic pressure, from fracture-guided fissures at the visible rising. Possible continuation of underground drainage beyond 'coincidental' local (sometimes man-made) resurgences is commonly overlooked when only a limited view is taken and the evidence of readily observable water trace results is accepted at face value. Confirming that part of the Slaughter catchment drainage passes beyond the Resurgence will require delicate and patient studies, though a combination of flood pulse and visible dye released into a nearby sink might supply rapid proof of any connection to the river bed and substantiate the 'boiling-up' reported by Richardson (1930). During drought conditions there may be leakage from the Wye into

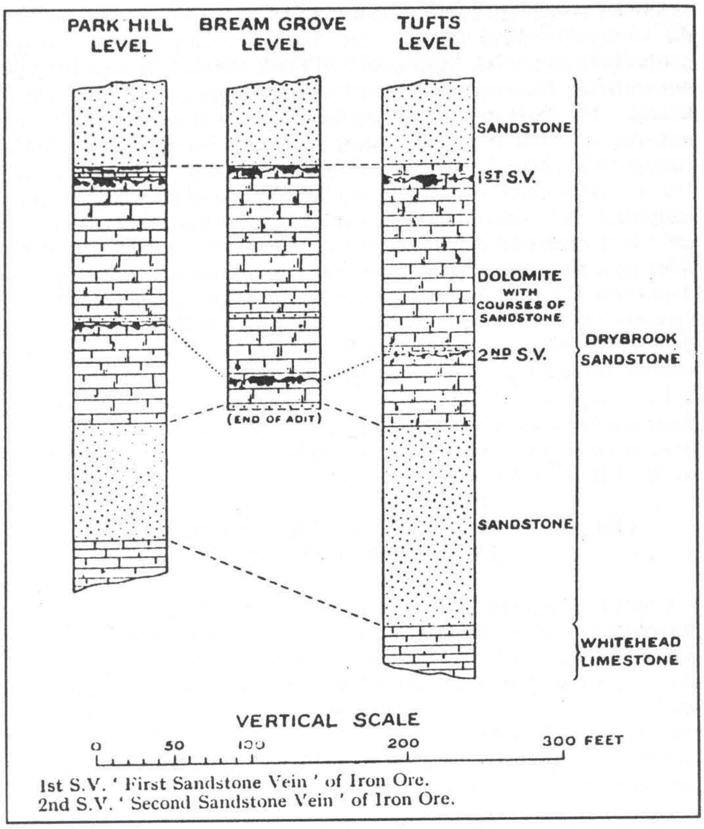


Figure 7. Sections showing the geological position of iron-ore in the Drybrook Sandstone in the neighbourhood of Bream and Lydney. Reproduced from Sibly, 1927, Fig. 3, with permission, British Geological Survey.

the underlying conduit and hence into the supposed regional groundwater body to the west.

It is also appropriate to reconsider the occasion, reported by Richardson (1930), when dyed water sinking at Hoarthorns Wood Swallet was 'seen' in Cannop Colliery. Later workers, including the present author, queried this report and, following a positive trace to the Slaughter Resurgence, it was dismissed as folklore. Why should water sinking into the Lower Dolomite, a speleogenic unit which hosts the major local resurgence and the major local swallets, move up-sequence into impermeable beds, containing no cave passages in the normally accepted sense? Such transfer has, however, been described elsewhere. Water emerging from the Coal Measures at Taffs Well in South Wales, for example, is at least partially derived from Dinantian outcrops to the north (Thomas and others, 1983). The Cannop Colliery workings are topographically lower, though higher stratigraphically, than Hoarthorns Wood Swallet and there could be a hydraulic gradient away from the Slaughter. Indeed, prior to intersection of the current spring(s) at the Slaughter, this (regional) hydraulic gradient might have been more favourable than that deduced to extend beneath the proto-Wye. Further speculation is pointless, but the supposed trace to the coal mine could have been real and indicative of limited leakage or overflow along a pre-existing and largely abandoned route. Whether such leakage could traverse a partially tectonic rather than dissolutional route during Good Friday to Easter Monday is unknown.

Elsewhere in the Forest of Dean other synclines have influenced cave formation during earlier speleogenesis. Ancient *palaeokarstic* voids, many subsequently infilled by iron-ore, are more than averagely common within synclinal areas. This is most noticeable in the Wigpool Syncline and the Lydney Syncline, but is apparent to a lesser extent in the Tydenham Chase Syncline. In the Lydney Syncline, beds not normally bearing iron-ore have been productive due to the presence of dissolutional voids localised by fold-related guidance.

4.2 The link between inception horizons, cave development and ore deposition

With minor exceptions the Forest of Dean iron-ore was deposited in just three stratigraphical locations within the Dinantian sequence (Table 5):

a. Near the base of the Crease Limestone – the major ore bearing level.
b. Near the Whitehead Limestone/Crease Limestone contact.
c. Within the Drybrook Limestone – the least common location.

Occurrences of ore within the Lower Limestone Shales, the Lower

Dolomite or (reputedly) the Coal Measures are unusual and, in the latter case, aberrant, situations. Figure 6, reproduced from Sibly (1927, Fig.2, p.9), illustrates the generalized distribution. The current author's experience indicates that the extent of ore within the Crease Limestone is exaggerated, possibly due to generalization, but the resemblance of the ore bodies to the morphology of a dissolutional cave system remains striking. This is also true of the limited ore bodies within the Lower Dolomite and Lower Limestone Shales. Certainly within the Crease Limestone, probably within the Drybrook Limestone and potentially within the Lower Dolomite and Lower Limestone Shales, much iron-ore was deposited within pre-existing dissolutional (possibly vadose-modified) voids. Some ore, representing ferrified bedrock (Lowe, 1989), was a by-product of reactions between calcium carbonate, magnesium ions and dissolved iron compounds. Magnesium was present within the dolomite bedrock or within the ore-bearing solution, adding an element of dolomitization to the depositional process. The second possibility was important locally, where dolomite-rich wall rock grades into undolomitized rock, within a few tens of centimetres or less (Lowe, 1974).

This stratigraphical segregation of pre-existing cavities is vital to the inception horizon concept. An extensive cavity system formed at the base of the Crease Limestone and a more limited set lies at the top of the same formation. Sibly's (1927) work implies that ore was deposited throughout the Crease Limestone, but the few voids in the middle of the unit were probably fracture- (rather than stratigraphically-) guided. This is demonstrated at Buckshaft on the Eastern Outcrop, where, *". . . virtually every opening that crosses the strike is a solutional rift."* (Solari and Lowe, 1974, p.68). Properties which made the upper and lower parts of the Crease Limestone more prone to speleogenesis than adjacent beds have not been investigated objectively. Solari and Lowe (1974) noted the tendency of upper, oolitic, beds of the Crease to decompose as the matrix of the weakly cemented rock dissolves. This could be relevant in the inception context as the oolitic facies has a high primary porosity, weathering to calcite sand by preferential loss of matrix. However, consideration of the dynamics of cave formation suggests this is not the full answer. Why do so many palaeo-cavities 'hug' the extreme top of the Crease, with intense dissolution recorded as pits and ridges in the lower surface of the overlying Lidstone bed (see photograph) at the base of the Whitehead Limestone? Logically, dissolutional effects should ramify down into the porous oolite, rather than being concentrated against the overlying bed – unless non-traditional *karst* processes operated. Even if the Lidstone acted as an aquiclude, preventing **upward** water movement, only non-traditional dissolution mechanisms can account for the cavity distribution. The rock below the Lidstone bed is an inception horizon.

Sibly (1927) considered that major ore bodies at this level extended into the Whitehead Limestone. This view may be erroneous if he was confused by the irregular nature of the Whitehead/Crease contact, as is suggested by his observation that the Lidstone bed forms the hanging wall of most ore bodies, though minor ore bodies certainly existed within the Whitehead. Consideration of more recent speleogenesis shows that small palaeo-passages could have cut into the Crease from a minor inception horizon above the Lidstone bed. Direct exploration of active but immature caves such as in Cross Joints Swallet (Lowe, 1981, 1989) confirms limited dissolution within the poorly speleogenic Whitehead Limestone, above the Lidstone bed. Subsequent vadose entrenchment and erosion, working back from fractures, has formed open links to major voids in the underlying Crease. Minor ore bodies would have filled such feeders to the Crease Limestone network system if similar processes were active in the past.

Links exist between the major dissolution zone at the top of the Crease Limestone and the base of the formation, as Sibly's illustration (Figure 6) indicates. In the pre-existing cave system context these represent late-stage vadose rifts, incised below the major phreatic level after uplift, or dissolutional rifts, guided by fractures, and contemporaneous with the sub-horizontal developments above and below. The intermediate beds are probably crossed by both passage types.

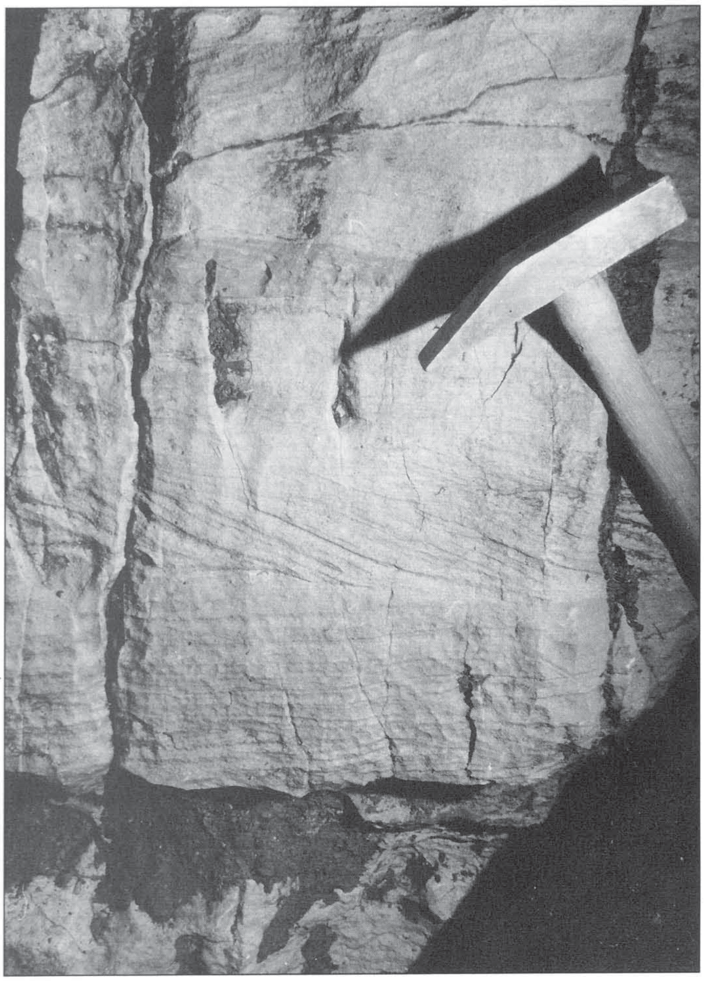
At the base of the Crease Limestone, overlying the Lower Dolomite, dissolutional palaeo-cavities are more common than in the upper Crease horizon. The rock is neither oolitic nor porous, but is generally a dense, crinoidal limestone, locally dolomitized to produce a saccharoidal texture. No clastic aquiclude occurs below, and the Lower Dolomite, though generally massive and crystalline, is speleogenic, locally with extensive, well-developed cave systems. Why palaeo-cavities formed at this level, considered here to be another inception horizon, has not been investigated, but the location of this and the upper Crease inception horizon at formational boundaries, probably also Stage/cycle boundaries (Lowe, 1989), may be significant. Viewed in this context, against the expanded timeframe offered by the Inception Horizon Hypothesis, rock now absent from the local sequence might have played as great a part in the palaeo-activity as that which remains.

Iron-ore occurrences within the Drybrook Limestone have not been studied closely. Sibly (1927) refers to deposits occupying dolomite bands at two levels within the Drybrook Sandstone. The *"First Sandstone Vein . . . follows the top of the dolomite closely"* (Sibly, 1927, p.14) and the *"Second Sandstone Vein . . . occurs immediately underneath a persistent course of sandstone within the dolomite* [but] *may transgress the strata considerably and may descend to a much lower position near the base of the dolomite."* (Sibly, 1927, p.14). The relationship of the *'veins'* to stratigraphy is shown in Figure 7 (reproduced from Sibly, 1927, Fig.3, retaining original nomenclature). Figures 6 and 7 reveal a dissimilarity between the style of ore deposits in the Drybrook Limestone and those within the Crease Limestone. The lack of cross-stratal ore bodies linking the *'First and Second Sandstone veins'*, though the intervening beds appear potentially speleogenic, is intriguing. If the two *'veins'* filled pre-existing cavities, as in the Crease Limestone, it must be deduced that earlier vadose downcutting did not link the upper and lower horizons and no fracture-guided dissolution complemented that guided by stratigraphy. Both deductions would be more acceptable if similar processes were not indicated below the *'Second Sandstone Vein'*, to account for its downward transgression.

Setting aside this minor paradox, it is apparent that the *'First Sandstone Vein'* represents ore-bodies occupying palaeo-voids directly beneath the Upper Drybrook Sandstone. If Figure 6 is realistic, a similarity between these cavities and maze caves formed by diffuse infiltration (Palmer, 1975) is evident. Such systems are reconsidered by Lowe (1992). Maze passages developed beneath porous caprock are commonly concentrated near the top of the carbonate unit (Palmer, 1975) and occupy a zone much thinner than the full formation. Palmer's early growth and development mechanisms can explain the lack of voids below the *'First Sandstone Vein'*, but if flow-lines in his Fig.3 are valid, additional deeper inception routes would be expected. It is more realistic to assume significant dissolution and lateral flow directly below the caprock, with minor, under-developed inception links descending to another inception horizon, now hosting the *'Second Sandstone Vein'*. If localised dissolution within a small vertical range reflects a rock-related factor, or factors, rather than Palmer's preferential flow regime, the susceptible rock may be viewed as an inception horizon and the lack of significant speleogenesis below this level is, at least partially, explained.

The putative inception horizon responsible for the *'Second Sandstone Vein'* palaeo-cavities is of another type. Sibly's (1927) description suggests that inception occurred beneath a laterally persistent sandstone within the dolomitic sequence. This relationship matches one of the potential *'carrier bed'* or *'aquifer'* types of Gardner (1935, p.1260) – *". . . a sandstone bed intercalated in limestone strata might serve as the original circulating medium until solution acts on the adjacent calcareous beds"*. For dissolution to commence below the sandstone, there must have been water in the sandstone, but the water source is uncertain. If the upper (*'First Sandstone Vein'*) dissolution zone operated as suggested by Palmer (1975), the succession was probably sub-horizontal, as would be expected if *karstification* was a late-Dinantian event, before intra-Carboniferous tectonism. If so, it is unlikely that meteoric water entered a dipping aquifer, as in Gardner's model, but if surface rivers cut the sequence, water could have entered sub-horizontal beds directly. Alternatively, sufficient water to commence dissolution might have been absorbed by the Upper Drybrook Sandstone at the surface, passed into a developing maze system at the top of the Drybrook Limestone and passed down isolated fractures to enter the thin sandstone. Despite a lack of recorded evidence (in the form of connecting ore-shoots) for fracture linkages, the latter view is probably the more realistic.

When the sandstone began to transmit water the potential for dissolution of adjacent carbonate began to be exploited. However, two paradoxes are apparent. First, water within the sandstone would be only slightly, if at all, aggressive, after crossing the carbonate beds between the two dissolution zones. Secondly, if the water was sufficiently aggressive to conceive the *'Second Sandstone Vein'* cavities, why did it not enlarge links through the carbonate above and why were cavities not formed in the carbonate above the sandstone? Inception horizon theory suggests that the carbonate rocks above and below the *'carrier bed'* are dissimilar and that pore water within the sandstone was rendered highly aggressive only at its lower contact. The chemical contrast responsible for such change is yet to be studied, but the lithological evidence shows that conditions changed



Cross bedded oolite close to the top of the Crease Limestone in the shaft of Sopers Pot. Similar rock is a favoured lithology for cavern development, just below a supposed inception horizon at or just below the Whitehead Limestone/Crease Limestone boundary. [D J Lowe].

Drainage from Wet Sink flows south-westwards at a constant horizon within the Lower Dolomite, remaining independent from water sinking at Hoarthorns Wood and Redhouse swallets. Passages at the south-western extremity of the system turn abruptly northwards, but drainage continues westwards in a flooded passage towards the axis of the Worcester Syncline. Reliable levelling data are not available and it is unknown whether the main drain beyond the present flooded limit, leading along the Worcester Syncline towards the rising will include unflooded passage. Joints and faults guide minor steps in the currently known major streamway and are assumed to link higher inception horizons with that in the Lower Dolomite, but the influence of the Worcester Syncline and its associated ripple folds is of primary importance to the form of the Slaughter drainage system. A similar situation has been reported in parts of the Otter Hole system (Westlake, Elliott and Tringham, 1989), where the main drain also lies within the Lower Dolomite (section 4.3). North of Wet Sink, the passages below Redhouse Swallet also trend generally towards the south-west (Figure 2), but await detailed geological examination.

On the basis of estimated quantities of water entering sinks in the Slaughter catchment, ignoring the potential increase due to diffuse input, it is clear that only part of the underground flow emerges at the rising. Yet there is no doubt that a single conduit is involved, since all sinks tested have given positive results via the visible output. It is likely that the main conduit within the Lower Dolomite inception horizon lies beneath the visible rising (on the bank of the Wye) and that much of the drainage either emerges in the river bed or passes beyond, to be assimilated into the regional groundwater body. The main conduit is assumed to be water-filled, accounting for upward leakage, under hydrostatic pressure, from fracture-guided fissures at the visible rising. Possible continuation of underground drainage beyond 'coincidental' local (sometimes man-made) resurgences is commonly overlooked when only a limited view is taken and the evidence of readily observable water trace results is accepted at face value. Confirming that part of the Slaughter catchment drainage passes beyond the Resurgence will require delicate and patient studies, though a combination of flood pulse and visible dye released into a nearby sink might supply rapid proof of any connection to the river bed and substantiate the 'boiling-up' reported by Richardson (1930). During drought conditions there may be leakage from the Wye into the underlying conduit and hence into the supposed regional groundwater body to the west.

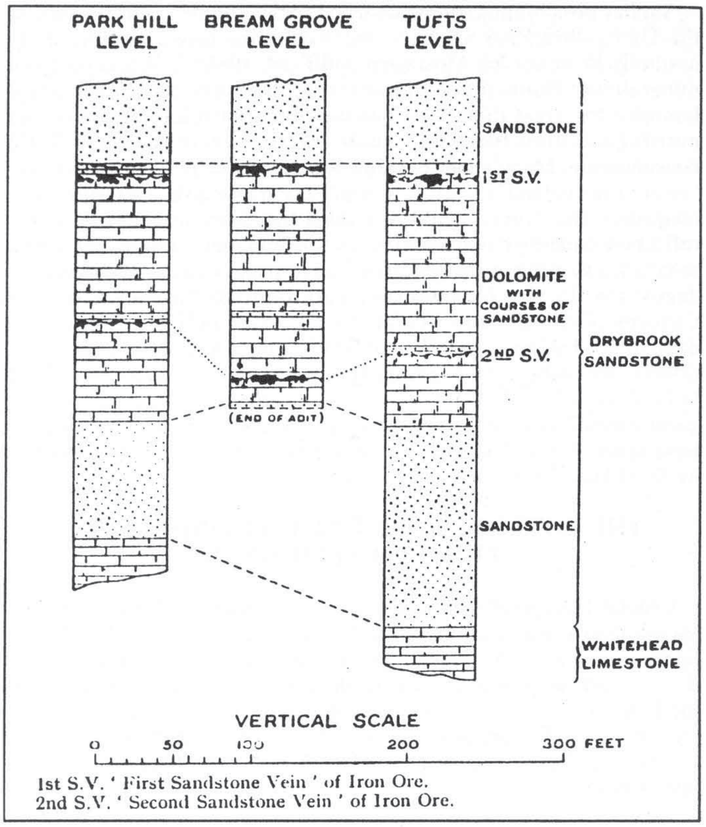


Figure 7. Sections showing the geological position of iron-ore in the Drybrook Sandstone in the neighbourhood of Bream and Lydney. Reproduced from Sibly, 1927, Fig. 3, with permission, British Geological Survey.

It is also appropriate to reconsider the occasion, reported by Richardson (1930), when dyed water sinking at Hoarthorns Wood Swallet was 'seen' in Cannop Colliery. Later workers, including the present author, queried this report and, following a positive trace to the Slaughter Resurgence, it was dismissed as folklore. Why should water sinking into the Lower Dolomite, a speleogenic unit which hosts the major local resurgence and the major local swallets, move up-sequence into impermeable beds, containing no cave passages in the normally accepted sense? Such transfer has, however, been described elsewhere. Water emerging from the Coal Measures at Taffs Well in South Wales, for example, is at least partially derived from Dinantian outcrops to the north (Thomas and others, 1983). The Cannop Colliery workings are topographically lower, though higher stratigraphically, than Hoarthorns Wood Swallet and there could be a hydraulic gradient away from the Slaughter. Indeed, prior to intersection of the current spring(s) at the Slaughter, this (regional) hydraulic gradient might have been more favourable than that deduced to extend beneath the proto-Wye. Further speculation is pointless, but the supposed trace to the coal mine could have been real and indicative of limited leakage or overflow along a pre-existing and largely abandoned route. Whether such leakage could traverse a partially tectonic rather than dissolutional route during Good Friday to Easter Monday is unknown.

Elsewhere in the Forest of Dean other synclines have influenced cave formation during earlier speleogenesis. Ancient *palaeokarstic* voids, many subsequently infilled by iron-ore, are more than averagely common within synclinal areas. This is most noticeable in the Wigpool Syncline and the Lydney Syncline, but is apparent to a lesser extent in the Tydenham Chase Syncline. In the Lydney Syncline, beds not normally bearing iron-ore have been productive due to the presence of dissolutional voids localised by fold-related guidance.

