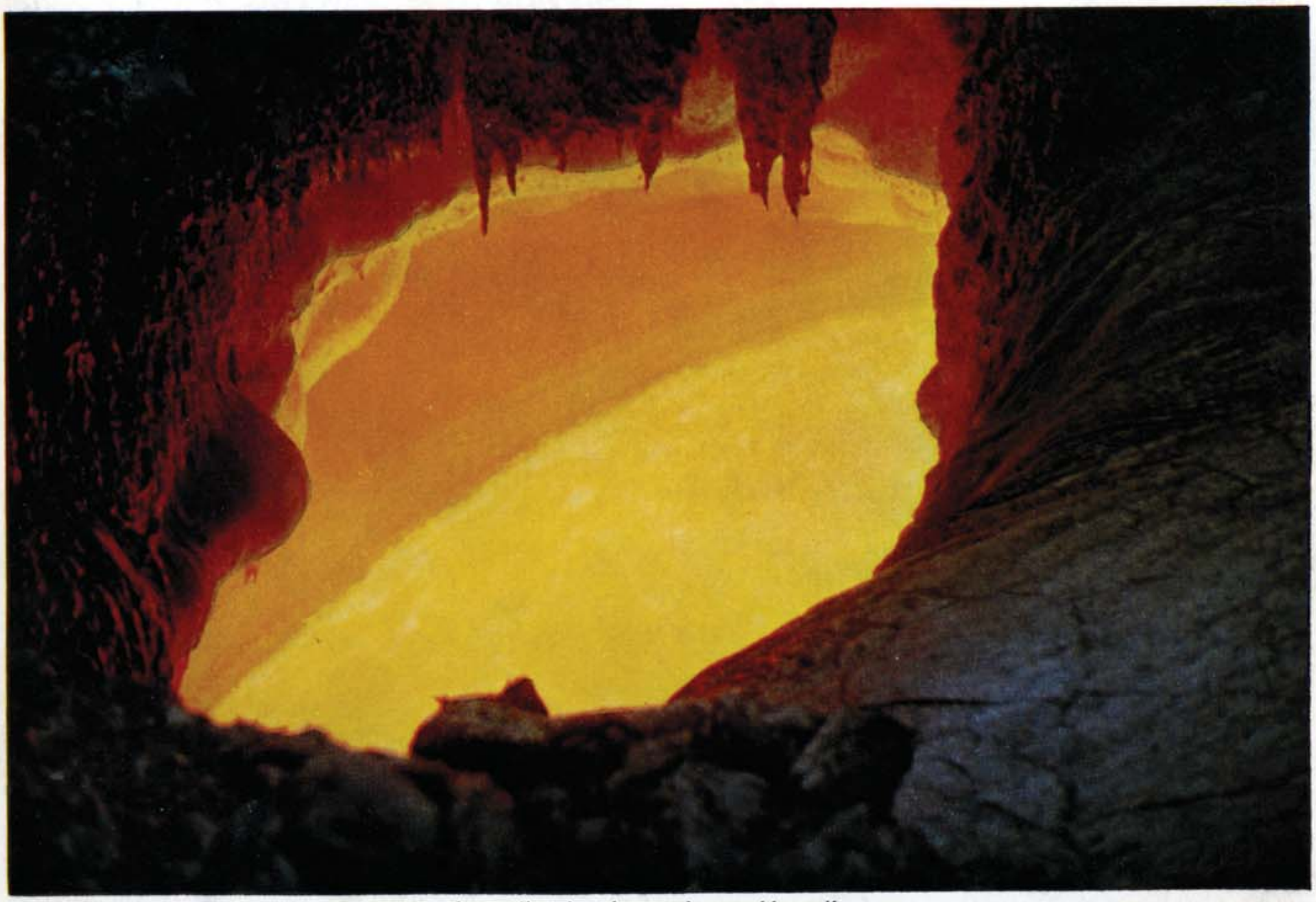
BCRA TRANSACTIONS

BRITISH CAVE RESEARCH ASSOCIATION

Volume 1 Number 1 January 1974



Lava flowing in a tube on Hawaii

INSTRUCTIONS TO CONTRIBUTORS

These notes are meant for guidance of contributors in the hope of reducing the amount of labour for both the editor and the contributors! Adherence to the rules is desirable but not absolutely essential.

As far as possible all material submitted for publication in the Transactions should be typed on one side of the paper only with double spacing to allow for editorial corrections where necessary. Paragraph sub-headings should be clearly marked. Metric measurements should be used wherever possible.

A very short summary of the principal conclusions should accompany every contribution.

References to other published work should be cited in the text thus . . . (Bloggs, 1999, p.66) . . . and the full reference with date, publishers, journal, volume number and page numbers, given in alphabetical order of authors at the end, thus . . .
Bloggs, W., 1999. The speleogenesis of Bloggs Hole. Bulletin X Caving Assoc. Vol. 9, pp. 9-99.

Italics are not normally used and only the volume number should be underlined. Periodical titles should be abbreviated in accordance with the World List of Scientific Periodicals, obtainable in any public library.

Illustrations: line diagrams and drawings should be numbered fig. 1, fig. 2, etc., and referred to in the appropriate place in the text. All such illustrations must be drawn in BLACK ink on clean white paper, card or tracing paper. Anaemic grey ink will not reproduce! Illustrations should be designed to make the maximum use of page space. If photo-reduction is contemplated all letters and lines must be of a thickness or size to allow for this. Captions may be typed on a separate sheet if space is left for insertion on the final illustration.

Photographs are welcome. They must be good clear black and white prints with sharp focus, and preferably about 6×4 inches. Captions may be appended by means of adhesive tape on the back.

If illustrations are submitted which have already been published elsewhere, it is up to the author to clear any copyright and acknowledgment matters.

Contributors in Universities and similar institutions are reminded that grants are often available from those which may help towards the costs of publication. The Editor will be pleased to advise.

If you have any problems regarding your material please consult the editor in advance of submission.

Authors may order reprints of their own contribution for their own private use, such as circulation to colleagues or for exchange purposes. The Editor should be notified of the number required at the time of submission of the contribution. Ten reprints are allowed free, if asked for, but the rest will be charged to the author.

TRANSACTIONS OF THE
BRITISH CAVE RESEARCH ASSOCIATION

Volume 1 Number 1 January 1974

CONTENTS

Cover photo – **Flowing lava in a tube between Mauna Ulu and Alae Crater, Hawaii, October 1970** by D.W. Peterson.