4.2 The link between inception horizons, cave development and ore deposition

With minor exceptions the Forest of Dean iron-ore was deposited in just three stratigraphical locations within the Dinantian sequence (Table 5):

a. Near the base of the Crease Limestone – the major ore bearing level.
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Occurrences of ore within the Lower Limestone Shales, the Lower

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The putative inception horizon responsible for the *'Second Sandstone Vein'* palaeo-cavities is of another type. Sibly's (1927) description suggests that inception occurred beneath a laterally persistent sandstone within the dolomitic sequence. This relationship matches one of the potential *'carrier bed'* or *'aquifer'* types of Gardner (1935, p.1260) – *"... a sandstone bed intercalated in limestone strata might serve as the original circulating medium until solution acts on the adjacent calcareous beds"*. For dissolution to commence below the sandstone, there must have been water in the sandstone, but the water source is uncertain. If the upper *('First Sandstone Vein')* dissolution zone operated as suggested by Palmer (1975), the succession was probably sub-horizontal, as would be expected if *karstification* was a late-Dinantian event, before intra-Carboniferous tectonism. If so, it is unlikely that meteoric water entered a dipping aquifer, as in Gardner's model, but if surface rivers cut the sequence, water could have entered sub-horizontal beds directly. Alternatively, sufficient water to commence dissolution might have been absorbed by the Upper Drybrook Sandstone at the surface, passed into a developing maze system at the top of the Drybrook Limestone and passed down isolated fractures to enter the thin sandstone. Despite a lack of recorded evidence (in the form of connecting ore-shoots) for fracture linkages, the latter view is probably the more realistic.

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Water cascading into the quarry-like hole of Wet Sink, Joyford, in 1936. Crossing a floor of silt and forest debris the stream sinks into a smaller hole where recent digging has opened the entrance to the Slaughter Stream Cave. [Geological Survey and Museum photograph A6780].

dramatically at the time of deposition. Whether these changes preview those which subsequently occurred at the Drybrook Limestone to Upper Drybrook Sandstone transition is uncertain. Potential extensions of the Palmer (1975) view of maze cave development, which might be applicable in this context, are discussed by Lowe (1992).

In contrast to the void development at the *'First Sandstone Vein'* level, that at the *'Second Sandstone Vein'* (which might also have exhibited an initial maze morphology, below the interbedded sandstone) was probably accompanied or superseded by incision into the underlying carbonates. As with the Crease Limestone palaeocavities, downward ramification could reflect contemporaneous lower level dissolution along fractures, or a combination of this with later, post-uplift, vadose incision. Another theoretical possibility is that dissolution was by acidic solutions derived from the underlying sandstone, rather than from overlying beds as most traditional wisdom would suggest. Sibly's illustrations provide no further evidence to add to this picture.

Iron-ore reputedly located within the Lower Dolomite and Lower Limestone Shales may be explained within a similar framework. The Lower Dolomite is cavernous and limited speleogenesis (analogous to that beneath the *'Second Sandstone Vein'*) probably ramified below the basal Crease Limestone inception horizon, either contemporaneously or following uplift. Most known caves within the Lower Dolomite of this area are fracture-guided, and the ore deposits (Sibly, 1927) occur in the Wigpool Syncline and close to Lydney and Bream, all near major fold axes (Figure 4). These folds probably began to develop during the late Dinantian, producing some of the earliest joint systems in the area. Bedding-parallel tube passage also occurs, possibly restricted to rare horizons of pristine, undolomitized rock within the succession.

Limited speleogenesis has occurred within the limestone beds of the Lower Limestone Shale sequence (Lowe, 1989). Iron-ore is so rare within the formation (Sibly, 1927) as to be considered insignificant. The host cavities probably represent isolated vadose-modified dissolutional conduits similar to those open today. Little evidence is available to construct an inception model for these beds. Strong joint-guidance is apparent locally and widened joints extend through the full thickness of some beds, suggesting that strong acid originating at the contact of carbonates with overlying (or underlying) pyritic shales might be involved. Vertical, joint-guided shafts, with limited associated horizontal development are found on some outcrops of the Lower Limestone Shales. Pyrite is a common mineral around Aylburton, where the Lower Limestone Shale ore bodies are located (Solari and Lowe, 1974). If this interpretation is correct, the limited passage involved in ore deposition probably indicates an initial lack of fractures within the Lower Limestone Shales, during *palaeokarstification,* prior to the major deformation of the Forest of Dean Basin. Sibly's (1927) note that the Aylburton deposits occur close to the extremity of the Lydney Park Syncline (cf the reference to synclines in the Lower Dolomite, above) is highly significant.

4.3 The context of Otter Hole and the Slaughter drainage system

Much of Otter Hole, a major cave system in the Lower Dolomite near Chepstow, south-west of the main basin, follows a single stratigraphical level (Westlake, Elliott and Tringham, 1989, p.121), with many fracture-guided passages. Like the Slaughter System, it lies within the limits of a significant synclinal fold. A branch of the Mounton Syncline holds Otter Hole, and the Slaughter System is restricted to part of the Worcester Syncline. Near Otter Hole, as in the main basin, relict beds of undolomitised or partially dolomitised oolitic limestone occur within the Lower Dolomite, but to what extent these potential inception horizons form links in the stratigraphical/structural inception network is unconfirmed.

Exploration and scientific examination of Slaughter Stream Cave, which captures much of the underground drainage between Joyford and Bracelands (Figure 2) is incomplete. Limited reconnaissance by the author, prior to many later discoveries, revealed major horizontal development within the Lower Dolomite about 40m below the entrance level. A vadose-modified canyon passage follows an alternation of sub-parallel fracture-guided rifts and perpendicular bedding or cross-joint guided passages. This local 'main drain' maintains a constant stratigraphical level as it trends westwards, following the plunge of a minor syncline on the north-eastern limb of the more complex Worcester Syncline. Along its course it captures several tributaries, at a similar stratigraphical level, flowing down-dip on the limbs of the minor syncline (Figure 5).

The main stream enters a flooded zone (sump) where it meets a major fracture zone, but abandoned, unmodified tubular passages, with partial clastic fill, provide a long, meandering by-pass, to regain the stream. The sump lies on the down-dip (in the sense of the oblique fold plunge) side of the stream passage whilst the dry by-pass follows a route along the northern limb of the syncline. This is almost certainly the route of the original phreatic drainage network within the Lower Dolomite inception horizon. Where the horizon is offset by the fracture zone the primitive drainage route seems at first glance to be up-dip on the limb of the minor syncline, but can be perceived to drop along its course, due to the fold plunge, into the Worcester Syncline. After a long, meandering (low hydraulic gradient) course, probably within the same horizon, the tube meets another (or possibly the same) fracture, regaining the main water flow. The flooded active route must have captured the main drainage relatively recently, though minor, 'exploratory' seepage always followed the fracture. Initially the inception horizon route, though intricate and of low overall gradient, provided a more favourable option than the fracture-guided line within rocks less susceptible to dissolution. When the inception tube began to drain due to uplift, relatively more flow followed the fracture-guided short-circuit. Eventually the main drain passage as far as the first sump cut down below the inception horizon due to vadose incision. The by-pass, largely unaffected by vadose processes, 'hangs' above the stream passage, but clastic deposits indicate that flood overflow has occasionally used the route.

CONCLUSIONS

A major part of the once extensive iron-ore deposits of the Forest of Dean, probably emplaced during the Triassic Period, represents neptunean infill of pre- existing *palaeokarstic* voids. The voids formed part of an extensive underground drainage network, or networks, possibly conceived during Dinantian times and pre-dating the tectonism that has since affected the area. Neptunean deposits of Namurian age confirm the pre-existence of significant *karstic* cavities, though the earliest date of speleogenesis, possibly related to unconformities within the Dinantian succession, is unproven.

Relationship of iron-ore-bearing cavities to stratigraphy indicates that major dissolution was confined to a relatively small part of the preserved carbonate succession. These stratigraphically guided 'zones' are not spaced equally through the sequence, but nor is their occurrence random. The more important 'zones', referred to as inception horizons, are related to unconformities within the succession, to horizons of contact between relatively pure limestone and other rock types or to beds with relatively high primary permeability within dolomitic sequences. In descending order the **major** inception horizons are:

1. The 'First Sandstone Vein' – contact between permeable sandstone and relatively pure carbonate within the Drybrook Limestone.
2. The 'Second Sandstone Vein' – as above.
3. The unconformity between the Whitehead Limestone (above) and Crease Limestone.
4. The unconformity between the Crease Limestone (above) and Lower Dolomite.
5. Zone (or ?zones) of relatively permeable oolitic limestone, less dolomitised than the adjacent beds, within the Lower Dolomite.

Other less important inception horizons exist, including those guiding limited speleogenesis immediately below the Lower Drybrook Sandstone (within the Whitehead Limestone) and above the Lidstone bed near the base of the Whitehead Limestone.

Acceptance of the presence and importance of inception horizons, marking lithological and/or chemical contrasts in the succession, in terms of an ancient ore-hosting cave system, allows an assumption that the same horizons are also important in the context of more recent speleogenesis. Relationships observed in parts of the active cave system draining to the Slaughter Resurgence on the banks of the Wye, have improved a skeletal model of the major drainage links, on the basis of the predicted interplay of one inception horizon (within the Lower Dolomite) with minor folds on the north-eastern limb of the Worcester Syncline. Partial solutions to historical questions relating to early, and far from sophisticated, water tracing experiments in the area are also suggested by elements of the Inception Horizon Hypothesis.

ACKNOWLEDGEMENTS

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Mollusc Taphonomy in Caves: A Conceptual Model

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Abstract: Subfossil mollusc shells provide an important, but underused tool for research into cave palaeoenvironments. The taphonomic pathways which can give rise to mollusc assemblages in caves are described and the factors influencing the composition of assemblages in caves are discussed.

INTRODUCTION

Subfossil mollusc shells have considerable potential in palaeoenvironmental and biostratigraphic research – they are strongly habitat-specific (Kerney & Cameron, 1979) and there have been extinctions and some incoming of new species during the Quaternary (Kerney, 1977). Molluscs immigrated into the British Isles during the late-Glacial and Holocene in a sequence first codified and developed into a biostratigraphical scheme by Kerney (1968). Occasionally, living molluscs are reported from caves (references in Dixon, 1974; Hazleton, 1975, 1977; Jefferson, 1989) and subfossil mollusc shells are reported from cave entrance-facies sediments and fissure-fills (for instance Evans & Jones, 1973, Evans, 1976; Jenkinson *et al.*, 1981, 1984; Gale *et al.*, 1984, 1992; Gale & Hunt, 1985; Hunt, 1989). Subfossil mollusc faunas have considerable potential for biostratigraphy and palaeoecology in the cave environment, since mollusc shells preserve well in calcareous sediments and some cave fills are well-stratified and preserve long environmental sequences (Hunt & Gale, 1985).

It has become evident, however, that problems exist in the use of cave mollusc assemblages for palaeoecology and biostratigraphy. In a recent paper in this journal, Hunt (1989) called for the erection of a separate late-Glacial and Holocene mollusc biostratigraphy specifically for British cave sites, since it was evident from this and previous studies (Gale *et al.*, 1984, Gale & Hunt, 1985) that terrestrial molluscs appeared at different times (usually earlier) in the late Pleistocene and early Holocene in caves than in open air sites of equivalent age. This problem was not addressed in a recent review (Jacobi, 1991), where the author dismissed the biostratigraphic evidence provided by molluscs because it was incompatible with the evidence from open air sites.

The ecological tolerances of molluscs and their ability to disperse across hostile terrain are probably the most important factors leading to the biostratigraphic discrepancy between caves and open air sites. Gale & Hunt (1985) have suggested that the discrepancy between cave and open air sites may be the result of molluscs being able to colonise caves in the Early Holocene before the developing vegetation cover enabled open air sites to be occupied. Taphonomy – the mechanisms by which organisms become incorporated and preserved in sediments – is also an important factor. Gale & Hunt's suggestion cannot be tested until a number of radiometric dates on mollusc assemblages from caves have accrued and the taphonomic pathways leading to the formation of subfossil mollusc assemblages in caves are better understood. Very little is yet known about the taphonomy of molluscs in caves, other than the work of Evans & Jones (1973) and Evans (1976). This paper is therefore an exploration of the routes by which molluscs disperse and become incorporated into and preserved within

Table 1: Mollusc species found subfossil in cave fills (Gale & Hunt, 1985; Hunt, 1989 and unpublished data) and found living in caves (Dixon, 1974; Hazleton, 1975; Jefferson, 1989)

	species subfossil in cave sediments	trogloxenes	troglophiles
Acanthinula aculeata	x		
Aegopinella nitidula	x	x	x
Aegopinella pura	x		
Arianta arbustorum	x		
Azeca goodalli	x		x
Candidula intersecta		x	
Carychium tridentatum	x		
Cecilioides acicula	x		
Cepaea hortensis	x	x	x
Cepaea nemoralis	x		
Cepaea spp.	x		
Cernuella virgata	x		
Clausilia bidentata	x	x	
Clausilia dubia	x		
Clausiliidae	x		
Cochlicopa lubrica	x		x
Cochlodina laminata	x		
Discus rotundatus	x		x
Ena obscura	x		
Euconulus fulvus	x		
Helix pomatia		x	
Helicidae	x		
Helicigona lapidica	x		
Helix aspersa	x		
Lauria cylindracea	x	x	
Limacidae	x		x
Lymnaea peregra	x	x	
Lymnaea truncatula			x
Nesovitrea hammonis			x
Oxychilus alliarius			x
Oxychilus cellarius	x		x
Oxychilus draparnaudi			x
Oxychilus helveticus	x	x	x
Pisidium sp.	x		x
Pisidium nitidum			x
Pisidium personatum			x
Pomatias elegans	x		
Potamopyrgus jenkinsi			x
Punctum pygmaeum	x		
Pupilla muscorum	x		
Succinea sp.	x		
Vallonia costata	x		
Vallonia excentrica	x		
Vallonia sp.	x		
Vertigo pusilla	x		
Vertigo sp.	x		
Vitrea contracta	x		
Vitrea crystallina			x
Vitrea sp.	x		

Table 2: Habitats of molluscs living or subfossil in caves (largely after Kerney & Cameron, 1979)

Taxa found in caves & cave fills	burrower	scree & rubble	cliffs walls & trees	leaf litter	herbage	open ground	general -ist	marsh	aquatic
Acanthinula aculeata				x					
Aegopinella nitidula		x		x					
Aegopinella pura					x				
Arianta arbustorum				x	x		x		
Azeca goodalli		x		x					
Candidula intersecta						x			
Carychium tridentatum				x	x				
Cecilioides acicula	x								
Cepaea hortensis				x	x	x	x		
Cepaea nemoralis				x	x	x	x		
Cepaea spp.				x	x	x	x		
Cernuella virgata					x	x			
Clausilia bidentata		x	x	x					
Clausilia dubia		x	x						
Clausiliidae		x	x	x	x				
Cochlicopa lubrica				x	x			x	
Cochlodina laminata			x	x					
Discus rotundatus		x	x	x	x				
Ena obscura		x	x						
Euconulus fulvus				x	x			x	
Helix pomatia				x	x				
Helicidae		x		x	x	x	x		
Helicigona lapidica		x	x	x					
Helix aspersa		x		x	x	x	x		
Lauria cylindracea		x	x	x	x				
Limacidae		x	x	x	x	x	x	x	
Lymnaea peregra									x
Lymnaea truncatula								x	x
Nesovitrea hammonis				x	x		x		
Oxychilus alliarius		x		x	x		x		
Oxychilus cellarius	x	x		x	x				
Oxychilus draparnaudi		x		x	x				
Oxychilus helveticus		x		x					
Pisidium spp.									x
Pisidium nitidum									x
Pisidium personatum									x
Pomatias elegans		x		x					
Potamopyrgus jenkinsi									x
Punctum pygmaeum				x	x		x		
Pupilla muscorum						x			
Succinea spp.								x	
Vallonia costata		x				x			
Vallonia excentrica		x				x			
Vallonia sp.		x			x	x			
Vertigo pusilla		x	x	x		x			
Vertigo spp.		x	x	x	x	x		x	
Vitrea contracta		x	x	x	x	x	x		
Vitrea crystallina		x		x	x		x	x	
Vitrea sp.		x	x	x	x	x	x	x	

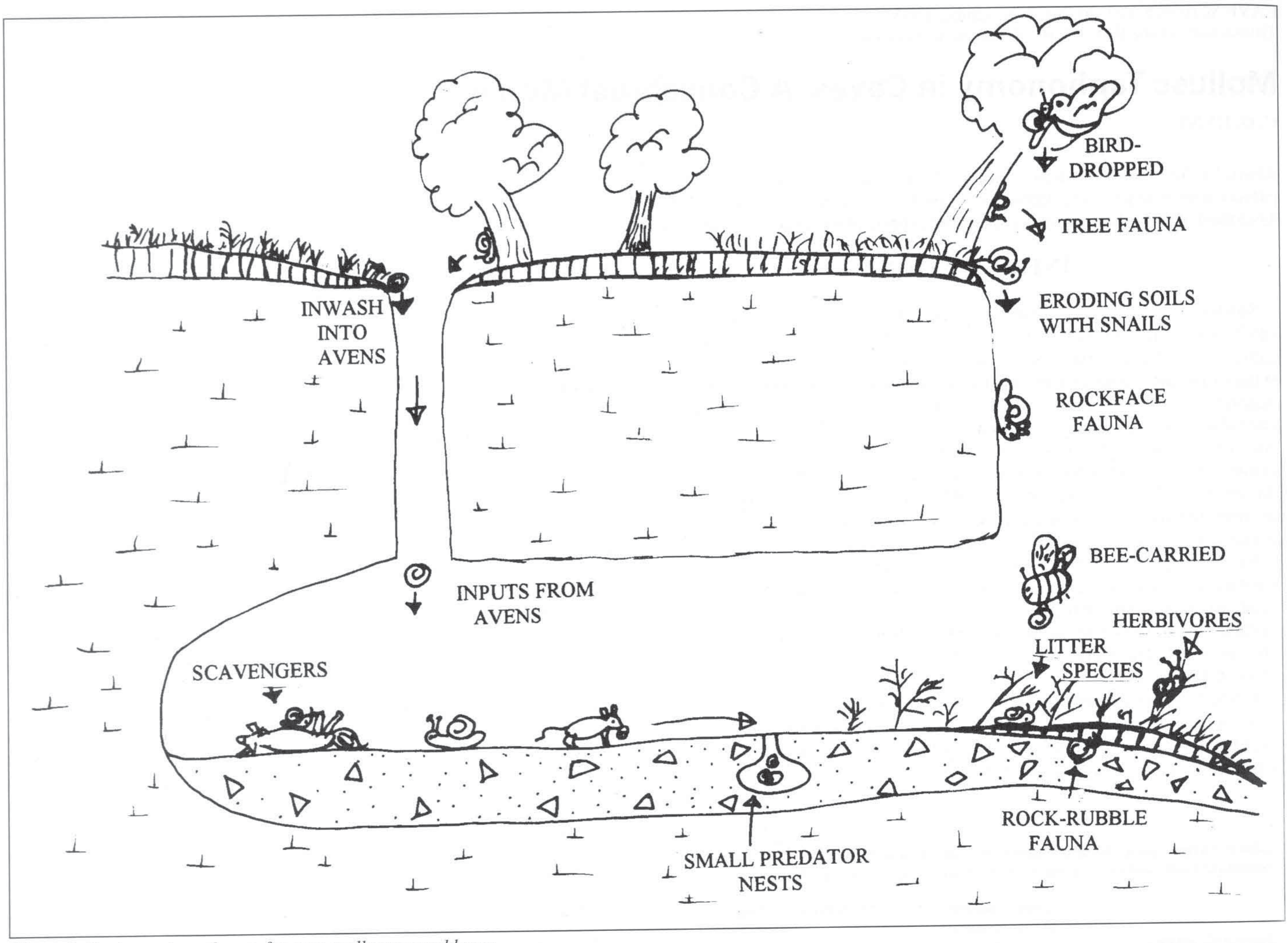

Figure 1. Taphonomic pathways for cave mollusc assemblages.

cave fills. It draws on our still-limited knowledge of living molluscs in caves, the literature on mollusc dispersal mechanisms and the few published records of subfossil mollusc faunas from caves. Experimental verification of the model proposed here is required before we can properly evaluate the significance of cave mollusc faunas for biostratigraphy and palaeoecology.

ECOLOGY OF TAXA FOUND IN CAVE FILLS

The ecological relationships of living molluscs in British karst areas are well-known (Kerney & Cameron, 1979). Virtually all British land molluscs and most freshwater aquatic taxa live in limestone areas, and many are environmental specialists, occupying specific niches. A considerable number of taxa have been reported as subfossil from cave fills, and many have been found as living or recently dead animals in caves and can be regarded as trogloxenes – species that are found in caves but cannot complete their life cycles there. Only a few species can be regarded as troglophiles – species that can maintain permanent populations in caves though not restricted to that environment (Table 1). These and other taxa are reported from other environments (Table 2) – rock rubble, scree, cliffs, walls, woodlands, scrub, herbaceous vegetation and aquatic habitats. It is clear from these tables that relatively few species are troglophiles: most subfossil material must represent trogloxenes or specimens that have been carried dead into the cave environment. The next section of this paper explores the transport mechanisms – taphonomic pathways – potentially involved.

TAPHONOMIC PATHWAYS

A number of potential pathways can be distinguished, though the present state of knowledge does not allow these to be quantified. First, there are the troglophile species that actually live within caves. Some

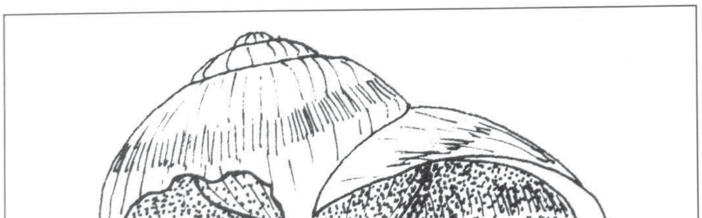

Figure 2. The characteristic damage pattern caused by shrew predation. Helix aspersa *from La Romieu, France, collected July 1993.*

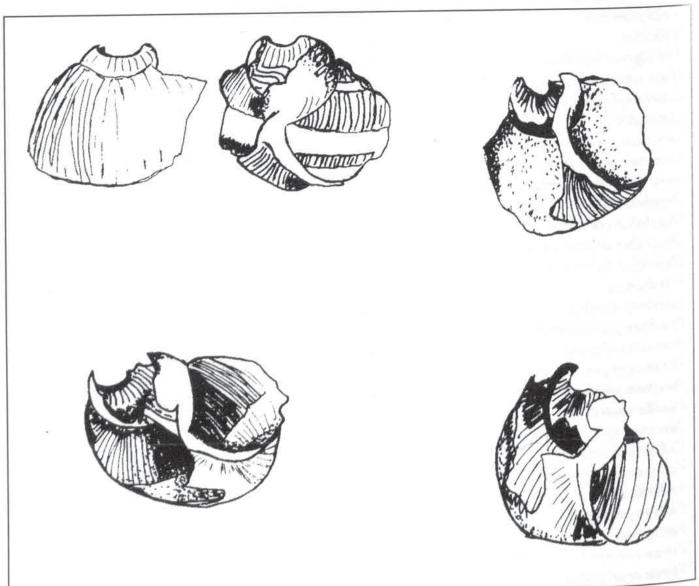

Figure 3. Characteristic damage patterns caused by bird predation. Helix aspersa *from Brimfield, Herefordshire, collected August 1993*

troglophile species, most notably *Oxychilus cellarius, O. draparnaudi* and *Vitrea crystallina* are animals that require damp, well sheltered habitats such as leaf litter and rock rubble and are able to cope with true subterranean life. These taxa are detritivores, carrion feeders and facultative carnivores *(O. draparnaudi,* for instance is a predator of earthworms) and are therefore able to live in caves beyond the limit of green plant penetration. A second group of troglophiles are aquatic species such as *Pisidium nitidum* and *P. personatum,* which are filter-feeders able to subsist on plankton and small organic debris carried from the surface in streamways. The trogloxenes are able to penetrate and, to some extent, live in the photic zone of cave entrance areas. Typically, these are species that graze on algae and other lower plants on rock faces, species that graze on higher plants growing in the entrance of the cave and detritivores who eat the leaf litter generated by these plants.

Some taxa do not seem to have the necessary adaptions for any of these ways of life and therefore were most probably carried into cave by any one of a number of agencies. The simplest is fall, mass movement or wash of living or recently dead specimens into caves, from overhanging cliffs and through avens. Similarly, fall, wash and mass movement of mollusc-bearing soils and Quaternary deposits from the slopes above the cave would recycle specimens into the cave. Aquatic molluscs are carried into caves by sinking streams, which will also carry terrestrial molluscs that have fallen or been washed into the water and subfossil material recycled from eroding stream banks and so forth. Elongate molluscs such as the Clausiliidae and Pupillidae are particularly liable to be carried by water since air is easily trapped in their shells. The gases generated by decomposition can also make most molluscs buoyant enough to float. These processes are well-known in surface situations (Gilbertson & Hawkins, 1978; Briggs *et al.*, 1990).

Molluscs can also be carried by animals, both by predators as part of feeding behaviour and inadvertently on fur or plumage. Birds are well-known predators and carriers of snails (Rees, 1965; Jenkinson & Gilbertson, 1984). The present author has observed shrews carrying molluscs such as *Cepaea* spp. and *Helicella* spp. to their burrows and eating them there and has also seen snail shell-filled small mammal burrows in cave sediments in the UK at Creswell Crags and at Gajn-el-Kbira near Victoria on Gozo in the Maltese Islands (Hunt, in prep.). Snails have been observed sticking to amphibians, mammals and birds and can be carried long distances in this way, including, presumably into caves. Rees (1965) has documented the behaviour of *Vitrea* spp., which produce sticky secretions and are carried long distances stuck to the plumage of migrating birds. Rees (1952) has described the inadvertent transport of molluscs by amphibians. Bumblebees, which occasionally nest in sandy cave sediments, have been observed inadvertently carrying molluscs sticking to their legs (Rees, 1965). All the terrestrial dispersal and taphonomic pathways are summarised in Fig. 1.

RECOGNITION OF TAPHONOMIC PATHWAYS

The recognition of taphonomic pathways is fraught with difficulty, but must be addressed before subfossil faunas can be interpreted reliably. Three important sets of evidence may be available. The first is context. The position of subfossil material in the cave, in relation to potential inlets and the position of the photic zone may provide an indication of potential pathways (Hunt, 1989). The sedimentary facies may provide a further indication – such lithologies as breccias resulting from mass-movement events and laminated sands resulting from wash processes are clear indications of sedimentary (and possible mollusc) input. In contrast, openwork breccias provide abundant habitat for autochthonous populations of *Oxychilus, Discus* and similar taxa (Evans, 1976). The associations of the subfossil fauna may provide further information. The shells of scavengers, especially *Oxychilus cellarius,* are often found close to the skeletal material of carcasses they have scavenged (Evans, 1976). Small mammal burrows often contain clusters of several dozen shells of large taxa brought in as food.

The second major line of evidence is the pattern of damage caused by predators and other transport agencies. Predators seem to have pronounced size preferences, most small mammals preferring the larger taxa like *Cepaea, Hellicella* and *Helix.* Small mammals produce characteristic damage patterns (Fig. 2), often either neatly removing the apex or biting a hole just behind the aperture in the final whorl. Birds, in contrast, tend to smash shells (Fig. 3) though some cleverly remove the snail from its shell without damage to the latter (Teichert & Seventy, 1947). Trampling by large mammals also produces fragmentation of shells (Jenkinson & Gilbertson, 1984).

The third line of evidence is the known tolerances and habitat preferences of living molluscs (Tables 1 and 2). Certain taxa can be identified as troglophiles and thus potentially part of a biocoenosis, whereas others have habitat preference incompatible with cave dwelling and were thus most probably introduced by some process. The ecological coherence of assemblages, and comparison between the palaeoenvironmental evidence from the mollusc fauna and that from the sediments from which the molluscs were recovered may provide indications as to whether the molluscs were *in situ,* recycled or intrusive in the context in which they were found. The size characteristics of assemblages may give some indication of how closely an assemblage approaches a biocoenosis, or whether other processes, for instance some form of size selection by predators or sedimentary processes, was operating.

POST DEPOSITIONAL PRESERVATION

The mollusc shell assemblages laid down in a cave may be modified by a variety of processes prior to and after burial. Before burial, shells may be damaged or redistributed by trampling, for instance by badgers (Jenkinson & Gilbertson, 1984). After burial, shells may be destroyed by dissolution during diagenesis if, for instance, fluids in the sediments are acidified by organic acids. Subtle diagenetic modification may occur when the least substantial shells are removed in this way, while more robust shells survive (Chave, 1964). Most molluscs have shells of aragonite, the more soluble form of Ca CO_3. Taxa with very robust shells such as *Pomatias elegans* are least vulnerable to this process; even more resistant are the calcite opercula of *Pomatias* and *Bythinia* and the residual shells, also calcite, of slugs.

RECOVERY METHODS

A final factor modifying mollusc assemblages is the method used to recover shells from the sediment (Evans, 1972). Hand sorting, the technique utilised in most of the older studies, gives a strong bias towards the larger and most robust species, while sieving gives a representative sample, but may miss large but very rare speciments. The processes of sediment breakdown and the mechanical battering associated with sieving can also destroy shells in fragile condition.

CASE STUDIES

The subfossil mollusc assemblages with which the author is familiar are from cave entrance facies and associated with archaeological investigations. Brief comments are made here about the taphonomy of published assemblages from Kirkhead Cave, Cumbria, Pin Hole Cave, Creswell Crags, Derbyshire, and from an unpublished assemblage from Dog Hole Cave, Derbyshire.

Kirkhead Cave, Cumbria is a truncated phreatic conduit in the Morecambe Bay Karst (Gale & Hunt, 1985). Molluscs were found in entrance-facies laminated silty loams with very thin stalagmite horizons of latest Late glacial (late pollen zone III) to mid Holocene (early pollen zone VIIa) age (Gale & Hunt, 1985). *Ena obscura, Punctum pygmaeum* and *Oxychilus cellarius* appear early in the sequence, during the latest part of pollen zone III. *Vitrea* spp., *Vallonia* sp., *Pupilla muscorum, Pisidium* sp., *Succinea* sp., *Carychium tridentatum, Euconulus fulvus, Vertigo* sp., Limacidae and Helicidae all appear in pollen zones V and VI. *Discus rotundatus* appears in pollen zone VIa. *Oxychilus cellarius* is the dominant species, and its numbers peak where there is evidence (charcoal, burnt bone) for human activity in or near the cave. The silty loams contain original depositional laminae and show no evidence of mixing or disturbance by burrowing: thus the shells were demonstrably *in situ.* The shells were most fragmentary and clearly broken in antiquity in most cases, but the fragments were 'sharp' and showed no sign of abrasion or corrosion.

Most specimens but very few taxa (*O. cellarius, D. rotundatus,* Limacidae ?*Vitrea* spp.) are troglophiles. The association between *O. cellarius* and signs of human activity is perhaps consistent with this species living in the cave and scavenging carrion and other detritus left by people. A further group (*E. obscura, C. tridentatum, V. pusilla, A. pura,* Clausiliidae) have a shade-loving or rupestral habit and thus have the adaptions necessary for a trogloxene habit, although none have been reported as trogloxenes (Table 1). The other taxa are neither troglophiles or trogloxenes and their presence is probably the result of being washed, or falling, or being carried into the cave.

Pin Hole Cave, Creswell Crags, is a truncated vadose canyon. The cave was largely excavated during the late 19th and early 20th centuries, with comparatively good records and occasional sediment samples being taken in the second phase of excavation by Leslie

Armstrong. Armstrong also hand-picked mollusc shells from the cave deposits, and these, together with specimens sieved from the sediment samples were identified by Hunt (1989). Armstrong started his excavations at a point approximately 3 m in from the cave mouth (the cave mouth deposits having been removed previously) and continued to approximately 25 m from the cave mouth. The sequence he excavated was approximately 5 m thick, and contained two Upper Palaeolithic and two Middle Palaeolithic industries (Jenkinson, 1984). The sequence spans much of the last Glacial period and started to accumulate some time after 110,000 BP (P. Rowe, pers. comm., 1985).

The surviving shells from Pin Hole were all in undamaged, unabraded condition, though shells from the lowest horizons had become bleached. Hunt (1989) plotted the distribution of all the shells for which locational information had survived. He was able to distinguish Early Devensian interstadial assemblages containing *Oxychilus cellarius, Helicigona lapidica, Cochlodina laminata* and *Cepaea* spp. and Late-Glacial assemblages with these taxa and *Arianta arbustorum, Aegopinella nitidula, Clausilia bidentata* and *Lymnaea peregra*. These and a number of other taxa including *Pomatias elegans, Vallonia excentrica, Discus rotundatus, Cernuella virgata, Vallonia excentrica, Vitrea contracta, Helix aspersa, Cochlicopa lubrica,* and *Pupilla muscorum* were found in Late Holocene contexts from the cave. When the horizontal distribution of molluscs was considered, a clear pattern could be seen, with most shells concentrated in the first 13 m of the cave – effectively the photic zone – though there were odd pockets of large specimens such as *Helicigona lapidica* and *Cepaea* spp. towards the rear of the excavated area. The *Oxychilus* spp. did not conform to this pattern, however, and were generally distributed throughout the excavated area.

A number of problems are apparent in the interpretation of the shells from Pin Hole. Perhaps the most critical is that most of the specimens were hand-picked by Armstrong. It is probable that small and damaged specimens were not collected and there is thus substantial bias in the assemblages. A second critical problem is that very little sedimentological evidence was recorded or has survived from Armstrong's excavations, so the possibilities of mixing of assemblages, as has been suggested by Jacobi (1991) cannot be assessed. Nevertheless, a number of observations can be made. First, the Early and Late Devensian assemblages are unlike those reported from open-air sites of equivalent age, which do not usually contain taxa such as *Oxychilus cellarius, Helicigona lapidica, Cochlodina laminata* or *Cepaea* spp. (Holyoak, 1982). There is no doubt of the identifications or of the coordinates assigned to the specimens by Armstrong, though the possibility of a labelling error by this extremely painstaking scientist must be admitted. There are, however, elements of similarity with the results from good contexts at Kirkhead Cave, discussed above, particularly in the appearance of *Oxychilus cellarius* during the Late Glacial, and there is thus a strong probability that the shells were *in situ*. If this can be demonstrated to be the case, then the hypothesis of Gale & Hunt (1985) and Hunt (1989) that molluscs were able to colonise caves earlier in the climatic cycle than they could colonise open air habitats must be upheld and the existing models of Pleistocene mollusc colonisation of the UK revised. Second, the distribution of most of the taxa largely coinciding with the photic zone suggests that they were operating as trogloxenes or as in the case of *L. peregra,* carried into the cave mouth, presumably by birds. The 'pockets' of large molluscs in the rear part of the excavated area may reflect transport into the cave by small predators, though no instances of characteristically damaged shells were recorded. The distribution of *O. cellarius* is consistent with this species operating as a troglophile.

Dog Holes Cave, Derbyshire, was excavated in the early years of the 20th Century by J. W. Jackson. The cave is a truncated phreatic conduit and was completely filled with sediment (mostly, probably of Late Holocene age) before Jackson's excavation (S. J. Gale, pers comm. 1984). The manuscript records of this excavation are preserved in the Buxton Museum and some bones are in the Manchester Museum. While examining the Manchester Museum collections, these finds were examined and a few molluscs found. The molluscs were contained in a dark brown slightly stony silty clay infilling the proximal head of a horse femur labelled in ink on the bone 105 but associated with a scrap of paper marked 101 in pencil. The assemblage (Table 3) is small, consisting of *Cernuella virgata, Discus rotundatus, Cecilioides acicula* and *Oxychilus cellarius,* one juvenile specimen of this latter species being 'fresh'.

Table 3: Molluscs from Dog Holes

Cernuella virgata	3
Oxychilus cellarius	2
Oxychilus cellarius (fresh)	1
Discus rotundatus	2
Cecilioides acicula	2
Indeterminate fragments	

This assemblage has certainly an intrusive element: the 'fresh' *O. cellarius,* and quite probably the specimens of *C. acicula* (which is a burrower). The assemblage has a late-Holocene aspect, with *C. virgata* very typical of open environments after agricultural clearance and especially with the latter part Kerney's (1968) biozone f (approximately the last thousand years). Since the location of the bone within the cave was not recorded the only taphonomic information available is that intrinsic to the mollusc assemblage and its location within the horse femur. The juvenile *O. cellarius* and the *C. acicula* are intrusive and thus consistent with the bone never being very deeply buried, but there is no particular reason to suspect that the rest of the shells are other than coeval with the arrival of the bone in the cave. *C. virgata* is a species typical of exposed habitats, and most probably was introduced to the cave with the sediment (which is unlike most Derbyshire cave sediments and more typical of agricultural topsoil), quite possibly by wash or mass-movement processes. *D. rotundatus* and *O. cellarius* are shelter-demanding taxa, which would not have flourished in an exposed agricultural landscape and were thus most likely living in the cave. These molluscs are flesh eaters and were probably scavenging the bone before they were buried with it.

CONCLUSION

Cave mollusc assemblages can have unusual features, when compared with assemblages from open-air environments. Part of this may be the result of efficient dispersal mechanisms for some taxa. The cave microclimate, with its humidity and equable temperature, seems to have enabled shelter-demanding species like *Oxychilus cellarius* to colonise parts of northern England before the spread of forests created suitable habitats outside caves, both in the Late-glacial and Early Holocene, as at Kirkhead Cave, and perhaps during earlier temperate phases at Creswell.

A consideration of the processes involved in the formation of cave mollusc assemblages allows the occurrence of apparently ecologically incompatible taxa to be explained. At Kirkhead Cave, *O. cellarius* seems to have been the only species operating as a troglophile. Its occurrence pattern, coinciding as it does with signs of human activity, is consistent with this species scavenging carrion, presumably left by the human users of the cave. *O. cellarius* was again operating as a troglophile at Pin Hole Cave. The abundant bones recovered from this cave point to an abundance of carrion as the principal food source. The occurence of other large taxa at the rear of the excavated area is most probably the result of the activity of small predators. At Dog Holes the occurrence of sheltered-habitat taxa like *D. rotundatus* and *O. cellarius* and the exposed-habitat species *C. virgata* is only compatible if it is considered that the former taxa were scavenging in the cave and the latter species was introduced into it from an exposed habitat outside the cave.

This essay has demonstrated something of the character of cave mollusc assemblages, both at the present day and in the past. Our sources of information about the ecology and behaviour of troglophile molluscs are very limited and there is scope for much basic research in this area. There is also considerable scope for research into trogloxene molluscs and the transport mechanisms that bring them into caves. The routes that convert living molluscs into fossil assemblages have been discussed here, but need exploration and quantification before our level of taphonomic knowledge will be sufficient to enable the full interpretation of subfossil assemblages. Finally, our knowledge of subfossil faunas from caves is still very limited, simply because few excavators have sampled for molluscs at all. The basic sequence and chronology of Quaternary mollusc faunas in British caves is still largely unknown.

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Syngenetic Karst in the Southern Cape, South Africa

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Abstract: Karst landforms are a significant component of the geomorphology of coastal Cape Province from Saldanha Bay in the west to Port Alfred in the east. This Cenozoic karst is dominated by enclosed hollows ranging from pan dolines to poljes. This paper focuses on that part of the southern Cape karst between Cape Aghulas and Mossel Bay.

Four east-west clearly defined karst regions, each with a distinctive assemblage of landforms, can be distinguished. Allogenic rivers incised into the underlying impermeable Cape System basement compartmentalise these karst regions.

Lithified dune ridges, interpreted as former headland by-pass dunes, have constrained karst evolution so that enclosed hollows occupy old inter-dune valleys. Furthermore the similarity in karst depression alignment throughout the karst region, suggests that the southern Cape karst may be an excellent example of syngenetic karst development as first postulated by Jennings (1982). The karst also reflects the influence of glacio-eustatic marine stillstands.

THE LOCALITY

The southern Cape coastal karst region lying between Cape Agulhas (longitude 20° 00E) and Mossel Bay (longitude 22° 00E) is relatively unknown (Marker 1981; 1987a; Russell 1982). It forms the central portion of a Cenozoic karst that stretches from Saldanha Bay almost to East London. This karst is characterised by dry valleys and enclosed hollows ranging in size from pan dolines, to deep funnel-shape dolines, or uvalas, and to elongated poljes. Cave development is localised and limited. Furthermore the distribution and alignment of the karst depressions suggests that the area is an example of **syngenetic karst.**

SYNGENETIC KARST

Syngenetic karst is relatively rare. It has been reported from parts of coastal Australia (Jennings 1968) but other references are few. Syngenetic karst is associated with young limestones. Jennings (1968) hypothesised that karst development on the Cenozoic aeolianites of Western Australia and parts of South east Australia was syngenetic in origin. He argued that syngenetic development implied simultaneous karst development and lithification of the dune sands. Lithification begins by case-hardening as calcrete on the surface and in the zone of aeration which preserves the initial dune topography. Karst develops on the case-hardened surface even above unconsolidated sands. Karst depressions are constrained by the dune topography and become aligned along interdune depressions. Ultimately the dune ridges are debased and it is the alignment of depressions which indicates the syngenetic origin of the karst. Karstification of dune landscapes results in rounding of dune crests, alignment of karst hollows in interdune corridors and localised deepening of interdune hollows, thus modifying but not completely changing the initial regressive topography. Thus the existence of syngenetic karst can be argued on the basis of karst landform pattern and on the lack of time for usual karst development. Karst evolution usually presupposes prior lithification of the karst host rock with subsequent karst evolution on the lithified surface. In the case of syngenetic karst development, prior lithification is unnecessary. Lithification and karst development proceed simultaneously.

THE KARST CHARACTERISTICS OF THE SOUTHERN CAPE

In the southern Cape, limestone sequences consisting of a basal shallow marine formation overlain by a thick aeolian beach calcarenite are of two ages; Mid to Late Pliocene and Mid to Late Pleistocene (Malan 1990). The most marked karst is hosted by the Pliocene aeolian calcarenites of the Wankoe Formation, whose degree of lithification depends on the initial ratio of calcareous material. The Pleistocene Waenhuiskrans Formation, located adjacent to the coast, and only locally firmly lithified, supports very limited karst. Both formations have been affected by Pleistocene glacio-eustatic marine stands which controlled both the altitude of the piezometric water surface and the subsequent time available for karst evolution.

Throughout the area, four clearly defined karst belts are aligned parallel with the coast. Each has a distinctive assemblage of landforms (Fig. 1). From the coast inland they are: a narrow belt on Pleistocene semi-lithified dune limestone with minimal karst development, a low plateau, 120-100 m in altitude replaced by marine planed benches at 60 m, 30 m and 15 m altitude close to De Hoop Vlei and west of the Gouritz river. These sources support some restricted syngenetic karst development. The topography is suggestive of lithified headland bypass dunes. The third region with the most pronounced karst development is a case-hardened plateau 160 m to 200 m in altitude. The fourth region is a border depression or border plain at 120 m to 70 m altitude, that separates the high karst plateau from the African Surface with residual deep weathering profiles. The drop from the karst plateau to the **border** plain which has occasional low limestone residuals, is steep (Fig. 2; Table 1). The lag deposits of marine conglomerate on the border plain testify to the former extent of the limestone. The Wankoe Formation limestone, the main karst host rock, is considered to be a beach equivalent of the African land surface. The east-west alignment of the four major karst regions is compartmentalised by allogenic south-flowing drainage which has cut

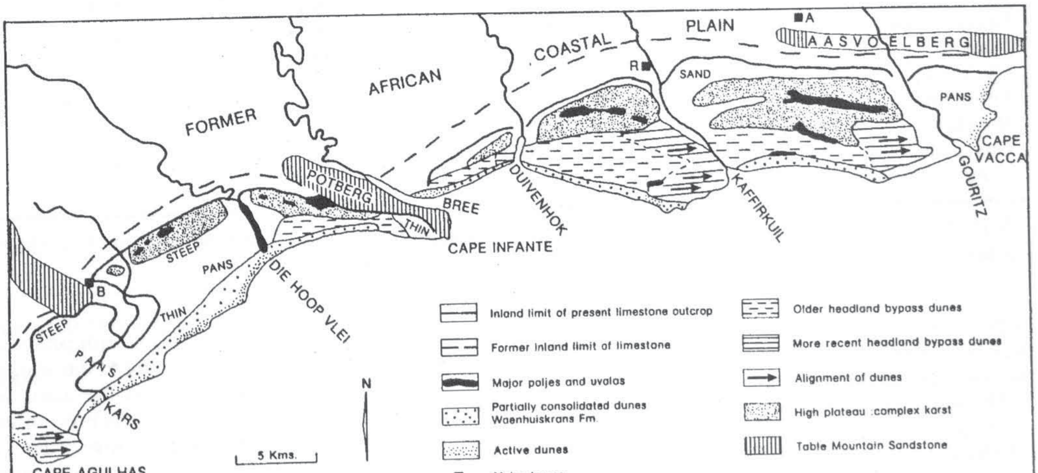

Figure 1. Major karst belts of the southern Cape between Cape Agulhas and Cape Vacca (Mossel Bay). (Areas of limited karst development and non limestone areas left white; Arrows indicate direction and alignment of headland bypass dunes; high plateaux stippled and major poljes shaded black. B=Bredasdorp; R=Riversdale; A=Albertinia).