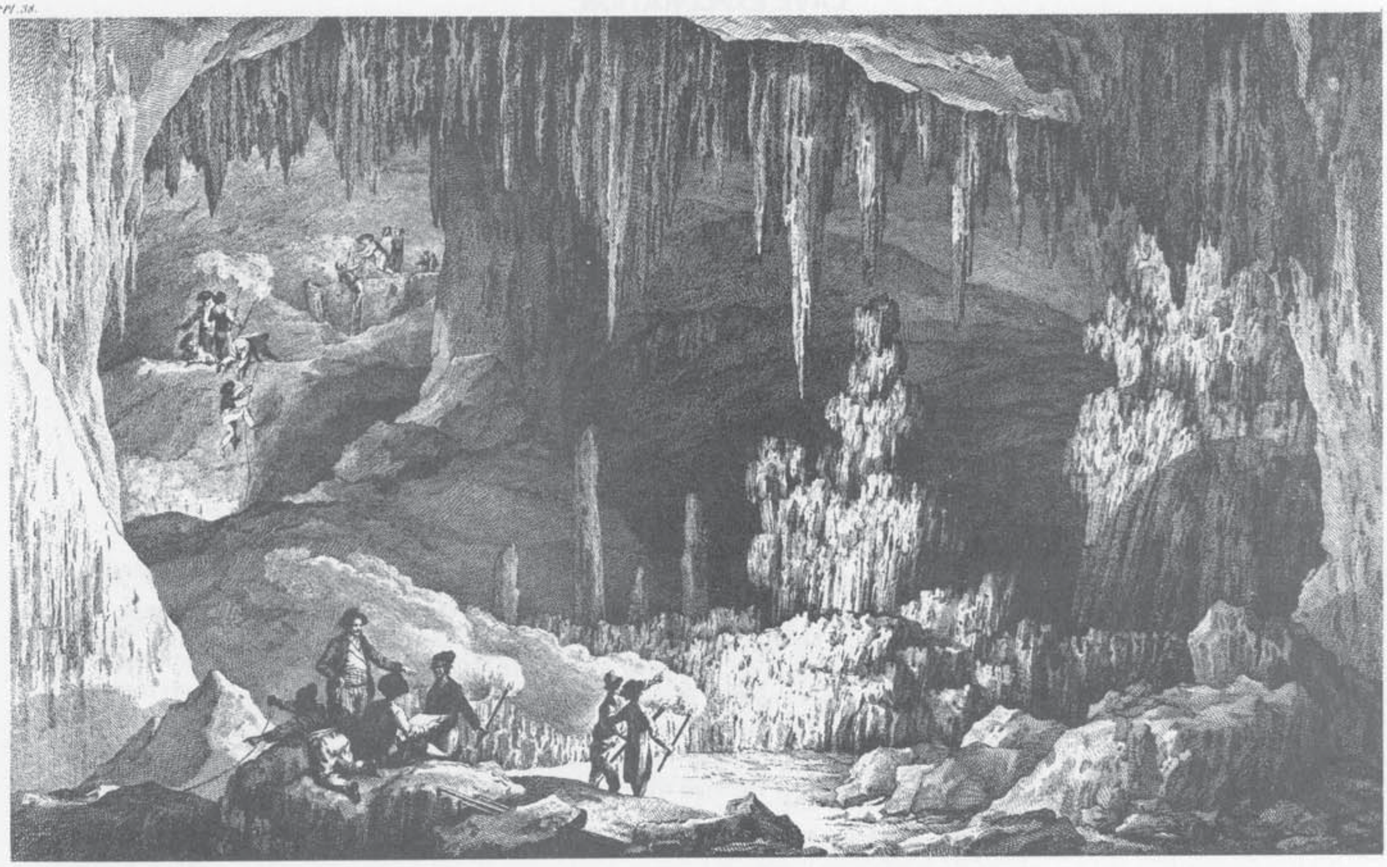
Published by and obtainable from
The British Cave Research Association

Bryan Ellis,
7 School Lane,
Combwich,
Bridgwater,
Somerset. TA5 2QS.

One copy issued free to members
Extra copies to members £1·00
Non-members price £1·50

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Vol. 1 No. 1 January 1974



VUE DE L'INTERIEUR DE LA GROTTE D'ANTIPAROS.

A SHORT HISTORY OF SPELEOLOGY UP TO 1900

by

Trevor R. Shaw

INTRODUCTION

The history of speleology extends right up to the present and indeed a large amount of historically significant work has been done and is still being done in the twentieth century. Nevertheless, this paper stops at 1900, with few exceptions, because by then the general approach to the subject was modern. In particular, by that time:

a) scientific outlook was no longer subject to external constraints from theology, etc.
b) many of the present day speleological theories had already been expressed, though sometimes only briefly.
c) the organization of speleology was modern, in that:
   i) societies existed, which could undertake more extensive explorations than had been possible previously,
   ii) several periodicals were devoted solely to publishing the results of cave research.

CAVE EXPLORATION

As early as 852 BC the Assyrian king Salamanazar III visited the sources of the Tigris and ordered exploration of the caves there. Classical Greek and Latin writers paid much attention to the courses of underground rivers, particularly the Timavo near Trieste and those of the Peloponnese, and Aristotle (4th cent. BC) described a stalactite cave in the island of Demonesus near Istanbul. Caves were also well known to the ancient Chinese and powdered stalactite is listed among their drugs in the 4th and 1st centuries BC.

Many mediaeval visits are known only from inscriptions on cave walls (e.g. 1213, 1323, etc. in Postojna) but about 1135 Henry of Huntingdon mentioned caves in Mendip and Derbyshire. Faber wrote a manuscript description of the Sirgensteinhöhle and Sontheimhöhle (Germany) some time between 1470 and 1502 (Binder, 1963, p.140) and Strein's detailed report of 1591 (reprinted in Schmidl, 1857, p.199-213) described his exploration of caves in Austria.

Sturmy (1678) explored the vertical Pen Park Hole near Bristol in 1669 and Beaumont (1681) was lowered down the 20 metre pitch in Lamb [Leer] in 1676 or before, Magni (1692, p.132-152) described the first recorded exploration of the Antiparos Cave, in the Greek Islands, in 1673. Many other explorations were made in the 17th and early 18th centuries, but in most cases they were the outcome of individual curiosity rather than systematic studies. Important exceptions to this were the regional investigations carried out by the three men who may be called the first real speleologists. Valvasor (1689) explored caves in northern Yugoslavia over a period of at least ten years and published lengthy descriptions of them together with an account of the underground drainage of the area. Von Steinberg (1758) studied the hydrology of the same area for 40 years from 1718 and published a complete book on it. Nagel made a series of journeys, through Austria, Yugoslavia and Moravia in 1747 and 1748, solely to explore caves; his MS report, with plans, has been largely printed by Schmidl (1857, pp.213-215) and Salzer (1936).

In 1839-1841 a need to provide Trieste with a larger water supply led to a series of important explorations by Lindner and Svetina. Unable to follow the Timavo far where it sinks at Skocjanska Jama, they tried to locate its underground course by exploring the deep potholes of the area. Thus they descended Padriciano (271m) in 1839, and in 1841 Lindner reached the river at a depth of 327m in the Grotta di Trebiciano.

Schmidl was probably the most notable cave explorer before Martel. He worked in the Postojna complex of caves and in Skocjanska Jama from 1849 to 1856, and his discoveries increased the length of the Postojna cave itself to 7km. The Ötscherhöhle (Austria) was surveyed by him and in 1856 he studied the cave of Aggtelek (Hungary) which, at 8.7km, remained the longest in Europe until 1893.