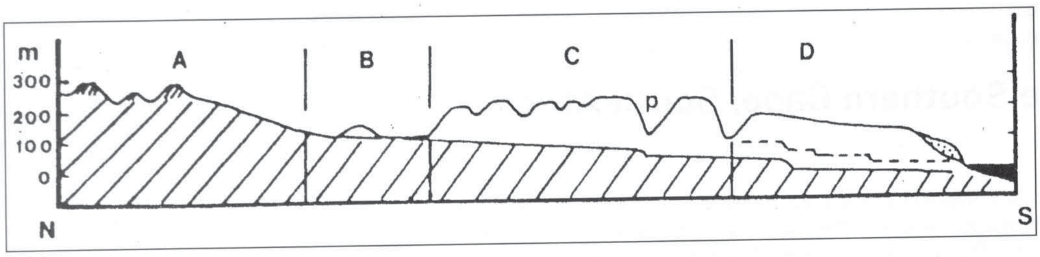

Figure 2. Section across the southern Cape from north to south, Cape System rocks hatched. Note steps in basement surface.
Region A = remnants of African surface showing residual silcrete capped hills (shaded); Region B = border depression; Region C = lithified higher karst plateau with major poljes indicated (p = position of Wankoe or Canca se Leegte); Region D = Lower karst plateau witn a pecked line to show relative position of marine benches at 90 m, 30 m and 15 m altitude.

through the limestone into the underlying older permeable rocks (Fig. 1).

Russell (1989) mapped the surface karst topography and demonstrated a spatial variation in the intensity of karst development (Fig. 1). Throughout the area, irrespective of the age of the surface, karst landforms are almost absent wherever slopes are steep, where limestone is very thin as along the border depression or close to river mouths where marine incursions have eroded the limestone and where the overlying Holocene sand cover is thick (Russell 1989). Minimal karst development is also characteristic of the Pleistocene Waenhuiskrans limestone along the coast.

The area of greatest karst density and diversity is associated with the case-hardened high plateau, which demonstrates a high density of enclosed depressions and a series of large poljes (Table 2). The three largest poljes are: Potberg, a polje aligned along the contact of the Table Mountain sandstone of Potberg and the limestone at the intersection of two faults. The development of a polje at this site can be explained in terms of increased acid run-off from the sandstone with accentuated water penetration at the fault junction. Wankoe and Canca se Leegte are narrow (<3 km in width), and 17 and 22 km in length respectively. They are aligned parallel to the coast and have extended by coalescence of aligned depressions. These two large poljes have been attributed to their location over a bedrock break of slopes which could have served to steepen the hydraulic gradient and thus accentuated solution. Other poljes and uvalas are aligned along the boundary of the high and coastal plateaux.

The lower plateau at 120-140 m altitude supports a less diverse and lower density karst. All hollows are shallow and more regular. Russell (1989) suggested that the difference is a function of time which has been insufficient for the development of a complete karst such as is characteristic of the high plateau. Certainly the lower plateau is less strongly case-hardened. Nevertheless on De Hoop Reserve the marine planed benches at 90 m and 60 m altitude, which there replace this plateau, show relatively strong karst development with complex but shallow depressions (Table 3). There is a clear relationship between the altitude of the bench and the intensity of karst development. Russell (1989) further suggested that this was a function of both time available since marine planation and height above the piezometric surface which would have controlled rates of flow-through (Table 3). The existence of deep dolines and uvalas along Die Duine at 180 m altitude supports a hypothesis of the importance of vertical infiltration. Hollow dimensions are also clearly a function of the available thickness of limestone (Table 4). However the De Hoop location is also underlain by Cretaceous sediments in contrast to the Bokkeveld shale substrate elsewhere (Malan 1990), which possibly promoted more effective karst development by facilitating water penetration. In the eastern Cape the presence of more permeable Cretaceous substate has been shown to have favoured stronger karst development (Marker and Sweeting 1983). The localisation of cave development below these marine benches where they overlie the Cretaceous strata is also suggestive. The caves are small, phreatic and developed at the former water table on a single level.

The widespread dry valley systems can be divided into four groups: on the high plateau a remnant series of east to west parallel shallow dry valleys are now interrupted by large enclosed depressions. The valleys represent the disrupted remnants of an early fluvial system. A different class comprise narrow incised 3rd or 4th order valley systems feeding to the allogenic rivers. Springs emerge at low altitude as tributaries to the main drainage lines. Breaks of gradient exist at 120 m and between 60 m and 40 m altitude. A third group comprise widely spaced low order valleys incised directly from the cliffed coastline. These are interpreted as former spring fed valleys that head at 60 m altitude. The fourth group are dry valleys feeding into the major poljes which terminate some 50 m to 80 m above the polje floors.

Low flying areas at all river mouths show aligned shallow pan

Table 1: KARST PLATEAU/BORDER PLAIN RELATIONSHIP

Longitude	Location	Border plain	Plateau rise	African Surface
21°45'E	Kalkberge	110	150	210
	Hornstras	40	150	210
21°05'E	Duivenhoks E.	67	73	315
	Duivenhoks W.	76	124	260
20°50'E	Bree river E.	67	53	175
20°30'E	De Hoop	90	120	256
20°05'E	Bredasdorp	46	98	215

(All altitudes in metres)

Table 2: POLJE DIMENSIONS

Name	Length (km)	Width/Length Ratio	Minimum Floor Altitude (m)	Distance Inland
Rietvlei	7.5	1:15	5	0.5
Grootfontein	9.0	1:10	101	4
Potberg	4.5	1: 3	104	5
Ou Werf	7.5	1: 3	37	9
Droevlakte	13.0	1:15	118	9
Wankoe	17.3	1:15	88	9
Canca se	7.5	1:33	80	9
Leegte	7.5	1:33	80	9.5

N.B: Only Rietvlei is hosted by the Pleistocene Waenhuiskrans Limestone. It is located on the junction between Wankoe and Waenhuiskrans Formation limestone.

doline development between lithified dune ridges that are interpreted as headland by-pass dunes dating from periods of low sea level with enhanced dune activity (Tinley 1985). Karst development on these former dune surfaces has clearly been constrained by the dune alignment. Such areas may be subdivided into those where the original dunes are debased to low aligned ridges and those closer to the river mouths where the original dune topography is clearly defined. The imprint of episodic aeolian activity is strong everywhere in this region.

THE ARGUMENT FOR SYNGENETIC CONTROL OF KARST

The alignment of the major poljes and uvalas, as well as the spatial pattern of the dolines, paralleling the by-pass dune topography closer to the coast, is evidence for the controlling influence of dune alignment and reinforces the view that syngenetic development has created the southern Cape karst. The general similarity in karst depression alignment throughout the karst region, even where remnant dune topography is totally absent, suggests that the southern Cape karst may have evolved under syngenetic development throughout its history, that syngenetic development proceded at discrete periods after coastal aeolian deposits were emplaced (Russell 1989). The southern Cape may therefore provide an excellent South African example of syngenetic karst development as first postulated by Jennings (1968).

OTHER KARST VARIABLES

Karst evolves as a system under the influence of a number of simultaneously acting variables. The importance of these other variables should also be considered. The effect of sea level fluctuations promoted by **glacio-eustatic** events has been strong. These have affected the **TIME** available for karst development and affected the **HYDROLOGY** of the area. The existence of marine benches at 90 m, 60 m, 30 m and about 15 m altitude are evidence of glacio-eustatic marine incursions. These benches, best documented on the De Hoop Nature Reserve demonstrate clearly that the combined influence of varying depths of limestone and the progressively shorter time available for karst evolution seawards, has affected the landscape (Tables 3 and 4). Russell (1982) demonstrated that the complexity of the karst hollow development decreased with lower altitude which she attributed to decreasing time available for development. She showed that the lowest and youngest bench carried the most regular, smallest and shallowest dolines (Table 4). However she also demonstrated that the form and depth of dolines is strongly constrained by the thickness of limestone available, itself a function of sea level erosion (Table 4).

The dry valleys are further evidence. All dry valleys record disruptions to fluvial systems. The coastal valleys that end at 60 m altitude, the major polje valleys that terminate at 50 m above the polje floors and the breaks of gradient at 120 m and between 60 m and 40 m altitude in the valleys tributary to the allogenic rivers indicate periodic incision with steepening of the local karst hydraulic gradient. Significant altitudes, 120 m and 60 m, are established marine stillstands (Davies 1971; Marker 1987b). Periods of marine stillstand further imply stable piezometric surfaces enhancing the development of karst; the subsequent eustatic low sea level with seawards movement of the shoreline onto the continental shelf, disrupted the process. The subsequent rise of sea level renewed the process. This implies that the karst development of the Southern Cape has been strongly influenced by glacio-eustatic sea-level changes.

The influence of climatic change is less clearly documented. Sea-level changes were synchronous with changes in climate. Temperatures were lower at times of low sea level and although it is postulated that enhanced cyclonic activity may have affected this area of the southern Cape, there is no unequivocal evidence of changes in effective precipitation. Nevertheless a lower sea level would undoubtedly result in increased continentality and probably reduced rainfall. The disruption to the normal drainage system as evidenced by the dry valleys cannot necessarily be attributed solely to falls in sea level. Climatic change from wetter to the present drier conditions may well have contributed to the abandonment of the valley system.

Table 3: DEGREE OF DEVELOPMENT ON DIFFERENT SURFACES

Surface altitude	% Depression area/total area	Pitting Index
90 m	57	1.7
60 m	50	2.0
30-40 m	25	4.0

Pitting index may be defined as the incidence of depression to area.

Table 4: LIMESTONE THICKNESS AND DEPRESSION DEPTH (after Russell 1988)

Surface altitude (m)	Limestone Thickness (m)	Hollow Depth (m)
200+	<200	<120
200+	<100	98
90-100	>80	<10
30-50	>50	<10
20	10-20	4

CONCLUSION

The southern Cape karst belt exhibits a variable diversity and density of karst landforms that can be explained in terms of the time available for development and thickness of karst host rock. Caves are scarce and extremely localised. Their general absence can be attributed to the incoherent limestone that cannot support large cavities. Although strongly affected by glacio-eustatic sea level fluctuations through their control of the piezometric water surface and the time available subsequently for karst development, the circumstantial evidence is strong that the Southern Cape is characteristic of a karst resulting from syngenetic development.

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Human impacts on processes in karst terranes, with special reference to Tasmania

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Abstract: Chemical, physical and biological processes of karst ecosystems are reviewed. Changes in these processes result from human activities altering the landscape. Consequences and examples of these changes occurring in Tasmania suggest these many processes are cross-linked in a complex manner. It is concluded that detailed understanding of the complex interrelated and interacting processes should underlie application of total catchment management principles.

INTRODUCTION

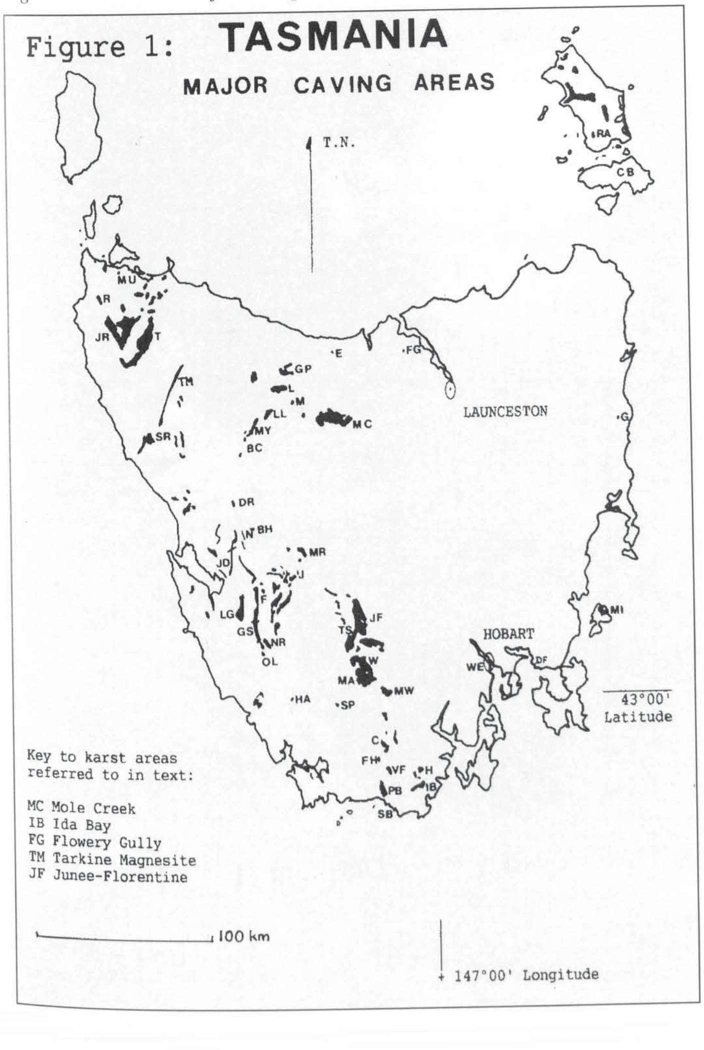
Since European invasion, Tasmanian economic activity has been dominated by outdated and unsustainable practices, based on mining the earth's crust, tree-mining for woodchips and timber, and soil-mining for agriculture . . .

Tasmania has over 150 karst areas (Figure 1), dating from the Precambrian to the Pleistocene. This state is disproportionately well endowed with caving areas compared with the rest of Australia. Some of these areas contain caves of world repute. For example, international significance has been recognised at Mole Creek in a proven double (possibly triple) surface divide breach of a stream, one cave being regarded as amongst the top 20 decorated caves in the world, a classic hum, and the presence of phototropic phytospeleothems.

Much of Tasmania's karst catchments are covered by intact temperate forest ecosystems, which preserve the integrity of the karst processes and ecology. Most of this forest is at risk of devastation at the hands of conglomerate woodchip companies, with support of a conservative State parliament. The Mole Creek area now suffers a catchment "management" plan for logging 80-100% of the forest cover. Clearing for agriculture and mining also threaten the karst.

Land management for karst values in Tasmania has traditionally been ignored; or at best, treated in piecemeal fashion, with examination of small, myopic units with arbitrary boundaries with no ecological basis, and consideration of only a limited suite of impacts and processes. The consequences of this management strategy often include "unexpected" results and sometimes ecological disasters.

Figure 1: Tasmania: Major caving areas.



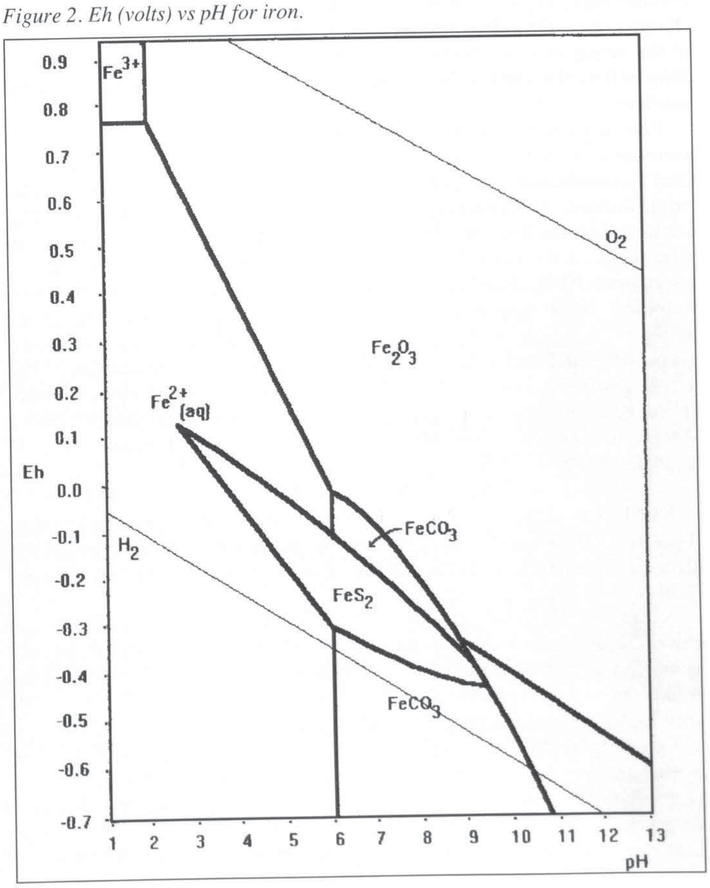
A multidiscipline suite of processes that operate in Tasmanian karst systems is reviewed in this paper, and what changes may occur after human impacts. The impacts of human visitation on caves are beyond the scope of this paper, as are gross engineering changes such as hydro-electric inundation. Rather, the consequences of the most common surface activities of fire, forestry, mining and agriculture are discussed.

The paper firstly considers the chemical processes affected by catchment disturbances, then deals with physico-chemical processes and karstic, hydrological, ecological and biological consequences of human activities.

CHEMICAL PROCESSES

As is well known to readers, the common (carbonate) karst process is based on the chemical reaction [1], (Jennings 1985, Ford & Williams 1989). The forward reaction (the dissolving of limestone) is promoted by elevated concentrations of CO_2 and organic acids found in soils. The thick organic matrix of natural forest soils provides both of these in abundance and is an important integral part of the karst process. The insoluble material (typically <5% of common Tasmanian karst bedrock) is all that remains of the rock, hence karst forest soils consist largely of organic matter. Physical erosion (steep topography), lack of rainfall or fire removal of organic matter all result in only thin residual soils. An example of this is Dogs Head Hill, Mole Creek (Lichon 1993a). Karst soils are complex and highly non-uniform. Duncan & Kiernan (1989) found soils on one Mole Creek limestone ridge to consist of pockets of fills in solution pipes, rifts and other sub-surface karst features, with sparse residual soils between. This was found to contribute to patchy soil-water distributions and poor drought

Figure 2. Eh (volts) vs pH for iron.



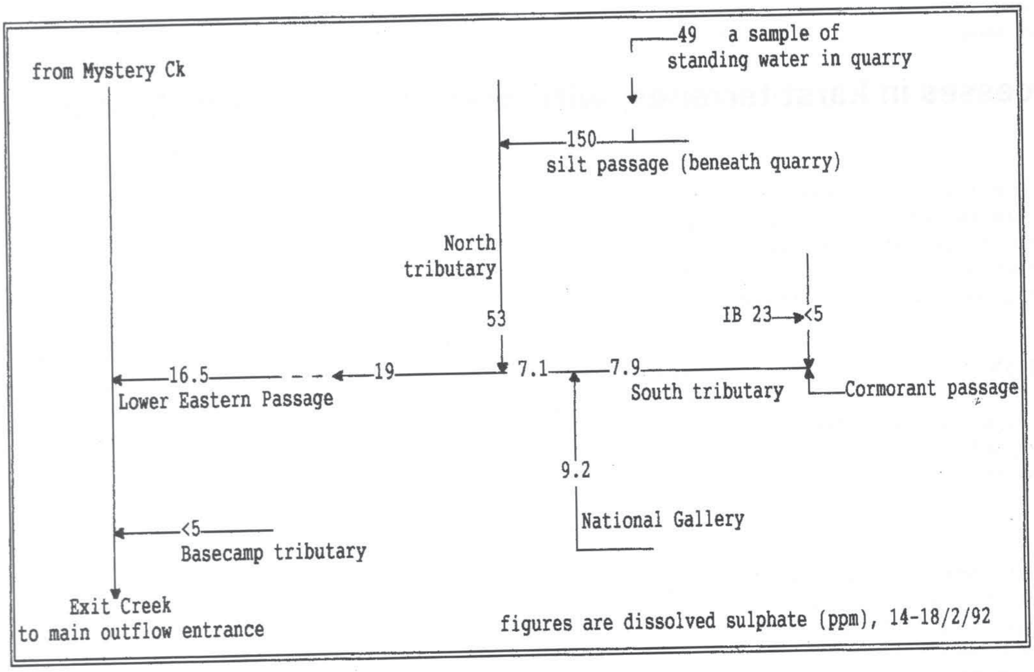


Figure 3. Distribution of dissolved sulphate in eastern Exit Cave (Household, 1992).

tolerance of the forest. Human disturbance (clearing, burning etc) results in the fragile soil cover being removed or eroded, organic matter depletion, degradation and eventual collapse of the structure of the soil. The caves below the catchment are filled with sediment.

$$CaCO_{3(s)} + CO_{2(aq)} = CaHCO_{3(aq)} \quad [1]$$

The reverse reaction [1] occurs when the CO_2 is allowed to escape from solution. The water may reach a cave (or outside) atmosphere, the CO_2 diffuses from the water forcing the now supersaturated solution to precipitate calcite as a speleothem (or travertine).

Gordon Limestone *{of Ordovician age, the common karst bedrock of Mole Creek, Ida Bay, Florentine etc.}* emits a foetid odour when freshly broken (Hughes 1957). This is due to presence of pyrite nodules/blebs in the limestone. The smell is due to atmospheric release of H_2S and SO_2 from the breaking pyrite reacting with the air. The interbed silts and clays of the Gordon Limestone are noted to have a high pyritic content. In addition to the native pyrite, some low grade mineralisation occurred during post-deposition granite intrusions and deformation events. The mineralisation is often evident in the more permeable structures such as paleokarst fills; along breccia zones, faults and fold lines. Pyrite is quite stable under reducing conditions, signified by low Eh (redox potential), Figure 2, (Krauskopf 1979). The dark colour of Gordon Limestone is in part due to the presence of carbonaceous matter, the reason for the low Eh. It is only when the rock is exposed to oxygen does the pyrite become reactive.

The action of oxygen in the presence of water on pyrite is summarised by reaction [2]. This is a normal, but very slow process that is continually happening as our karst is eroding in the natural environment. The reaction rate is hastened by the action of bacteria such as *Thiobacillus sp*. The increased reaction rate is well known in the context of acid drainage problems in the mining industry (Sengupta 1993). Ford & Williams (1989) recognise that the origin of sulphates in caves is usually from the oxidation of sulphides. Sulphide sources in karst include both mineral sulphides and hydrogen sulphide. The latter is known to leak from natural gas reservoirs in the USA. Northern Hemisphere karsts are also exposed to acid rain, incorporating both nitric and sulphuric acid (Ford & Williams 1989). An interesting exception is the Nullarbor, where the sulphate source is seawater (James 1991).

$$FeS_{2(s)} + 4O_{2(aq)} = FeSO_{4(aq)} + H_2SO_4 \quad [2]$$

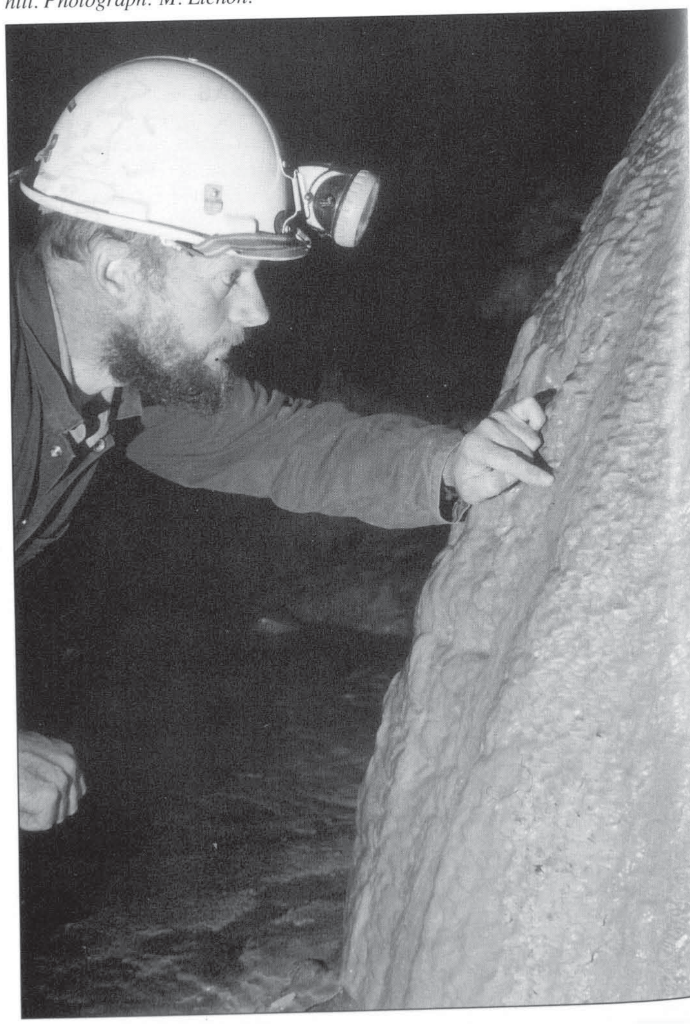
The reaction products of concern are both the sulphate and acidity. The iron (II) ions are rapidly oxidised further to (usually) insoluble iron (III) minerals, or carried away in solution, complexed by organic acids.

Reaction [2] is mitigated by exclusion of oxygen by humus and soil cover, and limited exposure and outcrop of massive bedrock. The soil is particularly important, as water passing through decaying organic matter of a natural forest soil loses oxygen and attains a sufficiently low Eh to prevent the rapid oxidation of pyrite.

One implication of surface disturbance in karst areas by human activities such as quarrying, roading, logging, burning off, and farming is the dramatic increase in the rate of this reaction. This is a direct result of removal of the organic soils and forest litter mantles that prevent exposure and oxidation of sulphides. The distribution of dissolved sulphate in the eastern sections of Exit Cave (Figure 3), in particular the elevated levels in cave passage below the quarry, is a result of artificially high rate of pyrite oxidation due to exposure and disturbance of clays at the quarry site. This is confirmed by corresponding lower pH's of the samples. It would have been informative if the samples had also been assayed for iron. The clay sized fraction of the cave sediments were found to contain abundant dark clays as well as goethite and lepidocrocite (iron hydroxide minerals).

Following the oxidation of sulphides by [2], the sulphuric acid readily attacks calcite to form the much more soluble calcium sulphate, reaction [3]. On a positive note, and at a large scale, it is

Corrosion channels etch into flowstone at Wet Cave, after repeated fire degraded the protective vegetation, litter and organic soils of the overlying hill. Photograph: M. Lichon.



believed that sulphuric acid solution of karst is solely responsible for creating voids such as Lechuguilla Cave, USA, a huge cave system profusely decorated with speleothems.

$$CaCO_{3(s)} + H_2SO_{4(aq)} = CaSO_4 + CO_{2(aq)} \qquad [3]$$

Reaction [3] occurs in cave streams where sulphate rich, acidic waters have entered from surface disturbances. The CO_2 produced by reaction [3] provides further calcite solvency via the reaction [1] mechanism. The reaction in the cave stream situation leaves no gypsum deposit as it is quite soluble. This reaction is responsible for the chemically-eroded gours in upper Croesus Cave (Mole Creek), whose catchment has been disturbed by road construction and limited logging. The same principle applies to eroded gours found in the Little Grunt Cave (Ida Bay) passage extending under a limestone quarry. Corrosive waters have recently begun to etch channels into flowstones of Wet Cave at Mole Creek (Plate 1), following a history of burning of the overlying hillock.

The forward reaction [3] is also promoted by seep introduction of acidic, sulphate rich water to a cave surface, or any such location where gas is able to escape. With stable, slow seepage and unsaturated humidity, the water evaporates simultaneously with the CO_2 escape into the cave air. Water is also consumed by the formation of (hydrated) gypsum. The calcite may thus be replaced by gypsum. Where this happens at an open surface, at natural slow fluxes, erratic speleothems such as gypsum flowers and crystals form. There many fine and varied examples in Genghis Khan (Mole Creek). Hairlike threads several inches long are found wafting in the cave breeze of Little Grunt Cave (Ida Bay), in passages as yet unaffected by the quarrying.

Clays are ion exchangers. The process of clay mobilisation results in the release of these associated ions. These may include toxic metals such as manganese and lead. There are anomalous lead sources known at Mayberry (Mole Creek), which have in the past generated interest in the form of base metal exploration drilling (Smyth 1983).

Some of the more stable complexes that immobilise metals involve both clays and organic fragment molecules. Disturbance and fire in particular may irreversibly liberate the metals.

Organic acids are weaker acids than carbonic acid (CO_2), but very good complexing agents, and will under natural conditions bind any metal ions and facilitate transport in solution in chemically unreactive forms of low toxicity. Under disturbance, where clay mobilisation is elevated and organic matter is depleted, there will not be sufficient complexation. The implications are the increased activity of free ions with consequent increased reactivity towards calcite and higher toxicity to cave fauna.

PHYSICO-CHEMICAL PROCESSES, HYDROLOGY, ECOLOGY.

The molar volume of gypsum ($CaSO_4.2H_2O$) is over double that of calcite ($CaCO_3$). Anhydrite ($CaSO_4$), a desiccated form (unlikely to occur in Tasmanian karst), also has a greater molar volume than calcite. The result of reaction [3] occurring in an evaporative, confined space is the well known effect of "crystal wedging" in caves. Ford & Williams (1989) describe this phenomenon as "chip and slab breakdown". The forces generated by the "expansion" of calcite replacement by gypsum are considerable. The massive block collapse piles in Kubla Khan and Genghis Khan caves (Mole Creek) have resulted from crystal wedging of thick bedded limestone (Spate, 1991).

This same process is responsible for the accelerated destruction of historic sandstone buildings in Hobart (Sharples, 1990). The source of the sulphuric acid in this case is the oxidation of atmospheric sulphur dioxide from motor vehicle emissions. The sulphuric acid attacks the interstitial calcite cement of the stone. The crystal wedging results in friable erosion, flaking, case hardening and breaking off of large corner chunks. Lime mortar is similarly disintegrated.

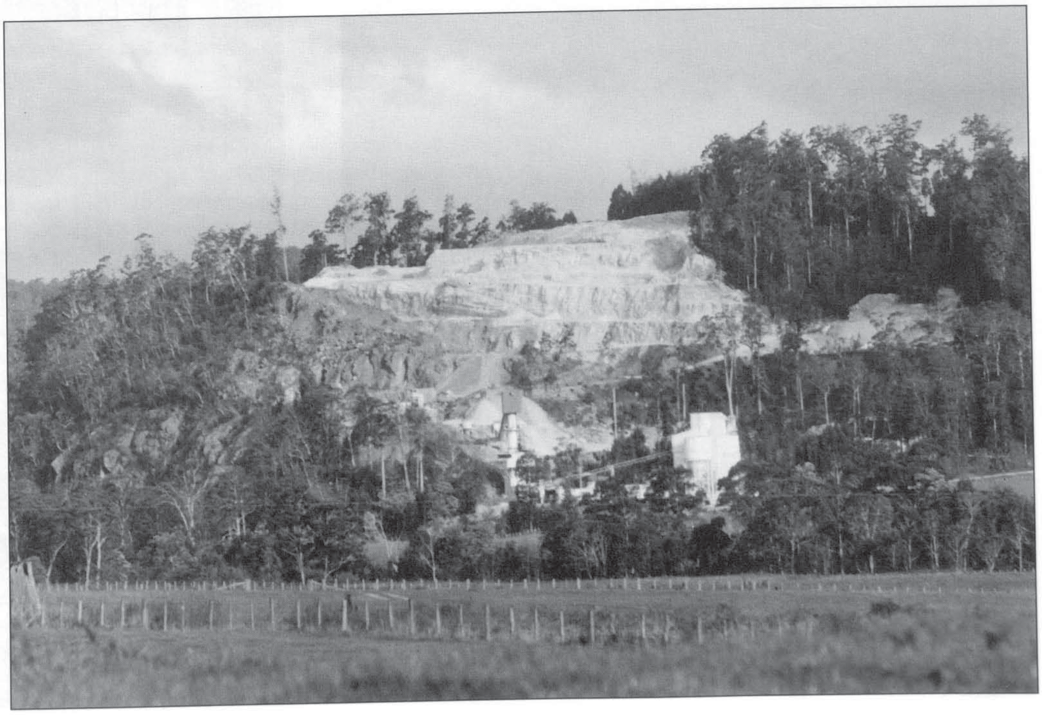
The interbedded clays of the Gordon Limestone were precipitated in a marine environment. The high ionic strength of seawater causes "soluble" colloidal clays to flocculate and settle out. When the clay beds are exposed and disturbed in the presence of rainwater (very low ionic strength), as happens to a great extent in the cases of human disturbances noted above, the clays once again become mobilised. The weakly hydrogen-bonded and van der Waals layered structures of clays are not readily reformed once disturbed.

Spate (1991) noted the thixotropic nature of clays in Kubla Khan Cave (Mole Creek). Once disturbed into suspension, it takes a long time for the clays to settle out again. In most situations the clays are transported in suspension until a quiescent area is reached.

Massive disturbance is apparent at an Ida Bay quarry (Lichon 1992a). As well as blasting and machinery disturbance, the action of raindrops on the denuded ground rapidly mobilises clays. There is abundant evidence of clay being washed from the quarry into Bradley Chesterman Cave, and Little Grunt which connects to Exit Cave. The deposition of 10-100 cm of fine clay in passages naturally otherwise containing silty gravels (Houshold 1992), has led to locally depauperate populations of cave fauna that depend on gravel habitats (Eberhard 1992).

The 21 year old Mole Creek quarry (Plate 2), has similar problems with clay exposure. The karst hydrology at this site remains unstudied. The settling ponds between the quarry surface runoff and the adjacent Mersey River have been known to spill over and release volumes of turbid water into the river. The mature elements of the mining industry have long understood the problem of erosion control of denuded ground, and refined techniques to minimise the effects (Sengupta 1993).

Very similar effects would result from clearing operations, roading and fire. The loss of the vegetation, litter and organic soil cover results in a complete loss of soil structure. Loss of vegetation, particularly trees, results in decay of the soil support through rotting of the binding root systems (Plate 3). Channels rapidly develop and downward



Mole Creek quarry: karst hydrology unknown, turbid runoff escapes into the Mersey River. Photograph: M. Lichon.

transport of soil accelerates (Plate 4). With the increased runoff comes increased sediment load. Evidence in the USA (Ketelle & Newton 1987) and at Mole Creek shows collapse and subsidence rapidly follow land clearing (Plates 3,5). An entire large paddock subsided by several metres in only a few years of clearing at Mole Creek. The loss of litter exposes the soil to raindrop impact, and removes the buffering against wet-dry cycling. The exposure of the ground promotes unnaturally high rates of clay mobilisation. It is far more common to find cave floors choked with clay deposits under farmland at Mole Creek than in caves under the undisturbed forests. Several caves in farmland are no longer possible to enter as a result of rapid sedimentation. Sheet erosion on very low angle slopes led to deposition of 1 m of sediment blocking a cave within 12 months of clearfelling in its catchment (Kiernan 1981). Spate (1991) recognised the deleterious effect fire has on karst soils above Kubla Khan Cave (Mole Creek), and recommended management for the prevention and suppression of fire.

Sediment mobilisation rates from unsealed roading have been found to be about 200 times greater than those from adjacent forested land (Haydon *et al*, 1991). The sediment mobilisation from clearfelled and burnt land would be of a similarly high magnitude, with an initial higher peak of fine sediment loss. Transport is both in terms of suspension (about 70%) and coarse particle movement. Taking account of local rainfall and topographical averages, total erosion rates could easily exceed 100 t/ha/year from logging in the Mole Creek catchment.

It is noteworthy that most examples of karren cited by Jennings (1985) have been exposed by soil erosion after clearing and farming. There are many examples of subsoil-formed karren (runnels and grikes for example) exposed by recent erosion at Mole Creek. Recent mining exploration has (rather actively) uncovered karst features on Precambrian magnesite in north-west Tasmania (Lichon 1992b). The presence of some types of bare-rock karren also indicates recent erosion. Some rillenkarren are formed in a matter of only a few years, or even months of limestone being denuded (Sweeting 1972). Rills and pitting have formed on recently exposed bare limestone on Dogs Head Hill.

The sedimentation of subterranean reservoirs results in a loss of the karst system ability to buffer water flows after rain events. Surface subsidence also tends to fill these subterranean voids. Hydrological studies at Mole Creek suggest this buffering ability may be quite important in ameliorating floods. Deforested lowlands at Mole Creek are prone to flooding. Rainfall absorption by the "sponge" effect of the soil, litter and forest cover, and the evaporative route provided by steady transpiration of moisture by forest trees both regulate and reduce runoff. This rainfall buffering and disposal mechanism is lost after clearing. Therefore the (increased) pulses of rainfall runoff must either be disposed through the underground conduits; or more likely, largely by overland routes further causing erosion and flooding, when underground conduits are silted up and cannot cope with the large transient volumes of water.

A massive new doline caused by clearfelling operation at Mole Creek. Note the person for scale, just above and left of centre of the photograph. Photograh: D. Hunter.

The clearing of land, hence loss of vegetation, thick absorbent soils, and sedimentation of subterranean conduits results in increased water runoff and flood hazard. Experience in the USA clearly shows land clearance leads to severe erosion and flooding cycles (Dougherty 1981). Following land clearance in Ireland, loss of thin karst soils led to subsequent long term desertification (Drew 1983). Reafforestation of cleared karst has been thwarted by soil erosion and disruption of previously stable hydrology (Yuan 1987). It is very likely that similar effects have application at Mole Creek. Even with natural vegetation cover, dry ridges at Mole Creek are prone to drought stress (Duncan & Kiernan 1989). Clearing of the vegetation and disturbance of the fragile soil structure would certainly lead to unnatural exacerbation of the problem. Many of the local farmers have recognised this intuitively and retained vegetation cover on limestone hillocks.

The hydrological buffer of vegetation and soil is lost after clearing. A celebrated display of glow-worms in the main tourist cave at Flowery Gully disappeared shortly after clearing the forested catchment: The permanent streamway in the cave became intermittent, and the constant humidity in the cave air required by the glow-worms was lost. The cave is no longer used for tourism.

The clearing of forests for farmland on the plains around Dogs Head Hill (Mole Creek) has tended to dry out the forest left on the hill. Dry sclerophyll vegetation now dominates the hill. The hill is frequently exposed to fire and weed infestation; damp vegetation communities have contracted to small isolated niches (Lichon 1993b), of insecure biological viability.

The stability and buffering properties of forested land are important factors in speleothem and flowstone formation. Helictite growth (Plate 6) is possibly more sensitive to changes in surface conditions. Recent land degradation (fire, uncontrolled livestock etc.) is probably responsible for several recent changes noted in the Wet-Honeycomb system at Mole Creek: An intermittent flowstone-corrosive waterfall has been activated in Wet Cave stream passage. Several massive flowstones show development of corrosion channels. The covering over of 150 year old signatures on the previously dry flowstone walls of the "Registry Office" is another recent change in Wet Cave. The failure of a well used handhold in Honeycomb resulted in a recent caving accident: Speculation has attributed the failure to hydrological changes weakening the underlying structure.

Collapse of soil structure after fire. Photograph: D. Hunter.

A collapse subsidence caused by farmland clearing and road-focused runoff, now used for dumping rubbish. Photograph: D. Hunter.

Tasmanian karst forests generally grow on nutrient poor, leached soils. The only, small input of nutrient elements is from rainwater. Coming from the roaring forties sweeping the Southern and Indian Oceans, is in effect very dilute seawater (Buckney & Tyler 1973). The nutrients are maintained in the ecosystem by recycling the fallen leaves via rotting processes; the roots immediately uptake this gradual release of nutrients from the forest compost (Jackson 1982). In most Tasmanian karst forests, with only residual and organic soils, most of the nutrient capital is in the standing plants, with the remainder in the layer of decomposing litter. Logging removes a significant part (60%) of the above-ground nutrient pool (in the actual logs). Fire directly removes large percentages of nutrients by two mechanisms: Fire volatilises around 20% of remaining above soil nutrients during burning (Harwood & Jackson 1975); these are lost to the wind both as particulate smoke and by sublimation. Fire also instantly releases large quantities of labile nutrients in the form of ash. The devastated forest system is not able to fix this large and sudden release of nutrient, so rainwater dissolves and washes away at least another 50% of the above ground nutrients left after logging (Harwood & Jackson 1975). Areas of steeper topography and higher rainfall result in greater losses. The total losses from the ecosystem will depend on the proportions of above-ground and soil-based organic nutrient stock, and how much of the litter and peat are also lost to the fire. Indirect loss of soil nutrients also occurs by the mechanisms as discussed previously. The forest can thus only ever partially recover from fire; after each fire it becomes further depauperate in nutrients. The replenishment of nutrient elements by capture from rainwater is very slow. The forest loses the ability to provide the ecological cover role on the karst. With fire recurring within 20 years, the vegetation type regresses first to sclerophyll wet scrub, further fires lead to sedgeland and opportunistic coloniser communities (Jackson 1968). Each stage of regression brings vegetation type and litter with higher fire risk attributes, thus exacerbating the chances of further regression. The soil loses stability and buffer capacity, and the karst degrades, integrating the deleterious effects discussed in this paper. Where the forest is not allowed to regenerate, as in clearing for farmland, leaching continues over the long term. This is illustrated by the need for Mole Creek farmers to maintain the soil of the lowland pasture through heavy application of fertilisers.

With release and leaching of forest nutrients comes the consequence of elevated nutrient loading of karst streams and contamination of water resources. This encourages bacterial multiplication, fungal growth and, in surface expressions of waters, algal blooming. Such (naturally) abnormal growth situations generate high pathogen and toxin concentrations. High nutrient and unnatural growth loading of the water may endanger or extinguish indigenous aquatic fauna, particularly already vulnerable cave adapted fauna, which may be poisoned or out-competed by opportunistic invaders. The water becomes aggressive towards the limestone from acidification and CO_2 enrichment. Water contamination also comes more directly from application of fertilisers (nitrates and phosphates in particular) and toxic farm chemicals (herbicides, pesticides, hormones etc). Underground karst conduits provide little purification by filtration and no ultraviolet light exposure to the passing water. It represents a human health hazard where the water resource is used for domestic catchment. At Mole Creek, further nutrients and bacterial populations are introduced from stock access to karst windows, dairy effluent runoff, and farm & domestic waste disposal in sinkholes, Plate 5 (Hunter 1989). Indeed the municipal tip was sited in polygonal

Helictite growth needs stable chemistry and hydrology. Photograph: D. Hunter.

	Natural karst	Disturbed karst
Landscape	Slow karst development	Rapid subsidence and collapse
Soil quality	High organic content	Depleted, erodible residue
Soil quantity	Slow accumulation, uneven distribution	Rapidly lost
Soil structure	Heterogenous, stable	Disintegrates and erodes
Caves	Stable karst processes	Caves fill with debris and sediment
Speleothems	Stable growth	Re-solution
Cave fauna	Fragile habitats maintained	Endangered by loss of habitat
Water quality	Good, hard	Turbidity, bacteria, contaminants
Vegetation	Many communities and niches	Diversity lost and weeds invade

Table 1. Effects of surface disturbances on karst.

karst. There is at least anecdotal evidence that there are abnormal rates of health problems amongst the local (human) population.

CONCLUSION

Table 1 shows a broad overview of some of the effects of human disturbance on karst.