In England a number of significant 19th century explorations were made in Yorkshire. Metcalfe and Birkbeck explored Alum Pot (89m deep) in 1847, and one or both of them descended Gaping Gill (104m), partly or completely, between 1842 and 1850.

Work in Yugoslavia commenced again in the 1880s when several groups of explorers formed themselves into the first speleological societies. Thus the Verein für Höhlenkunde was founded in 1879 at Vienna by Kraus; in 1883 the cave section of the Società degli Alpenisti Triestini and the coastal section of the Deutschen und Österreichischen Alpenverein were formed at Trieste. Some ten cave groups existed before 1900; their formation not only facilitated more difficult explorations, but their publications made their findings more accessible. Between 1886 and 1889 Putick explored more than 100 caves in a government-sponsored study to reduce flooding in part of Yugoslavia.

Martel (active 1888-1914) started his serious cave work when he was 29, publishing surveys of all he explored. Most of his original explorations took place in the course of 26 annual 'campagnes', in 18 countries. Even by 1894 he had visited 230 caves, of which 90 of the potholes had never been descended before and 75 of the others had not been fully explored. Martel is notable also for his progress in the scientific aspects of cave study, and is particularly important as the virtual founder of international speleology. Not only was he a sound speleologist but also publicist and traveller whose enthusiasm spread further by his personal visits and voluminous writings in several languages.

SPELEOGENESIS

Tectonic Causes

The earliest and simplest explanation for the origin of caves was that they were caused directly by cracking and fissuring of the rock. Descartes (1724, pp.369-372), writing in 1644, stated that quite big passages resulted from the disturbances associated with the formation of hills. Again, Hooke (1705) wrote in 1668 that earthquakes seem "to be that which generates Hills, and Holes, Cliffs, and Caverns, and all manner of Asperity and irregularity in the Surface of the Earth."

To De Luc (1811, pp.409-410) caves were caused by "catastrophes of the strata". They resulted "from the greater susbsidence of some of the lower masses of the strata, divided by fractures, and not followed by the masses above, the latter being supported on the sides, and forming the roofs of the caverns".

Virlet (1834) maintained that caves were the spaces formed between the beds of rock during folding, somewhat the same as the spaces that can arise if the leaves of a book are made to buckle by pushing the edges inwards. Farey (1811, *1*, 292), rather than depending on earthquakes or subsidences, believed that caves resulted from "the great degree of shrinking which this ... limestone seems to have undergone".

Drains for the Flood

Leibniz started from the basis that the biblical Flood was indeed just a flood of water over the present earth and did not involve wholesale destruction of the earlier rocks; he believed though that the water drained away afterwards into the "Abyss", a subterranean reservoir stretching beneath the surface of the whole world. Shortly before 1691 he wrote "of a great flood whose waters, at the end of it, found their way to the interior of the earth by narrow fissures and cave passages". Hutchinson (1749, p.198), writing before 1738, explained that the water of the Flood drained partly through holes in the bottom of the sea and partly through "Fissures, Swallows, and Cracks in the Strata", thus enlarging them into caves by erosion.

Alexander Catcott (1761), who was familiar with the Mendip area, restated more explicitly Hutchinson's ideas on the origin of swallow holes and caves. As evidence in favour of this theory, he repeated the commonly accepted statement that Eldon Hole was supposed to have been plumbed to 808m without touching bottom, with the last 73m through water, implying that it connected with the "Abyss". He also argued that swallow holes could not have been formed by river water, as many of them were on the tops of hills. Noting that many of the pebbles found in caves were not of local origin he thought that they could only have been brought there by the waters of the Flood. His writings did, however, make the case for caves having been formed by the action of water – clearly argued and published before Esper's far-fetched explanations of 1774.

Gas Bubbles in new Limestone

Esper (1774, p.104) introduced the novel theory that caves were formed by the decomposition gases from the rotting bodies whose bones now remain in many caves. The carcases, he supposed, were deposited at the same time as the new rock during the biblical Flood. This was consistent with then current ideas that the Flood involved a tumultuous solution or suspension of previous rocks which only gradually settled to form present-day rocks. The gases from the animal bodies pressed the cave walls outwards wherever they were not yet hard enough to resist.

Penn (1825, p.345), writing in 1823, developed this theory in more detail. The continually increasing gas would force its way upwards until a vent was made to the surface. Small caves resulted from this vent occurring at an early stage in their formation; if the gas were retained for longer the caves became more lofty.

Erosion of Soft Limestone

Esper (1774, p.106) put forward also an alternative theory of cave formation which he himself did not favour. While the new rock was still soft and covered with the waters of the Flood, any fissuring of its surface would admit water into it. If this fissuring penetrated right through the new rock to the "Abyss" beneath, the fissures would serve as passages for the water draining away and, the rock being soft, would be enlarged by erosion. This is a soft-rock variant of Leibniz's theory above.

John Hutton (1780, p.39) and Eaton (1820, pp.230-231) presented a more down-to-earth version of the theory which did not depend on the biblical Flood. They maintained that cave passages were formed by underground streams acting in fissures while the limestone was still new enough to be soft.

Erosion

Theories of speleogenesis by erosion can be divided into two sorts. From the 16th to the early 19th century they existed alongside the tectonic theory: Faventies and Buffon were opposed to the tectonic explanation while Virlet regarded erosion as complementary to it. In the second half of the 19th century erosion was considered alongside solution theory, either as complementary to it (Bischof and Martel) or in opposition (Flamache).

Faventies (1561) spoke of "tremendous caves ... It is quite certain that all this is mainly the work of water". He did not make it clear whether he was thinking of cataclysmic floods or normal underground streams. Buffon (1749, p.546) wrote that "caves from which issue strong springs or rivers, have been formed

INTRODUCTION

The history of speleology extends right up to the present and indeed a large amount of historically significant work has been done and is still being done in the twentieth century. Nevertheless, this paper stops at 1900, with few exceptions, because by then the general approach to the subject was modern. In particular, by that time:

a) scientific outlook was no longer subject to external constraints from theology, etc.
b) many of the present day speleological theories had already been expressed, though sometimes only briefly.
c) the organization of speleology was modern, in that:
   i) societies existed, which could undertake more extensive explorations than had been possible previously,
   ii) several periodicals were devoted solely to publishing the results of cave research.

CAVE EXPLORATION

As early as 852 BC the Assyrian king Salamanazar III visited the sources of the Tigris and ordered exploration of the caves there. Classical Greek and Latin writers paid much attention to the courses of underground rivers, particularly the Timavo near Trieste and those of the Peloponnese, and Aristotle (4th cent. BC) described a stalactite cave in the island of Demonesus near Istanbul. Caves were also well known to the ancient Chinese and powdered stalactite is listed among their drugs in the 4th and 1st centuries BC.

Many mediaeval visits are known only from inscriptions on cave walls (e.g. 1213, 1323, etc. in Postojna) but about 1135 Henry of Huntingdon mentioned caves in Mendip and Derbyshire. Faber wrote a manuscript description of the Sirgensteinhöhle and Sontheimhöhle (Germany) some time between 1470 and 1502 (Binder, 1963, p.140) and Strein's detailed report of 1591 (reprinted in Schmidl, 1857, p.199-213) described his exploration of caves in Austria.