While all of the chemical and physical processes discussed in this paper are entirely natural, it must be emphasised that they normally operate over *geomorphological* time scales in balance with other natural events. Once human disturbance intervenes, these processes accelerate by orders of magnitude into *human* time scales, and the impacts and effects extend far beyond the capacity of natural balancing counter-processes.

The mechanisms put into play by human disturbance are interlinked and form vicious spirals of cause and effect resulting in rapid degradation of karst.

The responsible path for man to deal with karst terranes is one of total catchment management, based on detailed multidiscipline understanding of natural processes and their interactions. Human activity can then be modified and restricted to minimise impacts.

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The Very Few Caves Known in Tibet

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Abstract: The Tibetan Plateau contains only small areas of pure limestone, and karst development is restricted by climatic factors. The few known caves are noted, and the main potential interest is recognised in the rather inaccessible west of the plateau.

THE TIBETAN PLATEAU

Most of Tibet is a cold desert plateau at a mean elevation of 4500 metres, laced by towering mountain ranges only marginally less impressive than the Himalayas along the southern edge. This unique topography makes Tibet one of the world's more mysterious and unattainable destinations.

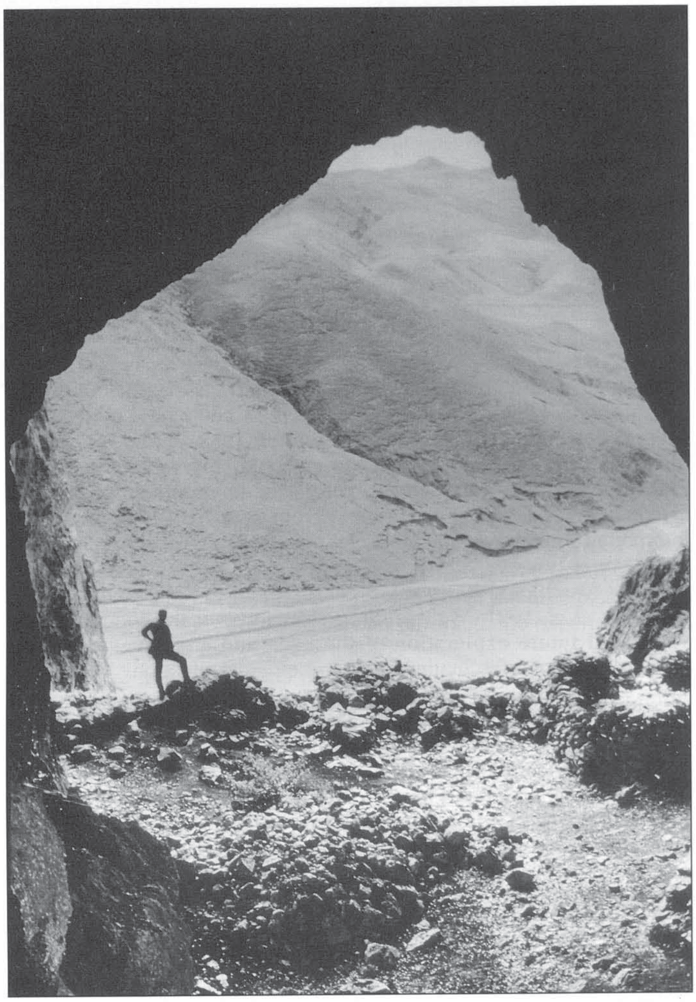
Various geological maps show great swathes of limestone across Tibet. They are however rather misleading, because many of these outcrops are of deformed and mixed sequences of rocks containing only a small proportion of limestone or impure carbonate. The geology of Tibet is certainly not just a slab of limestone uplifted from an ancient Tethys Ocean. Instead it is a structurally very complex accretion zone where slabs of continental crust have been rammed together. Limestone survives in narrow faulted slices, and much of it is metamorphosed.

Cave development in Tibet is certainly restricted. The climate is against it. The plateau is a desert in the rain shadow of the mighty Himalayas. It is also so cold that frost shattering dominates the weathering processes. Much of the plateau is truly periglacial with discontinuous permafrost completely halting underground drainage. Vegetation is sparse and there is little biogenic carbon dioxide in the meagre soil groundwater. In the cold climate, limestone is resistant to erosion, and most outcrops are high so that runoff water flows from and not onto the limestone. In addition, most of Tibet is geologically very young; the plateau and the adjacent Himalayas have been uplifted by kilometres of elevation within the last few millions years – which is within the timescale of mature cave development in such a restrictive climatic regime.

Elsewhere in the world caves do exist beneath mountain snowfields (in the French Alps), beneath glaciers (Canada's Castleguard), in deserts (in Australia), and in narrow bands of marble (in Norway); but none of these places has all the geological and climatic factors stacked against them on the scale found in Tibet.

KARST STUDIES IN TIBET

Before 1950, the Tibetan Plateau was seriously inaccessible except by many days' travel on a horse or yak. Neither geological science nor cave exploration were high on the list of monastic priorities. But since then, the Chinese have studied the terrane with remarkable diligence, mapping the geology and making a start on geomorphological studies. Even so, the Chinese data on Tibetan karst is easily summarised in four pages (Yuan, 1991), and refers to very few caves. Two recent studies have added just a little to the data bank on Tibetan caves.



Looking out of the entrance of Chagong Chimu, above the village of Nilong.

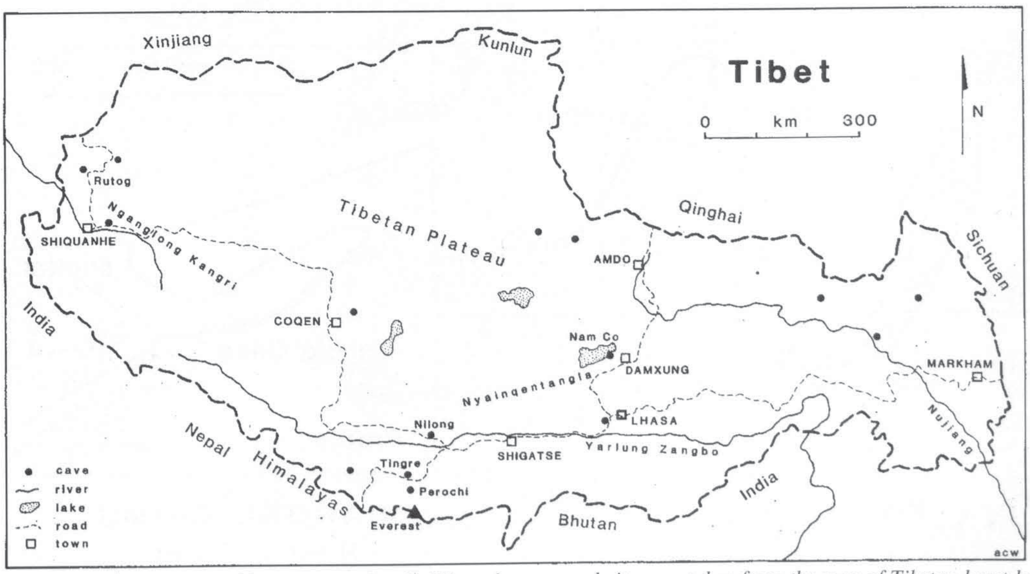


Figure 1. Location map of known cave sites in Tibet; the unnamed sites are taken from the map of Tibetan karst by Yuan (1991).

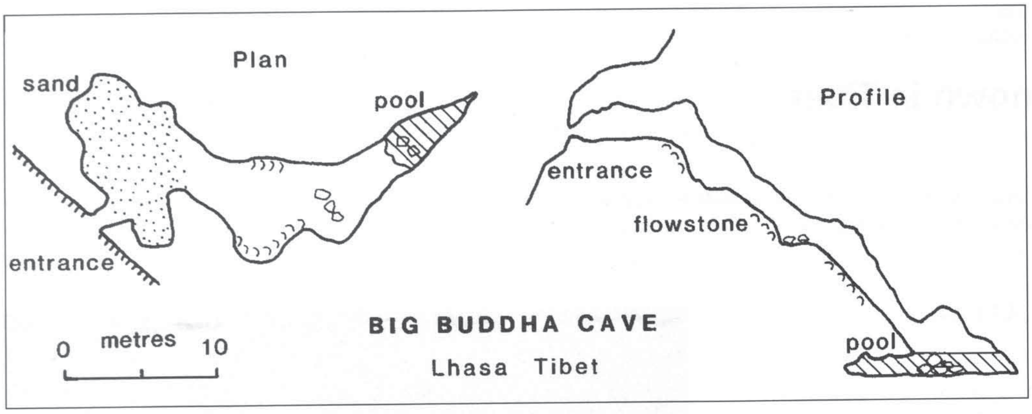


Figure 2. Survey of Big Buddha Cave (from Zhang, 1991).

Zhang Dian, from Guiyang, completed a PhD study on Tibetan karst as part of an Anglo-Chinese geographical study (Zhang, 1991; Sweeting *et al,* 1991). And the China Caves Project included a Tibet reconnaisance while in China for the Xingwen explorations (Waltham & Willis, 1993). It is these investigations that prompted this review.

The concept of warm, wet lowland conditions in Tibet just a few million years ago is seriously tenable in view of the very recent uplift of the plateau and creation of the Himalayan rain shadow cutting off the monsoon rains from the south. There is geological evidence to support this notion (Xu, 1981; Dewey *et al,* 1988). From it came the idea that Tertiary paleokarst and caves could survive on the Tibetan Plateau, preserved in the modern periglacial environment of minimal erosion. Early Chinese literature (Yang *et al,* 1981; Chui, 1983) interpreted some limestone pinnacles and caves as Tertiary relics. The evidence is however debatable, and the current concensus is that Tertiary fossil karst has not yet been proven to exist (Yuan, 1991; Sweeting *et al,* 1991; Waltham in prep). However the concept is still valid, and future exploration of the karst and any caves could yet provide proof of a fascinating geomorphological situation.

CAVES IN TIBET

The list of known caves in Tibet is at present very short. All locations are marked on Figure 1, and descriptions and comments are grouped below geographically. There are many sites of tufa and geothermal karst in Tibet, but they are excluded from these notes.

Southern Tibet

On the western outskirts of Lhasa, the frost-riven limestone pinnacles of Xi Shan contain a few conspicuous frost pockets, but no solution caves; a large quarry in the limestone has exposed no solution features.

Big Buddha Cave (Zhang, 1991) lies in the limestone shoulder which houses the painted rock carving of Buddha beside the road south from Lhasa, about 20 km from the city. It is a remnant of phreatic rift, 25 metres long, with solution features in the roof and some old stalagmite on the floor (Figure 2).

At Nilong, the lake of Comenkan has a high limestone ridge along its northern side. Chagong Chimu (Big Cave) is the largest cave known in the ridge; its entrance is 15 metres high and wide, but the walls close in to a narrow fissure in solid rock just 50 metres inside (Figure 3). The cave has been enlarged mainly by frost action fed by seepage water on faults; there is a little stalagmite in both it and the adjacent rock shelter. An unnamed cave 1 km to the west has 20 metres of passage between four entrances; it is a solutional phreatic remnant, but is now heavily frost shattered. No caves were found on a recce of the high ridge, but plenty of limestone outcrop remains unsearched.

Mount Zebri is the highest of the limestone mountains around Tingre. Many fragments of cave, each just a few metres long, have been recorded (Zhang, 1991); the largest is a rift 40 metres long, heavily modified by frost action.

The northern approach to Mount Everest passes limestone crags near Perochi; these contain some small cave fragments, but the largest fissure cave, with monastic building remains inside, is largely frost excavated.

Further west, Ngangzhang Mountain contains a fossil cave fragment (Yuan, 1991).

Eastern Tibet

The deep, forested valleys of Tibet's far east form a terrane very distinct from the barren plateau to the west. Geologically this region is a continuation of the fold mountains of Sichuan and Yunnan, and has a much wetter climate than the plateau. Yuan (1991) refers to numerous caves in these valleys, including stream caves several hundred metres long near Markam.

Northern Tibet

Within the Nyainqentangla Mountains, white crags of massive limestone can be seen from the Lhasa-Nagqu road just north of Damxung, but have not been searched for caves.

The great salt lake of Nam Co has limestone outcrops on its southern side. The cliffs on the Zhaxido peninsula have at least 20 cave entrances; the largest constitute Buddhist shrines and house their hermit guardians. The caves are phreatic solution rifts heavily modified by wave erosion when the lake level was just above the old

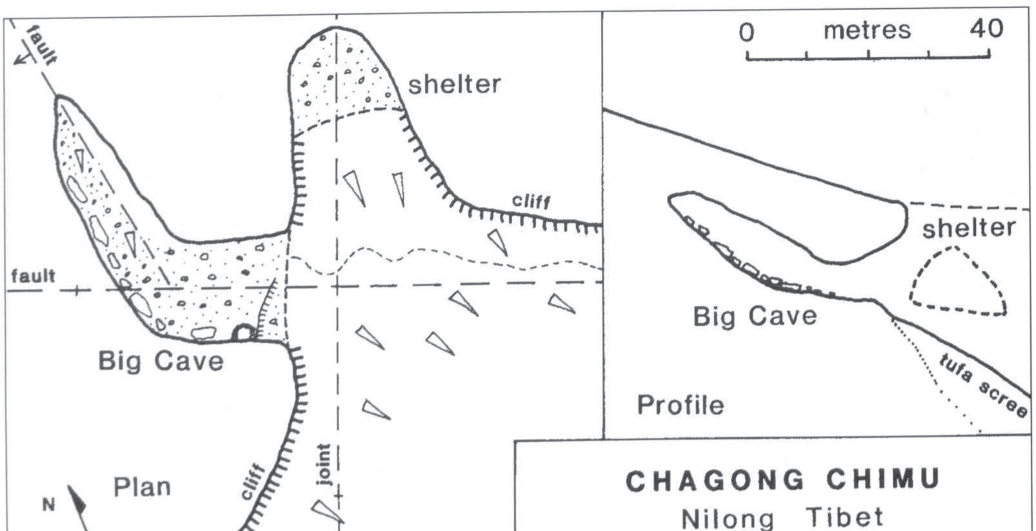
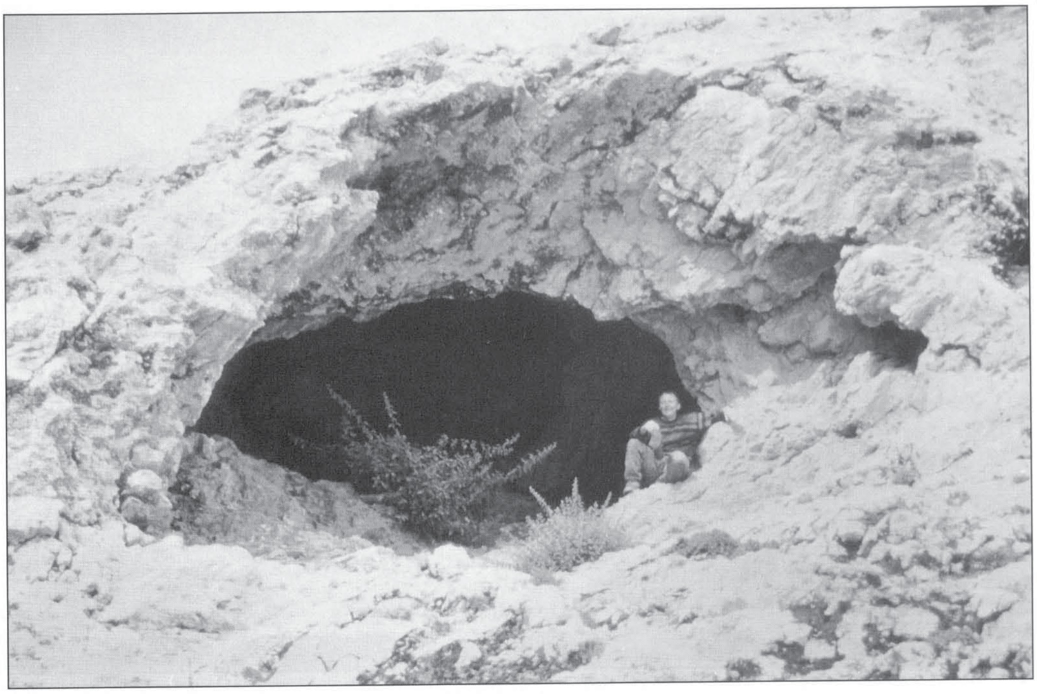


Figure 3. Survey of Chagong Chimu (by China Caves Project).

The phreatic cave fragment west of Chagong Chimu.



wave-cut platform which now extends in front of them. The longest rift penetrates about 20 metres, and there are fossil stalagmites in some.

At Amdo, the limestone hill just north of the town has many small fragments of cave exposed in its frost shattered pinnacles.

North and west of Amdo, Yuan (1991) records isolated caves but no details are given.

In the far north, the Kunlun Mountains have large outcrops of limestone, but the most extensive and interesting karst appears to lie on the northern slopes, in the province of Xinjiang (Yuan, 1991).

Western Tibet

Large outcrops of limestone occur within the Nganglong Kangri mountains from Coqen westwards to the Indian frontier. Caves are known in the limestone of the Shiquanhe valley, including some well decorated with stalagmite, some with streams, some fossil caves which have been used for storage, and some cave chambers "large enough to hold several hundred people" (Yuan, 1991).

Further west, crags in massive limestone at Rutog contain a fossil cave 100 metres long. It lies on a fault with entrances at both ends, and internal dimensions reach 8 metres wide and 15 metres high (Yuan, 1991).

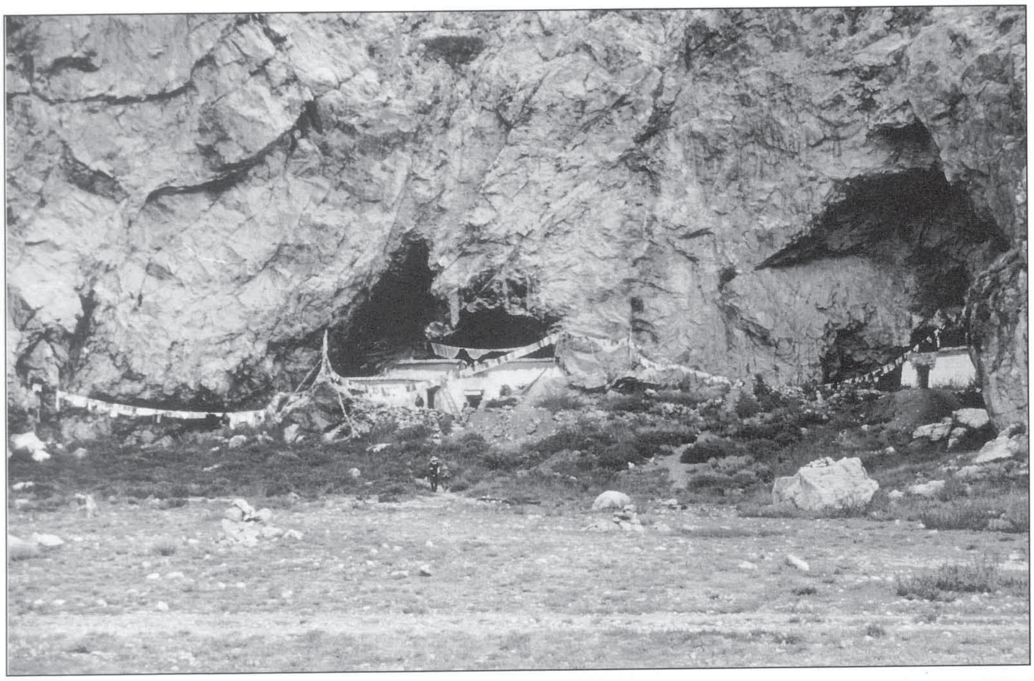
FUTURE EXPLORATION

Tibet offers a distinctive challenge to cave explorers. There is no real prospect of discovering massive cave systems – though caves are notoriously unpredictable and optimism should not be put down. The excitement of Tibet is the unique environment of the high plateau, and a visit searching for caves provides an unforgettable experience even if little time can be spent underground.

The more accessible parts of central Tibet, closest to Lhasa, offer little prospect on the basis of the two recent studies. Eastern Tibet probably has more caves than anywhere else; but this region lacks the excitement of the plateau, and time searching for caves in forested valleys would probably be better spent in China's great karstlands not far to the east.

The most exciting prospect remains the limestones of western Tibet around Rutog and Shiquanhe. Caves are known there, and new discoveries probably await; the signs are that the caves are large enough and complex enough to provide positive evidence on the existence or not of Tertiary fossil karst on the plateau. The area was a target destination for the China Caves Project in 1992; but access was impossible, partly due to politics, and largely due to an unusually bad monsoon which washed out nearly all the roads. These caves still await their first visit by westerners.

Limestone buttresses with cave fragments near Perochi.



The Buddhist caves above the foreshore of Nam Co.

Access to Tibet

Any cave explorer aiming for Tibet will be challenged by monumental barriers and problems. They come in two forms – political and physical.

The politics of access to Tibet vary unpredictably from year to year, dependant largely on the state of civil unrest. Currently any tourist can go to Tibet, via Chengdu and at a price. But it is difficult or impossible to get away from guided tours to designated sites. Independent travel is officially banned at present, and is next to impossible for any but an inconspicuous solo traveller. Official, invited visits (such as applied to the China Caves Project) require very good contacts, scientific credentials and endless diplomacy, and even then can encounter problems in reaching some of the more remote areas which are normally closed. All visits, whether tourist or invited scientific, are expensive, as westerners are regarded as a rich source of hard capital suitable for charging various fees.

The physical barriers are of sheer scale, both horizontally and vertically. Altitude sickness hits every unacclimatised visitor, but for most it declines after a week or so. The distances make organised travel justifiably expensive. Most roads are only fit for trucks and 4WD vehicles and fuel is a major factor; buses are erratic; landcruisers with obligatory drivers can be rented in Lhasa, at a price. In winter, the cold is staggering. In summer, the rains reach over the Himalayas to a variable extent and frequently wash out roads and bridges or bury them beneath landslides. October is probably the best month to be there, or alternatively May – each month being in the windows between certain cold and potential rain. The drive from Lhasa to Shiquanhe in the west takes a week in good conditions. A visit to the caves of western Tibet will be neither simple nor inexpensive.