Sturmy (1678) explored the vertical Pen Park Hole near Bristol in 1669 and Beaumont (1681) was lowered down the 20 metre pitch in Lamb [Leer] in 1676 or before, Magni (1692, p.132-152) described the first recorded exploration of the Antiparos Cave, in the Greek Islands, in 1673. Many other explorations were made in the 17th and early 18th centuries, but in most cases they were the outcome of individual curiosity rather than systematic studies. Important exceptions to this were the regional investigations carried out by the three men who may be called the first real speleologists. Valvasor (1689) explored caves in northern Yugoslavia over a period of at least ten years and published lengthy descriptions of them together with an account of the underground drainage of the area. Von Steinberg (1758) studied the hydrology of the same area for 40 years from 1718 and published a complete book on it. Nagel made a series of journeys, through Austria, Yugoslavia and Moravia in 1747 and 1748, solely to explore caves; his MS report, with plans, has been largely printed by Schmidl (1857, pp.213-215) and Salzer (1936).

In 1839-1841 a need to provide Trieste with a larger water supply led to a series of important explorations by Lindner and Svetina. Unable to follow the Timavo far where it sinks at Skocjanska Jama, they tried to locate its underground course by exploring the deep potholes of the area. Thus they descended Padriciano (271m) in 1839, and in 1841 Lindner reached the river at a depth of 327m in the Grotta di Trebiciano.

Schmidl was probably the most notable cave explorer before Martel. He worked in the Postojna complex of caves and in Skocjanska Jama from 1849 to 1856, and his discoveries increased the length of the Postojna cave itself to 7km. The Ötscherhöhle (Austria) was surveyed by him and in 1856 he studied the cave of Aggtelek (Hungary) which, at 8.7km, remained the longest in Europe until 1893.

In England a number of significant 19th century explorations were made in Yorkshire. Metcalfe and Birkbeck explored Alum Pot (89m deep) in 1847, and one or both of them descended Gaping Gill (104m), partly or completely, between 1842 and 1850.

Work in Yugoslavia commenced again in the 1880s when several groups of explorers formed themselves into the first speleological societies. Thus the Verein für Höhlenkunde was founded in 1879 at Vienna by Kraus; in 1883 the cave section of the Società degli Alpenisti Triestini and the coastal section of the Deutschen und Österreichischen Alpenverein were formed at Trieste. Some ten cave groups existed before 1900; their formation not only facilitated more difficult explorations, but their publications made their findings more accessible. Between 1886 and 1889 Putick explored more than 100 caves in a government-sponsored study to reduce flooding in part of Yugoslavia.

Martel (active 1888-1914) started his serious cave work when he was 29, publishing surveys of all he explored. Most of his original explorations took place in the course of 26 annual 'campagnes', in 18 countries. Even by 1894 he had visited 230 caves, of which 90 of the potholes had never been descended before and 75 of the others had not been fully explored. Martel is notable also for his progress in the scientific aspects of cave study, and is particularly important as the virtual founder of international speleology. Not only was he a sound speleologist but also publicist and traveller whose enthusiasm spread further by his personal visits and voluminous writings in several languages.

SPELEOGENESIS

Tectonic Causes

The earliest and simplest explanation for the origin of caves was that they were caused directly by cracking and fissuring of the rock. Descartes (1724, pp.369-372), writing in 1644, stated that quite big passages resulted from the disturbances associated with the formation of hills. Again, Hooke (1705) wrote in 1668 that earthquakes seem "to be that which generates Hills, and Holes, Cliffs, and Caverns, and all manner of Asperity and irregularity in the Surface of the Earth."

To De Luc (1811, pp.409-410) caves were caused by "catastrophes of the strata". They resulted "from the greater susbsidence of some of the lower masses of the strata, divided by fractures, and not followed by the masses above, the latter being supported on the sides, and forming the roofs of the caverns".

Virlet (1834) maintained that caves were the spaces formed between the beds of rock during folding, somewhat the same as the spaces that can arise if the leaves of a book are made to buckle by pushing the edges inwards. Farey (1811, *1*, 292), rather than depending on earthquakes or subsidences, believed that caves resulted from "the great degree of shrinking which this ... limestone seems to have undergone".

Drains for the Flood

Leibniz started from the basis that the biblical Flood was indeed just a flood of water over the present earth and did not involve wholesale destruction of the earlier rocks; he believed though that the water drained away afterwards into the "Abyss", a subterranean reservoir stretching beneath the surface of the whole world. Shortly before 1691 he wrote "of a great flood whose waters, at the end of it, found their way to the interior of the earth by narrow fissures and cave passages". Hutchinson (1749, p.198), writing before 1738, explained that the water of the Flood drained partly through holes in the bottom of the sea and partly through "Fissures, Swallows, and Cracks in the Strata", thus enlarging them into caves by erosion.

Alexander Catcott (1761), who was familiar with the Mendip area, restated more explicitly Hutchinson's ideas on the origin of swallow holes and caves. As evidence in favour of this theory, he repeated the commonly accepted statement that Eldon Hole was supposed to have been plumbed to 808m without touching bottom, with the last 73m through water, implying that it connected with the "Abyss". He also argued that swallow holes could not have been formed by river water, as many of them were on the tops of hills. Noting that many of the pebbles found in caves were not of local origin he thought that they could only have been brought there by the waters of the Flood. His writings did, however, make the case for caves having been formed by the action of water – clearly argued and published before Esper's far-fetched explanations of 1774.

Gas Bubbles in new Limestone

Esper (1774, p.104) introduced the novel theory that caves were formed by the decomposition gases from the rotting bodies whose bones now remain in many caves. The carcases, he supposed, were deposited at the same time as the new rock during the biblical Flood. This was consistent with then current ideas that the Flood involved a tumultuous solution or suspension of previous rocks which only gradually settled to form present-day rocks. The gases from the animal bodies pressed the cave walls outwards wherever they were not yet hard enough to resist.

Penn (1825, p.345), writing in 1823, developed this theory in more detail. The continually increasing gas would force its way upwards until a vent was made to the surface. Small caves resulted from this vent occurring at an early stage in their formation; if the gas were retained for longer the caves became more lofty.

Erosion of Soft Limestone

Esper (1774, p.106) put forward also an alternative theory of cave formation which he himself did not favour. While the new rock was still soft and covered with the waters of the Flood, any fissuring of its surface would admit water into it. If this fissuring penetrated right through the new rock to the "Abyss" beneath, the fissures would serve as passages for the water draining away and, the rock being soft, would be enlarged by erosion. This is a soft-rock variant of Leibniz's theory above.

John Hutton (1780, p.39) and Eaton (1820, pp.230-231) presented a more down-to-earth version of the theory which did not depend on the biblical Flood. They maintained that cave passages were formed by underground streams acting in fissures while the limestone was still new enough to be soft.

Erosion

Theories of speleogenesis by erosion can be divided into two sorts. From the 16th to the early 19th century they existed alongside the tectonic theory: Faventies and Buffon were opposed to the tectonic explanation while Virlet regarded erosion as complementary to it. In the second half of the 19th century erosion was considered alongside solution theory, either as complementary to it (Bischof and Martel) or in opposition (Flamache).

Faventies (1561) spoke of "tremendous caves ... It is quite certain that all this is mainly the work of water". He did not make it clear whether he was thinking of cataclysmic floods or normal underground streams. Buffon (1749, p.546) wrote that "caves from which issue strong springs or rivers, have been formed and shaped by water carrying sand and silt ... and it would be wrong to attribute the origin of these caves to subsidences and earthquakes". When Virlet (1835) visited the Grotte d'Osselles (France) he saw what would now be recognised as joints modified by the action of water. To him these were "dislocations" that had determined the passages and there were traces of erosion where they had acted as water channels; he noted the "quite deep marks of erosion along the walls, indicating different water levels".

Bischof (1847-51, *1,* p.26) and Martel believed that the erosive action of water was important but that it was consistent with solution occurring also. Flamache (1896), however, objected to the solution theory because he maintained the water would be saturated with calcium carbonate everywhere except close to the surface. Thus he was forced to favour erosion. He was in some difficulty here, for he accepted that there must have been a preliminary stage before the cave passages were large enough to carry streams. He argued that, until one of the passages was large enough to take all the normal flow, there would be a network of passages, initiated by erosion from water forced through them by the difference in height between the inlet of the water and its exit.

Solution by Juvenile Water

The earliest proponents of the solution theory recognised that only solution could explain the configuration of some caves, but they did not realise that ordinary rain water possessed the power of dissolving limestone.

Thus Aubuisson de Voisins (1819, *2,* p.383): "the main cause of their formation seems to be the solution of the minerals which originally occupied the places that are now empty cavities; these places, perhaps of gypsum or marl or even salt, will have been dissolved or diluted by the water and carried away by it. It is even possible that water containing original acid, such as occurs in the interior of the earth, has acted on the limestone itself and carried it off in its underground circulation: the shape of the cave walls and the rounded contours of projecting parts all agree in showing the effects of solution".

Parandier (1833) maintained that caves were dissolved by specially corrosive water which was hotter and more dense and contained more carbon dioxide than it does today. The fissures in which the water acted had been produced previously by earth movements. Parandier's theories were copied almost entire by De Serres (1836), without acknowledgement.

Dupont (1894, pp.204-5) excavated caves in Belgium from 1864 to 1872. He saw clearly that the caves had been formed by solution by carbonic acid, but up to about 1880 he supposed that this aggressive water was of mineral origin. His later ideas are treated below.

Solution by Vadose Water

Buckland (1836), in a paper read the previous year, noted that "the interior of caverns usually presents an irregular carious surface, similar to that which is produced on a mass of limestone submitted to the action of an acid." This acid, he supposed at that time, was a carbonic acid vapour or solution of juvenile origin. But by 1839 (Buckland, 1840) he considered that the carbonic acid contained in rainwater produced similar effects in corroding cavities on the surface of chalk. He never explicitly stated, however, that rainwater was sufficient to dissolve limestone.

Bischof (1847-51, *1,* pp.25-26) noted the amount of calcium carbonate carried off in rivers from limestone areas. Cracks and fissures were produced in the rock by contraction as it dried and it was through these that there flowed the rainwater containing carbon dioxide which hollowed out caves by solution, aided to some extent by erosion. Phillips (1853) was among those who followed Bischof.

Martel is commonly thought to be a strong advocate of speleogenesis by erosion. He was, but he held also that solution played an equally important part. Even when he referred (Martel, 1897, p.350, 355) to Gaping Gill as "an abyss formed by erosion" he went on "it is certain that, as much by corrosion as erosion, the water has excavated the cave", and this insistence on the dual role of solution and erosion persisted throughout his writings. He specifically (Martel, 1896, p.31) referred to scalloping as characteristic of the effects of corrosion — "the turbulent appearance of the walls, cupped with shallow cavities close together". Avens in cave roofs he also attributed to turbulence, "being formed by the spiral action of torrents" (Launay & Martel, 1891, p.148). Martel insisted that all this action occurred with trickling water and the water of underground streams. He was adamant that there was no water table but only discrete stream channels.

Solution by Phreatic Water

Dupont (in Willems, 1894, p.376), after asserting that caves resulted from solution by water containing carbon dioxide, pointed out that this could occur either in the ground water zone or above. "The deep circulation collects into a series of channels which come to the surface as risings. Water that descends below the level of the valley bottoms fills the spaces (fissures, fractures, faults, etc) existing in it and constitutes a reserve of underground water." In arguing that many cave passages were formed entirely by solution he gave diagrams of passage cross-sections which showed clearly that they were completely filled with water at the time of their formation (fig. 1). Mechanical erosion could not form cave passages but could modify their shape in cases where the passage contained a running stream at some stage. Dupont (1894, p.209) described scalloping as small bowl-like cavities in cave walls, the result of "chemical action aided by the movement of little waves" in passages containing streams; he contrasted it with the large and irregular cavities dissolved by still water.

A violent controversy ensued between Dupont and Flamache who, with his followers, thought that cave formation was a purely mechanical action. An indication of the interest taken in speleogenesis in Belgium in the 1890s is given by the fact that the Bulletin de la Société Belge de Géologie contains twelve papers totalling 397 pages on the subject in that decade, in addition to more general papers on limestone hydrology and cave exploration.

Barnes and Holroyd (1896, pp.229-230) argued, like Dupont, that cave passages were formed by solution in ground water. Over the turn of the century (from 1893 to 1918) Cvijić and Grund published several major papers on speleogenesis by solution in fissures, largely at or beneath the water table.

SPELEOTHEMS

Vegetative Growth hypothesis

The hypothesis of vegetative growth although not the earliest, stands on its own and does not form part of any developing sequence of concepts as do most of the others. Beaumont (1676), who considered that fossil shells had grown in the rock where they were found, believed that stalagmites grew like plants: "those Stone-plants have true life and growth"; "these are shap'd like them [plants], having inward pith or sap, and likewise joynts, ... and sometimes cells, which may very well supply the place of veins and fibres."

The distinguished French botanist Tournefort (1741, *1*, pp.203-4) visited the Antiparos cave in August 1700. He too believed that stalagmites and stalactites were plants, and noticed the concentric circles resembling tree rings in their structure. Also, the caves were dry so " 'tis impossible this should be done by the Droppings of Water, as is pretended by those who go about to explain the Formation of Congelations in Grottos. It is much more probable, that these ... Congelations ... were produced by our Principle, namely, Vegetation."

This theory still had its supporters as late as 1775 when the Abbé Passeri, describing stalactites in a cave in Monte Cucco, maintained that they were not a deposit from water, but drew their nourishment from the rock itself and grew as plants do, from some hidden seed.

By Solidification of Water

The Earliest and simplest explanation of stalactite formations was that they resulted directly from the solidification of water. So thought Aristotle in the 4th century BC and also Pliny; Avicenna, writing about 1022 AD, and Albertus Magnus (1967, p.15) between 1254 and 1262, held the same views.