ACKNOWLEDGEMENTS

This review is a contribution from the China Caves Project. Thanks are therefore due to the members and sponsors of the Project, especially the Royal Society, the Royal Geographical Society, the Mount Everest Foundation, the Ghar Parau Foundation, the Sports Council, and Cathay Pacific Airways for major support, and Andy Eavis for handling all the advance planning and negotiations. The Tibet team in 1992 was Zhu Xuewen and Zhang Ren from the Institute of Karst Geology in Guilin, and Dick Willis, Kenny Taylor, Pete Francis and Tony Waltham from the BCRA; all contributed to the new data in this review. Thanks also to Zhang Dian for helpful discussions.

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The Caves of Doshan, Guizhou, China

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Abstract: In association with Guizhou Normal University, Guiyang, the caves of the Dosahn area of An Long County were examined by British expeditions in 1988 and 1989, leading to the discovery of 22 km of passage and one of the world's largest known chambers.

A number of expeditions (Lewis, 1988; Smart, 1988; Fogg and Fogg, 1988; Dunton, 1989; and Waltham, 1986) have now been made to the Guizhou Plateau which forms part of the world's largest area of limestone karst. An Long County was chosen for exploration on the basis of information obtained from the Institute of Karst Geology at Guilin and from Guizhou Normal University. A reconnaissance in 1986 was followed in 1988 by a 16 person expedition, largely from the Wessex Cave Club, which surveyed the bulk of the cave passages discovered. Some surveys were produced but not published. The expedition during March 1989, led by Bruce Dunton with 9 members, aimed to reconcile data and find the missing pieces of the jigsaw.

The 1989 expedition was based at Doshan, a small village forming the administrative and educational centre for the area in which all discoveries were made (Fig. 1). Doshan lies approximately 20 km north eash of An Long and some 220 km south west of Guiyang, the capital city of Guizhou Province. 4 km north east of Doshan lies the impressive An He doline featuring cave development at three distinct levels.

Geology and Geomorphology

The limestones around Doshan are Triassic in age. Permian and older rocks, mainly but by no means all limestones, outcrop south of An Long, whilst An Long itself has extensive Quaternary deposits around it. Sandstones and shales succeed the limestones; a sharp facies transition to sandstones is also mapped near the Si Fang resurgence, although it could easily be taken to be faulted. Around Doshan local observations revealed varied dips, an upward and westward transition from massive to thin bedded limestones containing brachiopods and then to shales containing ammonoids. In the Ban Dong entrance the limestones show fragmented fossil algal mats, which, with the occurrence of large gypsum nodules, suggest that the depositional environment was a sabkha similar to that in the present Persian Gulf.

To the north of Doshan is a distinctive, gently northward sloping plateau which contains some impressive collapse dolines and vadose shafts. The shafts probably relate to the removal of the overlying impermeable cover. Adjacent to the sandstone to the north east is the huge, complex closed depression of An He with a seasonal river and residual hills inside its cliffed sides. Between An He and the sandstone is an area of steep fencong clustered hills with some elongated depressions. To the south and east of Doshan is an area of fencong depression karst, a sea of cones with remarkably accordant summit level leading off in to the haze or fog.

Faulting, chiefly northeast/southwest, predominates; one such disturbance may account for the An He – Doshan – Lishu communication line. Cave entrances occur generally at certain well defined levels, with both low level active and high level fossil systems, and suggest long histories of episodic uplift and rejuvenation.

Subterranean water courses in the area resurge chiefly at Si Fang (Fig. 2) which has an estimated flow of 15-25 m^3/sec during the dry season. The river resurging at this point flows some 5 km to the confluence with the Beipan river. The Chinese have mapped four primary "flow lines of conjecture" converging on Si Fang and these amount to four drainage systems from four main sinks. The most northerly of these flow lines reaches out of the area covered by the expedition's access permit. To the northwest is the Paxi gorge sink, a massive shakehole choked with mud and vegetation; west loosely relates to the main Ban Dong system; and to the southwest is South Sink, a small active sink that was explored to a sump in 1988.

The fengcong karst of Dosan.

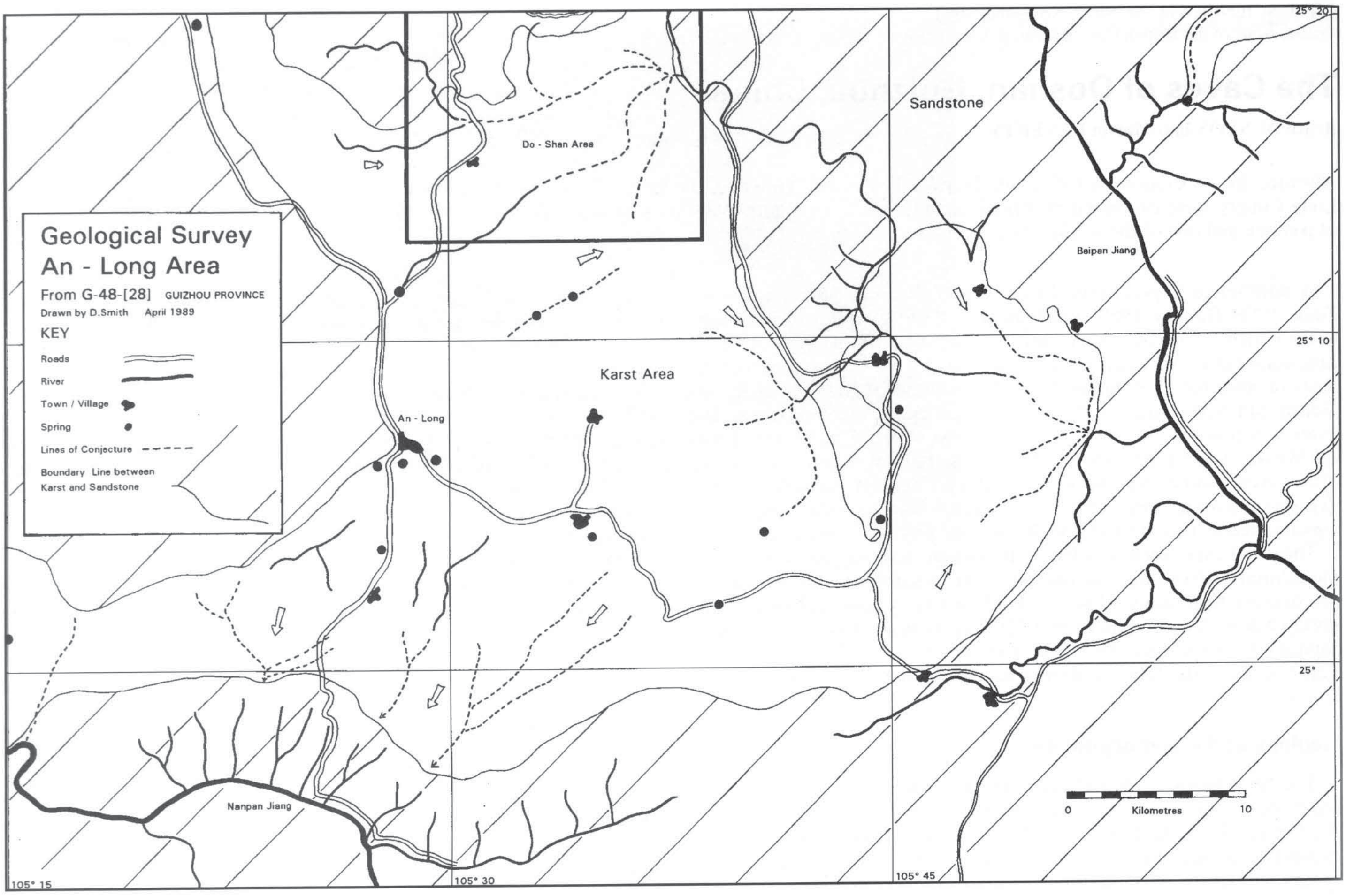


Figure 1

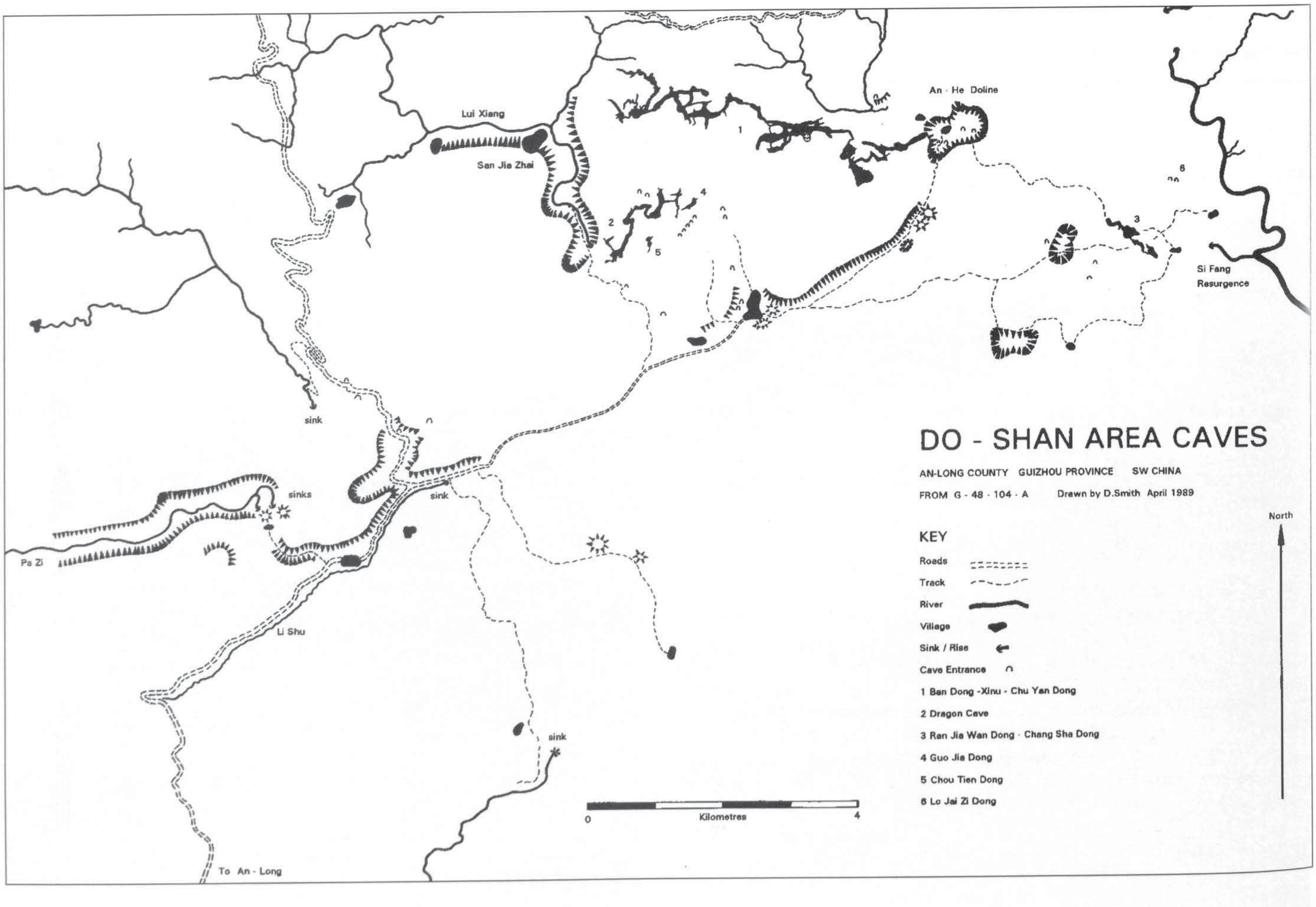


Figure 2

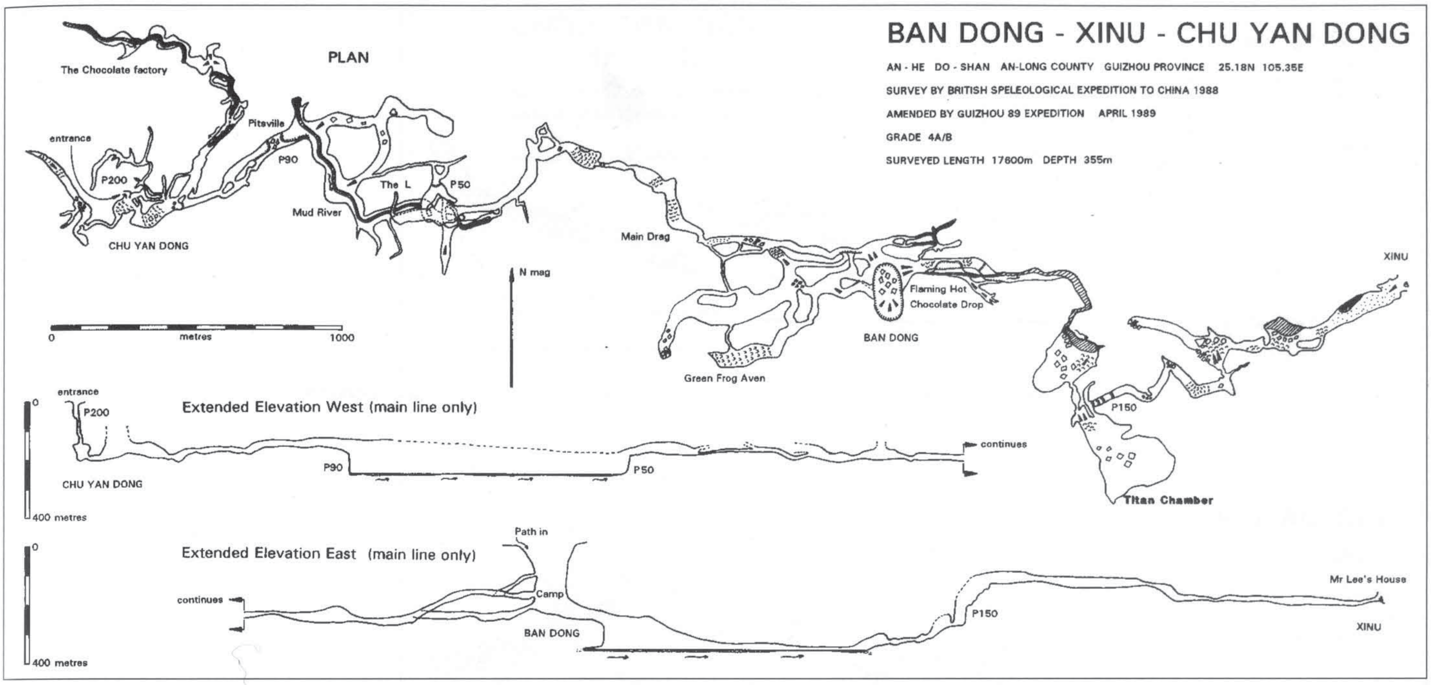


Figure 3

THE CAVES

The 1988 Discoveries

The An He doline is approximately 1 km in diameter and contains a number of cave entrances, and a small settlement. Perhaps the most significant cave entrance is that of Xinu Dong, some 75 m and 15 m high (Fig. 3). The passage continues west for 1 km, largely maintaining these proportions, and is home to an inversion layer, formed as the warm humid air comes into contact with cooler air outside. This large and dense cloud usually extends from chest height, where the temperature on one occasion was 9°C, to the ceiling, where the temperature measured 16°C. The nature of the cloud required those passing to stoop down in order to see. Casual references suggesting that An He is a collapse doline are given an eerie element of credence by the existence of a chamber 300 m x 150 m x approx. 50m high. This is one of the largest known chambers in China.

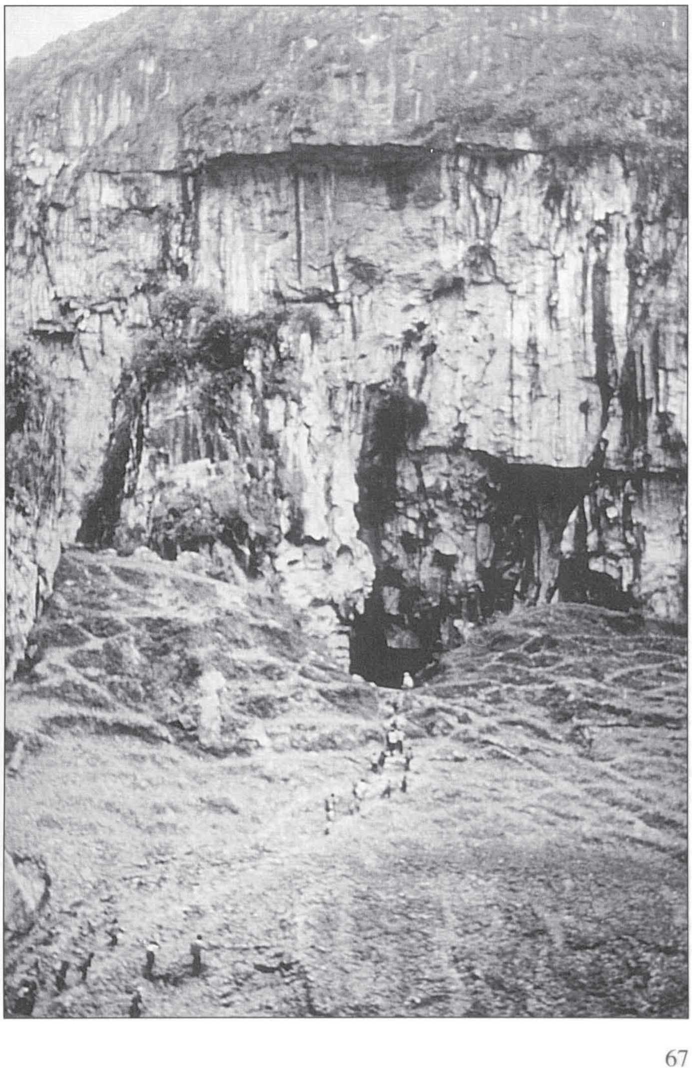
Following the main passage upstream, the Ban Dong surface entrance shaft is encountered 200 m x 100 m x 225 m deep. The bottom of the shaft can be reached from the surface by negotiating a narrow path down to a window and thence to the bottom via a cave passage. This trip is regularly made by locals with lighted torches to gather pig food in the form of the large stems of the banana plants that grow at the bottom of the shaft. Continuing west the passage drops down to the active level and eventually reaches Chu Yan Dong; this point can be reached from a stream sink via a 200 m free-hanging descent. From Chu Yan Dong, the cave once again heads west in the direction of a series of possible connections with the surface.

An obvious entrance in a large shakehole 4 km south east of Ban Dong is that of Dragon Cave, with approximately 5 km of passage, 150 m wide and 50 m in some places. It heads 1.5 km towards Ban Dong (Fig. 4). Dragon Cave was discovered towards the end of the 1988 expedition, and data was not sufficiently processed to consider the correlation between the two caves.

The 1989 Discoveries

Despite ingenious efforts with maypole made from bamboo, no obvious link was found between Dragon and Ban Dong, although some minor additions were made, and loose ends were tidied up. One spectacular discovery was that of Guo Jia Dong (Fig. 5). With a depth of 178 m it was expected that this might have intersected the passages of the main system. Despite a draught a route onward proved elusive. Nearby is the huge daylight chamber of Chou Tien Dong (Fig. 6). However, the most significant find was Ran Jia Wan Dong, not uncovered until the last days of the expedition (Fig. 7). Rand Jia Wan Dong was explored and surveyed for over 1 km to the head of Barnstorm pitch, which was very loose but appeared to be of some considerable depth.

The entrance to Dragon Cave.