After the Renaissance, individual thought began to produce alternative explanations. Palissy, although he spoke of the congelation of water, explained that a salt was deposited by it; but the earlier theory still persisted in places, or perhaps was repeated uncritically. Borrichius (1680), however, did think about the subject, and explained the solidification as occurring thus: "the continuous stillness of the particles of water collected in places where they are not subject to any disturbance at all from the outside air" causes them to "readily bind together because of their homogeneity".

From Vapours

In the 17th and 18th centuries several writers believed that the water which formed stalactites came, not from percolation through the rock, but from condensation of vapours. Thus Jacob (1652), in a poem describing Wookey Hole, wrote in 1632:

> "Chill exhalations reeking up,
> Reverberated into dew a top,
> Habituated to this rock-pend Ayre,
> Steale an unthawing hardness ..."

Beaumont (1676) gave, as possible alternatives to his vegetative theory, formation "from Steams coagulating either Dew ... or Waters issuing from the joynts of Rocks underground".

Hill (1748, pp.369-70) noticed stalactites formed under brick arches; they seemed to him to hang not from the mortar but from the bricks and, besides, microscopic examination misled him into thinking they contained material not present in mortar. He explained both these stalactites and those in caves as follows: "Spar ... is capable of being raised with Water in vapours. That it continually is thus raised in the Earth, is unquestionable; and such vapour, so loaded with Spar, ascending up, and at length concreted into drops ... easily deserted the Spar they had before brought up in form of vapour".

The origin of these "vapours" is not made clear, but it seems to be the normal humidity found in caves. De Clave (1635, pp.476-82), however, had believed that the vapours rise from "cavities near the region of the central fire" carrying up with them "the suitable nourishment" for the growth of stalactites, "that is to say one of very small particles ... so subtle as to be almost imperceptible". His idea of these rising "steams" or vapours is consistent with a contemporary theory which explains the origin of springs by the condensation of such vapours (e.g. Agricola, Kircher, etc.).

Deposit from Suspension or Solution in Water

The writers mentioned in this section did not take account and were probably not aware of the presence of dissolved carbon dioxide in water.

Palissy (1564) saw stalactites in a cave near Tours and explained them thus: "The rainwater which passes through the ground above the rock picks up some kind of salt which causes the formation of these stones". Ray (1692, p.76) wrote of the water precipitating "stony particles". The word particles, as used

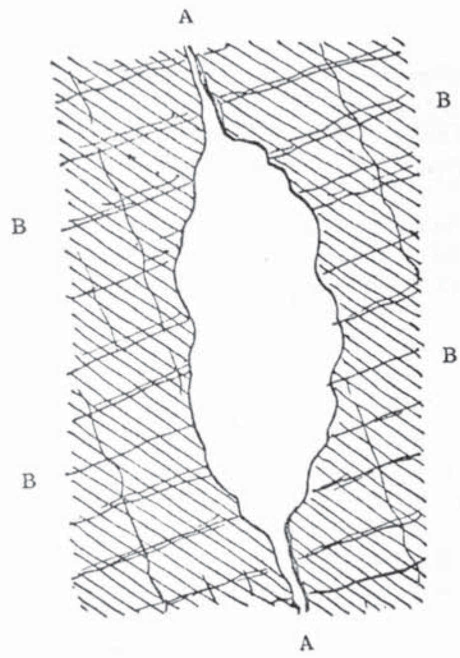


Fig. 1. Diagram by Dupont (in Willems,1894) showing cross-section of joint-determined cave passage formed by solution when entirely water-filled.

Fig. 2. Speleothems illustrated in a Chinese book of 1596, the Pên Tshao Kang Mu by Li Shih-Chen

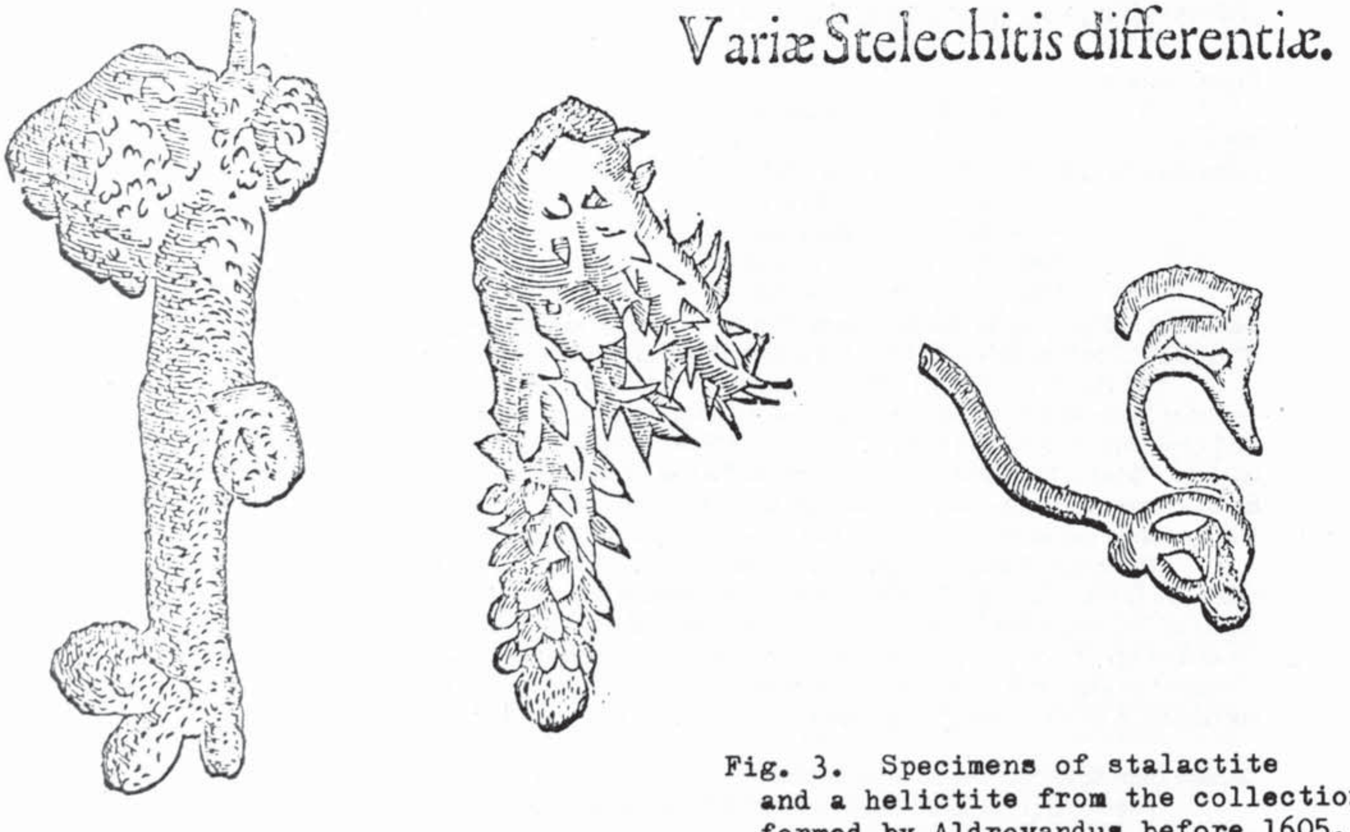


Fig. 3. Specimens of stalactite and a helictite from the collection formed by Aldrovandus before 1605. (from Aldrovandus,1648)

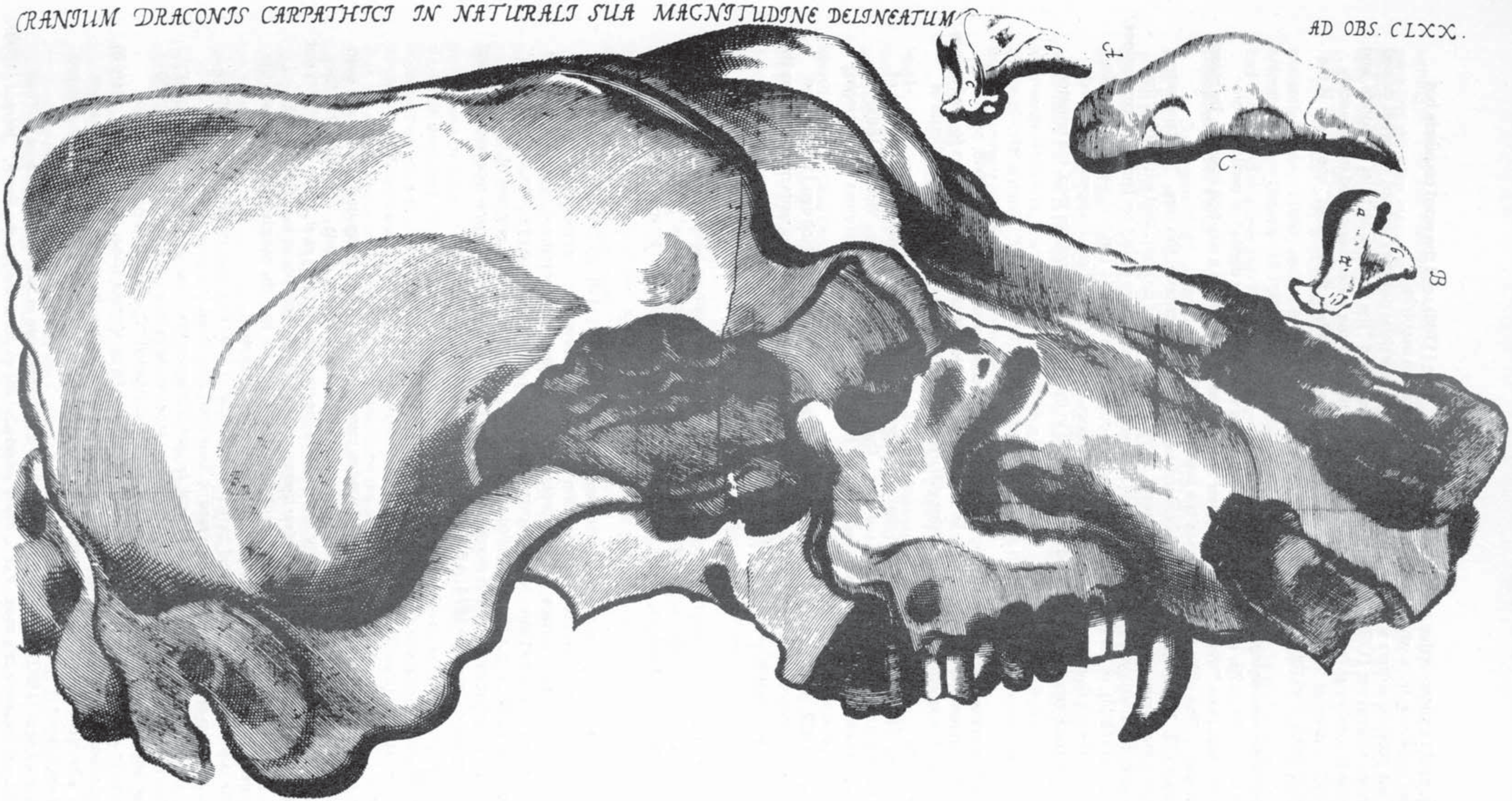


Fig. 4. A 'dragon' skull from a cave in Czechoslovakia, published by Vollgnad in 1676; in fact it is a bear skull.

at that time, might indicate either a suspension or a solution. King (1768) used the word corpuscle but clearly meant a solution from which he talked about crystallization occurring.

These previous writers spoke of the water depositing its particles but they did not say what caused this deposition. Whitehurst (1786, pp.30-31) for the first time stated "the aqueous particles evaporate, and leave the mineral substances to unite according to their affinities." If the water evaporated more quickly than it exuded, crystals or spar were formed; if it evaporated nearly as fast, then "tubes" appeared; if the flow was much faster than the evaporation, then stalactites occurred.

Deposit from Water containing Carbon Dioxide

Kirwan (1784, p.25) supposed that many stalactites were formed by deposit of particles from suspension, but also some "transparent spars appear to have been formed from a solution in water, by means of the aerial acid." This is the first mention of the present day theory.

Cuvier (1812, *1*, p.21) was more explicit and explained all stalactites in this way. "Certain waters, after depositing the calcareous substances, by means of the superabundant carbonic acid with which they are impregnated, become crystallized when the acid has evaporated, and form stalactites and other concretions."

Williams (1834), in his unpublished manuscript notebook, wrote: "It [calcite] varies in quantity and quality in different Caves, being less coherent & compact in some than others, it appears to depend materially on the quantity of carbonic acid gas, contained in the water that percolates thro' the limestone rocks."

Helictites

The first known picture and description of a helictite occurred in Aldrovandus (1648, pp.502-3) (see fig. 3). This shows one of the specimens in the mineral collection of Ulysses Aldrovandus formed before he died in 1605. It is labelled "Variae Stelechitis differentiae" and shows a rather complex helictite of constant thickness.

Bournon (1808, *1*, pp.170-1) stated that protuberances and branches from the sides and end of stalactites resulted from blocking of the central tube. They were made of aragonite. Wallace (1865) suggested that "the fluids may circulate in the pores [of helictites] by capillary attraction" thus bringing the water to the point where growth is continuing.

Hovey (1882, p.186) was the first to use the term helictite. Barnes and Holroyd (1896) called them Anemolites: according to them "They arise from the presence of changing currents of air blowing the water to one side or upwards", an idea put forward earlier by Brezina (1890).

Mondmilch

Agricola (1546) was the first to describe mondmilch, but the example he saw was evidently in a quarry not a cave. Gesner (1555, p.66), who introduced the term "lac lunae", found it in a Swiss cave and considered it to be a sort of fungus. It was Lang (1705) who first recognised its calcareous nature.