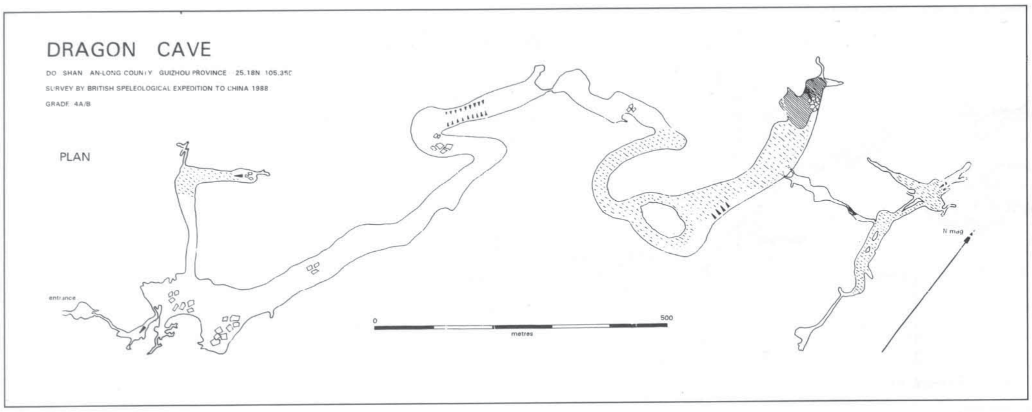


Figure 4

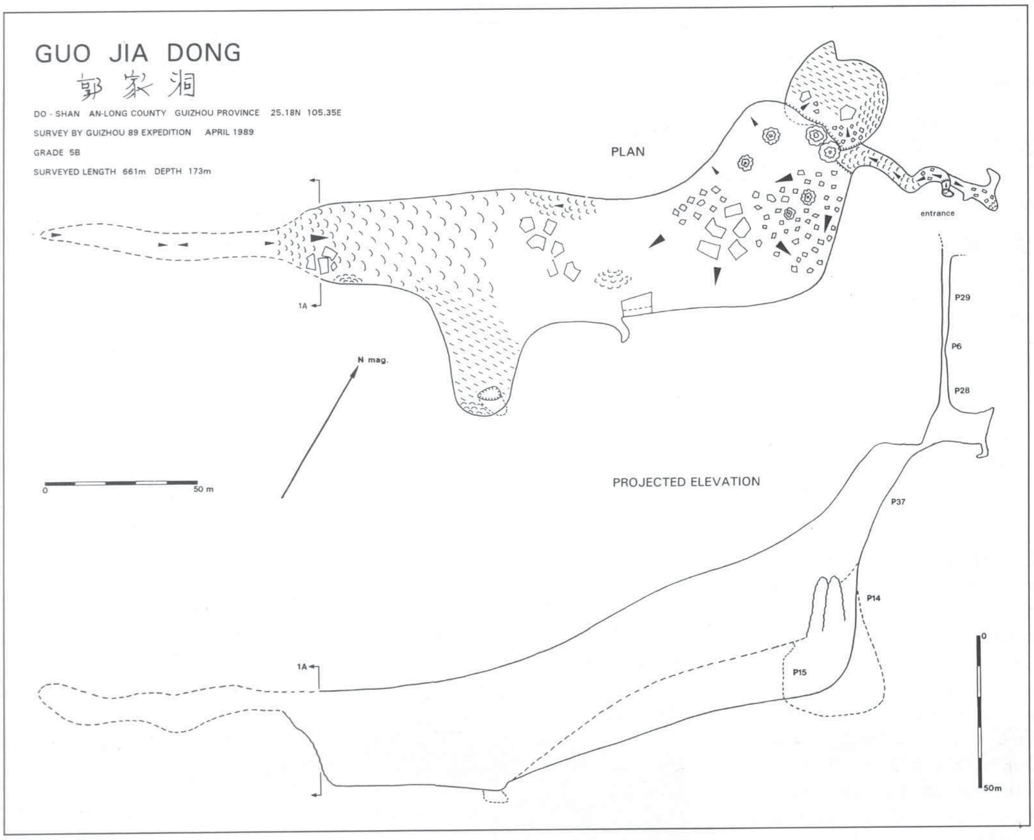
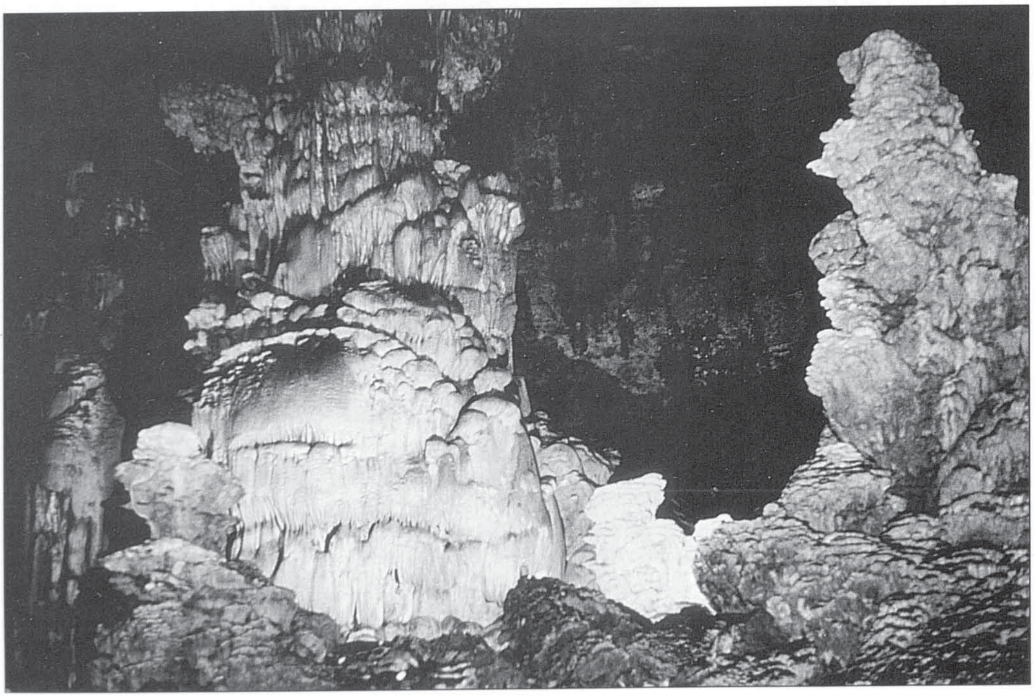


Figure 5

Stalagmites in Guo Jia Dong.



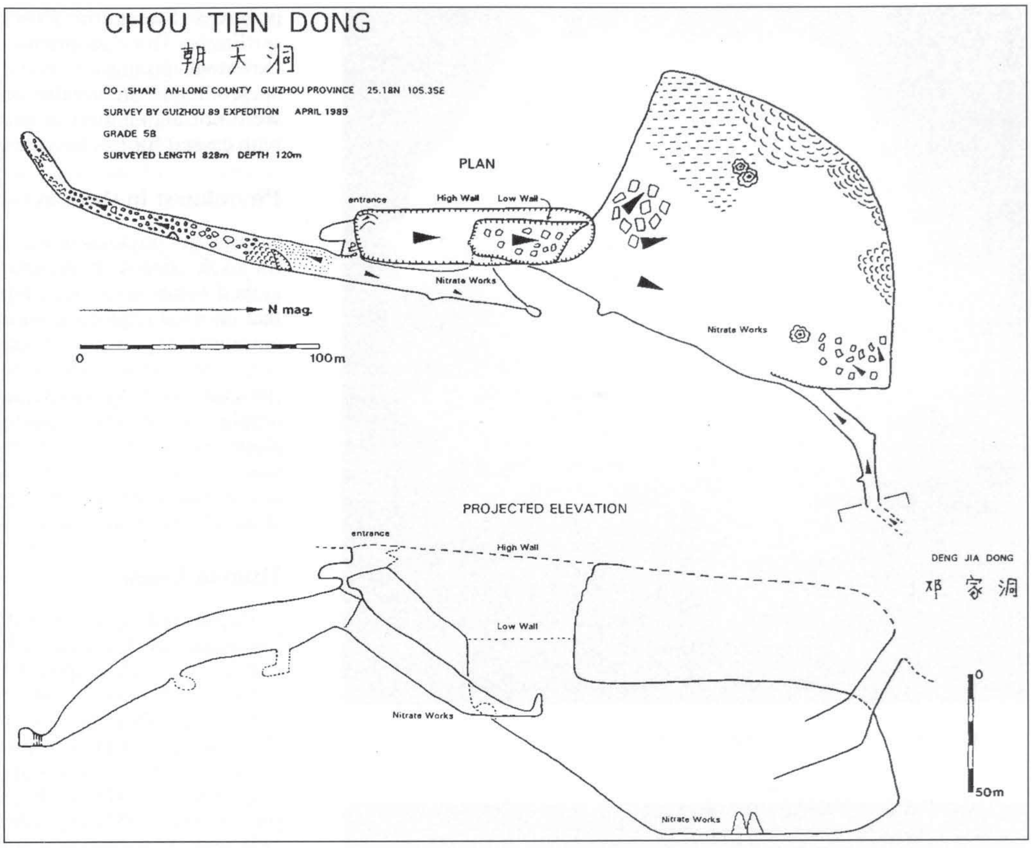


Figure 6

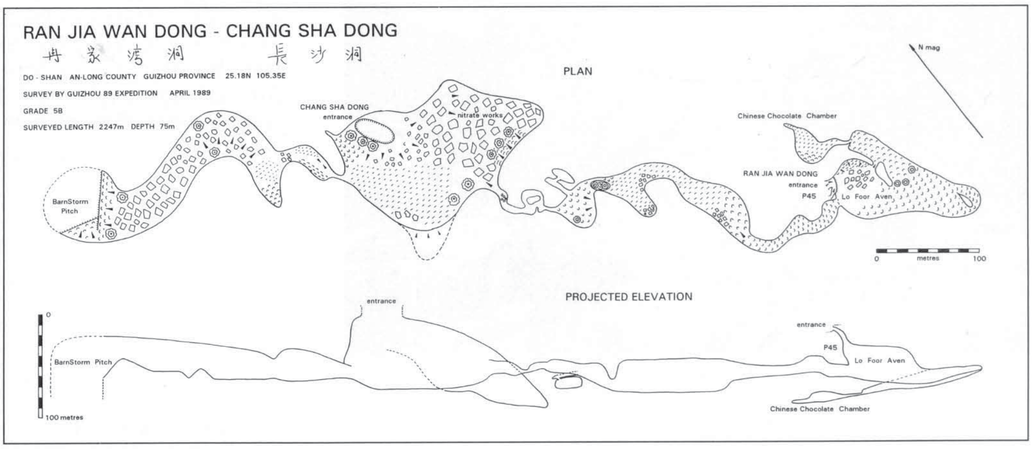
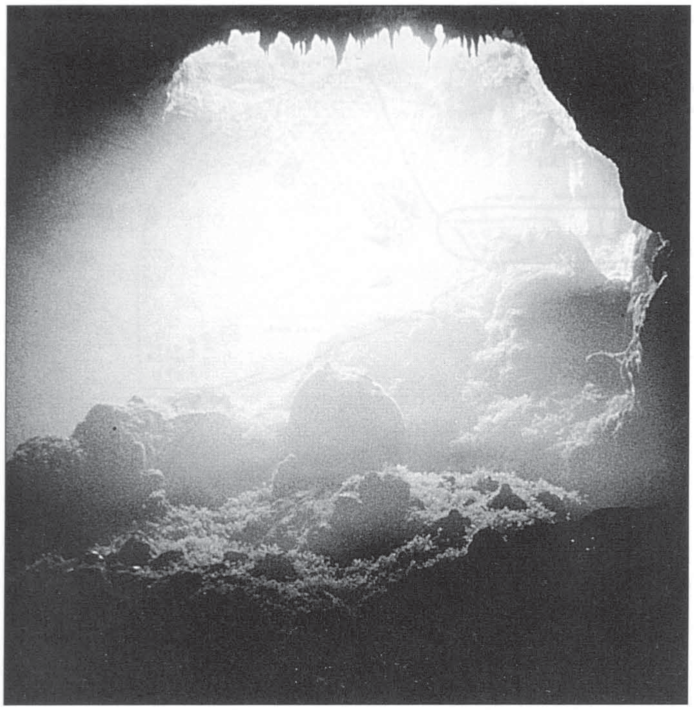


Figure 7

Cave Sediments

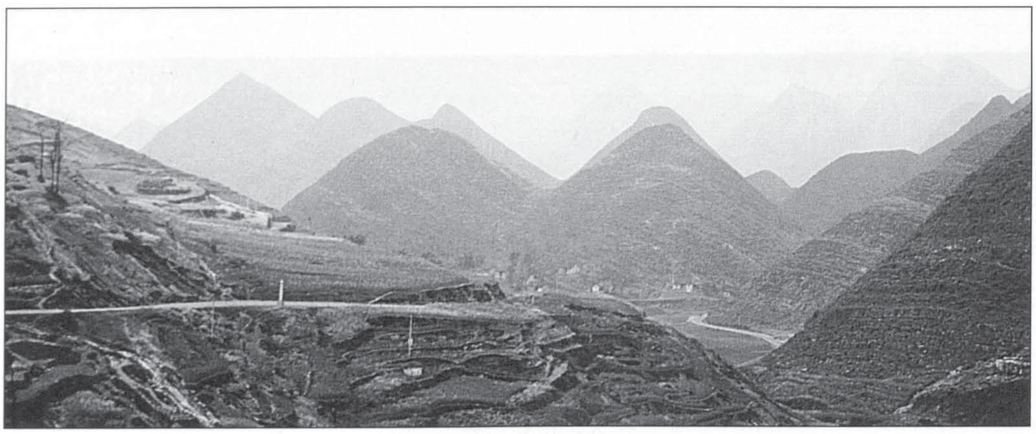
The fossil caves appeared to be rather lacking in a general abundance of sediments, or at least in exposures thereof although there was much sticky clay in the active Ban Dong Mud River and its inlets. The typical sediment was a pellet sand; this consists of cylindrical pellets about 2 mm x 0.5 mm diameter, brown in colour. The precise origin of the pellets is not known, but clearly points to the loss of significant biological inputs. There is also the fact of removal of quantities of sediment to leach for the making of potassium nitrate (a party of locals followed us into the cave one day to taste the sediment in an unsuccessful search for more). It is though that the nitrogen derives from activity of soil organisms in certain types of leaf litter. The intensive agriculture and its associated forest destruction in this area probably means that nitrate minerals will not regenerate as they may have done in the past; if they were instead derived from guano deposits they will again not regenerate as the fauna is now comparatively sparse.

The caves also had a notable lack of breakdown, making for easy



Daylight in the entrance of Chang Sha Dong.

Remains of the nitrate works in Ban Dong.



Conical hills in the Dosan karst.

progress. Stalagmite flows tended to be cracked (perhaps due to settling of floor sediment) and crystalline facets were common on flowstone giving a velvety, sparkling appearance to otherwise dry speleothems. Stalagmite bosses and columns up to 10 m in height were not uncommon in parts of the caves, and low rimstone pools with crystal fillings are common on flat passage floors.

Phytokarst in the Caves

Directed phytokarst was first reported in cave entrances in Mulu, Sarawak (Brook & Waltham, 1978; Bull & Laverty 1982). Similar etched forms have been reported elsewhere. It was thus anticipated that directed phytokarst would be found in sheltered positions in cave entrances exposed to limited direct sunlight. This was found to be true; one example is to be found on a large boulder about 30 m down the entrance slope of Xinu Dong; Chou Tien Dong also has a fine display below where daylight illuminates the foot of the entrance slope. These observations suggest that occurrences of phytokarst are under-recorded or misidentified, but it should not be thought that it is a common phenomenon anywhere. It is certainly very fragile and should be given special attention in future conservation strategies.

Human Usage

Populated sparsely until recent times, this densely forested landscape saw the main influx of Han Chinese begin during the early 19th century, whereupon deforestation commenced to coincide with a general and dramatic increase in population, often displacing the indigenous ethnic groups of Miao and Buyei. The lack of karren on the limestone stumps exposed in the fields suggests that they have been exposed by soil loss arising from agricultural use.

Caves have always been used by man for shelter, even to the present day, with some houses at An He constructed inside large cave entrances. More recently nitrate mining has been the main occupation of the cave visitor. An inscription on a large slab of rock in Ban Dong reads, "Between 1960 and 1961 potassium nitrate was obtained from this cave and taken to Doshan for sale at 3.6 yuan per weight". The idea and techniques for extraction came with migrant prospectors from Yunnan province between 1900-1950 and the nitrate was used for making gunpowder. The path inside Ban Dong shaft was constructed in 1946 solely to facilitate the retrieval of nitrate.

The best preserved example of nitrate works were encountered in Ran Jia Wan Dong where crockery and eating utensils had lain in place since the last days work during the 1960s, "The climb down into the cave was so difficult that workers would inhabit the cave for up to three months to avoid the climb" an ex-miner recounted as we watched a member of the team de-kit after a very brief SRT trip in and out. Elsewhere we were told that caves had been useful sources of gypsum which had been used for processing beancurd and mercury used for cosmetics.

As deforestation caused the tree line to recede, the larger mammals, such as tigers and pandas, were driven out of the area. Skeletal remains of possibly one or the other were discovered in Ran Jia Wan Dong. The largest mammalian inhabitant of the caves is now the bat which is still to this day occasionally collected and prepared as an exotic constituent of some forms of Chinese medicine.

In more recent years caves have ceased to become of any financial worth to the local community in physical terms. However the notion of attracting tourists to the area, especially those with foreign hard capital has now become a much vaunted topic, paradoxically our expeditions being cited as causality. In 1992 it unexpectedly came to light that that, encouraged by our project, Xinyi Prefecture Tourist Bureau have decided to develop the An He doline as a national tourist attraction. Using a most esoteric doctrine as a blueprint, the local authorities have planned to build a food oil processing plant, a one hundred acre tree orchard, a market and a new middle school all within the An He doline, which will be linked with a new 100 km 8 metre highway connecting it to Zhenning, near Anshun.

Future Prospects

The possibilities for future expeditions are enormous, so unfortunately, it seems, are the implications! The main problem with Doshan is the inaccessibility of the place although, ironically that seems about to change. Two weeks of any expedition are taken up with inward and outward travel. An Long county also remains a 'closed area' to foreigners for whom an aliens' permit, with all its attendant problems and delays, is required. This very significant area would benefit from a detailed and methodical exploration, possibly best served by regular expeditions able to operate under their own control. Until this time it may be just a case of watching and waiting.

ACKNOWLEDGEMENTS

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Team members were Keith Barnes, Derek Davies, Gareth Davies, Bruce Dunton, Martin Laverty, Stephen McGowan, Neil McHugh, David Smith and Richard Storm. David Smith prepared all the maps and surveys for this paper, and Richard Storm provided the photographs.

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Forum

Readers are invited to offer review articles, shorter scientific notes, comments on previously published papers and discussions of general interest for publication in the Forum section of Cave Science.

'A tale of two Pollnagollums: Correction to "The Palaeo-environments of Coolarken Pollnagollum (Pollnagollum of the Boats) Cave, County Fermanagh, Northern Ireland: Evidence from Phytolith Analysis" by Thompson and Maloney.

Ireland has a profusion of caves with the name Pollnagollum which translates as Cave of the Doves (Jones, 1974) and has nothing whatsoever to do with Tolkein's mythical character in **The Hobbit** and **Lord of the Rings.** Unfortunately, this has confused many people, Thompson and Maloney being the latest victims. The cave in which they undertook their research is correctly known as Pollnagollum Coolarken (Jones, 1974, p.34). They have confused it with Pollnagollum (of the Boats) an entirely different cave which forms part of the Marble Arch system (Jones, 1974, p.75). The human skulls which Thompson and Maloney refer to were recovered from Pollnagollum (of the Boats) and *not* from Pollnagollum Coolarken

REFERENCE

Jones, G. Ll. 1974. The Caves of Fermanagh and Cavan. The Watergate Press, Enniskillen.

CORRECTION OF MISPRINTS

During the production stage of Trevor Shaw's paper "The Bristol Speleological Research Society 1912-1914", several typographical errors pointed out by the author in proof were not corrected. The most important of these are:

(a) Page 20, column 1, Membership of the Society. The third name in the list should be Crandon, not Crownsey.

(b) Page 21, column 2, the Simpson reference, Lancaser should be Lancaster.

(c) Page 21, column 2, Appendix I, POSITION, line 3.
"... to o skull ..." The o should be the symbol for male, o.

Several minor errors, not affecting the sense, exist in some of the quotations.

B.C.R.A. RESEARCH FUNDS AND GRANTS

THE JEFF JEFFERSON RESEARCH FUND

The British Cave Research Association has established the Jeff Jefferson Research Fund to promote research into all aspects of speleology in Britain and abroad. Initially, a total of £500 per year will be made available. The aims of the scheme are primarily:

a) To assist in the purchase of consumable items such as water-tracing dyes, sample holders or chemical reagents without which it would be impossible to carry out or complete a research project.
b) To provide funds for travel in association with fieldwork or to visit laboratories which could provide essential facilities.
c) To provide financial support for the preparation of scientific reports. This could cover, for example, the costs of photographic processing, cartographic materials or computing time.
d) To stimulate new research which the BCRA Research Committee considers could contribute significantly to emerging areas of speleology.

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant(s) must be the principal investigator(s), and must be members of the BCRA in order to quality. Grants may be made to individuals or small groups, who need not be employed in universities, polytechnics or research establishments. Information and applications for Research Awards should be made on a form available from Simon Botterill, Dept. of Earth Sciences, University of Leeds.

GHAR PARAU FOUNDATION EXPEDITION AWARDS

An award, or awards, with a minimum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Rowlands House, Summerseat, Bury, Lancs. BL9 5NF. Closing date 1st February.

SPORTS COUNCIL GRANT-AID IN SUPPORT OF CAVING EXPEDITIONS ABROAD

Grants are give annually to all types of caving expeditions going overseas from the U.K. (including cave diving), for the purpose of furthering cave exploration, survey, photography and training. Application forms and advice sheets are obtainable from the GPF Secretary, David Judson, Rowlands House, Summerseat, Bury, Lancs. BL9 5NF and must be returned to him for both GPF and Sports Council Awards not later than 1st February each year for the succeeding period, April to March.

Expedition organisers living in Wales, Scotland or Northern Ireland, or from caving clubs based in these regions should contact their own regional Sports Council directly in the first instance (N.B. the closing date for Sports Council for Wales Awards applications is 31st December).

THE E. K. TRATMAN AWARD

An annual award, currently, £50, made for the most stimulating contribution towards speleological literature published within the United Kingdom during the past 12 months. Suggestions are always welcome to members of the GPF Awards Committee, or its Secretary, David Judson, not later than 1st February each year.

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

CAVE SCIENCE — published three times annually, a scientific journal comprising original research papers, reviews and discussion forum, on all aspects of speleological investigation, geology and geomorphology related to karst and caves, archaeology, biospeleology, exploration and expedition reports.
Editor: Dr. Trevor D. Ford, 21 Elizabeth Drive, Oadby, Leicester LE2 4RD. (0533-715265).

CAVES & CAVING — quarterly news magazine of current events in caving, with brief reports of latest explorations and expeditions, news of new techniques and equipment, Association personalia etc.
Editor: Mark Dougherty, 7 Edinburgh Terrace, Armley, Leeds LS12 3RH (0532-639288).

CAVE STUDIES SERIES — occasional series of booklets on various speleological or karst subjects.

No. 1 Caves & Karst of the Yorkshire Dales; by Tony Waltham and Martin Davies, 1987. Reprinted 1991.

No. 2 An Introduction to Cave Surveying; by Bryan Ellis, 1988.

No. 3 Caves & Karst of the Peak District; by Trevor Ford and John Gunn, 1990. Second Edition 1992.

CURRENT TITLES IN SPELEOLOGY — annual listings of international publications
Editor: Ray Mansfield, Downhead Cottage, Downhead, Shepton Mallet, Somerset BA4 4LG.

CAVING PRACTICE AND EQUIPMENT, edited by David Judson, 1984. Second edition 1991.

LIMESTONES AND CAVES OF NORTHWEST ENGLAND, edited by A. C. Waltham, 1974. (out of print).

LIMESTONES AND CAVES OF THE MENDIP HILLS, edited by D. I. Smith, 1975. (out of print).

LIMESTONES AND CAVES OF THE PEAK DISTRICT, edited by T. D. Ford, 1977, (out of print).

LIMESTONES AND CAVES OF WALES, edited by T. D. Ford, 1989.

Obtainable from B.C.R.A. Administrator
B. M. Ellis, 20 Woodland Avenue, Westonzoyland, Bridgwater, Somerset TA7 0LQ