Cave Pearls

The earliest description of cave pearls seems to be that by Hill (1748, pp.370-1) who called them White Stalagmodiaugium. They are "found in form of a perfectly round ball ... sometimes in clusters ... [with a] perfectly smooth ... surface ... When broken, they are found to be composed of a vast number of [concentric] crusts, ... [:sometimes] a small Sparry nodule, of a coarser kind, may be seen, as the nucleus".

Bournon (1808, *1*, p.175), who called them pisolites, explained that the evenness of the deposit was due to their constant agitation and movement while forming. This explanation was repeated by several others including Boyd Dawkins (1874, p.66) who introduced the term "Cave-Pearl".

BONE CAVES

Dragons, etc.

In the 16th and 17th centuries bones found in caves were not always recognised as such and, even when they were, they were often assumed to be those of dragons, unicorns or giants. The belief that they belonged to giants or unicorns was evidently held only by the peasants (Sennert et al, 1632, pp.370-71) but the expression "fossil unicorn's horn" was nevertheless widely used for cave bones (e.g. Gesner, 1551, pp.781-6). For a long time they were used medicinally and it is likely that the search for them caused the caves to be more thoroughly explored or even new ones to be discovered.

The skeleton of a dragon was said to have been found in 1602 in a cave on Mount Pilatus in Switzerland, and live dragons were also supposed to have been seen about this time (Kircher, 1665, *2*, pp.89-97). Hain (1673) described remains of what he called dragons from two caves in central Europe; his illustration shows teeth and bones which are clearly recognisable as those of a bear. Vollgnad (1676) published an engraving sent him by Hain showing a skull and labelled "Cranium Draconis Carpathici" (fig. 4); this too is identifiable as bear. A map published in 1678 by Vischer (Abel & Kyrle, 1931, plate 6) marks the location of the Drachenloch in Austria as "cave two miles long from which dragon bones are obtained". The dragon identification was continued as late as 1739 by Brückmann, who nevertheless had some misgivings about it.

Sennert *et al* (1632, pp.370-71) believed that fossil bones were in fact "mineral stones". Their shape should not "stumble any man. For ... many wonderful things are shaped in the Earth." Héréus (1898), writing in 1719, also concluded that these bones could not have come from animals because some of them were just shapeless masses at one end, quite unlike real bones. The specimens in question, which unfortunately he does not illustrate, may have been curiously shaped pieces of stalagmite; they may have been fossil bones with a mass of stalagmite at one end; or they may have been bones deformed by arthritis. Abel and Kyrle (1931, plates 104-113) show photographs of bear bones almost unrecognizably deformed by disease.

Concurrently with these various colourful interpretations, some writers understood the bones correctly. Gesner (1551, pp.781-6) and De Boodt (1609, p.209) attributed them to deer, elephant and other animals; and on October 24 1666 Moray reported to the Royal Society that "great bones and vast teeth" had been found in a cave near Plymouth. (Birch, 1756-57, *2*, p.117).

Deposited by the Flood

Conringius (1665, p.36) and also Leibniz (1859, pp.97-8) who wrote shortly before 1691, whilst they did not specifically mention the biblical Flood, were evidently thinking of it when they referred to animal bones being swept into caves by a great flood whose waters were retreating to the interior of the earth by way of the caves. Esper (1774) also attributed the presence of bones to the Flood, although by a different mechanism, (see p.3).

Buckland (1822, pp.204-7, 215), although a believer in the Flood, did not argue that it was responsible for the presence of the bones in the caves he had studied, but only for covering them with mud afterwards. However, it is possible, he wrote, that in some other caves animals might "have been washed in by the diluvial waters". Young (1828, pp.302-5) disagreed with Buckland and believed that some of the drowned animals floating about at this time drifted into caves.

Animal Dens

This theory, sometimes called the hyaena den theory of Buckland, was in fact originated by Hunter (1794) who said that the animal bones in the Gailenreuth Cave had accumulated through its being occupied by wild beasts during "many thousand years". Cuvier (1812, *4*, iv (i) pp.12-13) also believed this, and Buckland (1822) argued the case in more detail.

Stratification in Cave Deposits

Recognition of the importance of stratification in cave deposits was delayed by Buckland's influence. As he had explained the mud in bone caves as having been washed in after the animal remains by the waters of the Flood, there could be no question of successive layers. The whole contents of a cave and indeed of different caves were therefore commonly regarded as similar and were excavated for specimens without recognising the need to record their position.

However, De la Beche (1835, p.183) wrote "When an observer discovers bones in a cavern ... He must be careful to mark whether different kinds of bones or teeth occur in particular beds, or are all mingled together". When the Brixham Cavern was excavated in 1858-1859 to resolve once and for all the crucial question of the antiquity of man, the deposits were excavated successively, bed by bed, in order to obviate any risk of mislocating specimens.

The Antiquity of Man

One of the most violent controversies of the 19th century with which caves were associated was over the question of whether or not man was contemporary with extinct animals. Horst (1654, p.10) stated that a human skull was dug up among the animal bones in a cave in the Harz mountains, but he did not comment on its age. The first detailed record of human bones being found associated with those of extinct animals was by Esper (1774, p.26) who found them together with cave bear bones in Gailenreuth in 1771. He considered carefully whether or not they were contemporary but considered that he had insufficient evidence for such a momentous interpretation. "... I do not, however, suppose without adequate reason that these human remains are of the same age as the other animal petrifactions. They must have come together with the others by chance." This extract is taken from the original German version of Esper's book; a French translation of it was published in the same year, in which the sense of this sentence is reversed, and this has led some modern commentators into error.

In 1790 Frere (1800) made his famous discovery, though not in a cave, of flint tools beneath a deposit containing prehistoric animal bones and which seemed to him to belong "to a very remote period indeed; even beyond that of the present world". This was followed at intervals by several finds of flints and human remains alongside the bones of extinct animals in caves. In many cases they were interpreted by their finders as contemporaneous but this was not generally accepted for many years.

Jouannet, in 1815 or 1816 (Cheynier, 1936, pp.27-28) found worked flints together with fossil animal bones in the Grottes de la Combe Grenant (Dordogne). He realised the significance of this association and drew attention to it but he did not himself express a definite opinion either way.

MacEnery excavated in Kent's Cavern from 1825 to 1829 and left a detailed manuscript account of his work there which has since been published (Pengelly, 1869). He found worked flints and bones of extinct animals together in the same bed and he thought about the significance of this long and hard. His considered opinion was that man occupied the cave shortly after the Flood that had brought in the mud surrounding the animal bones, and that the flints sank down into this mud. It has been argued (e.g. Daniel, 1950, p.35) that this is not his considered opinion at all but a recantation due to deference to Buckland and to his own religious beliefs and position, and many modern commentators have credited MacEnery with having realised the correct interpretation. This appears, however, to be unjustified (see also Pengelly, 1881, p.391, and Gruber, 1965).

Tournal in 1827 and 1828 found worked flints and human remains together with animal bones in the Grotte de Bize (Aude). The human bones were in just the same condition as those of the animals and in 1829 he announced that he had found some of the extinct animal bones bearing marks of cutting tools (Daniel, 1950, p.34).

Schmerling (1833-34) excavated several caves near Liége between 1829 and 1833. He found human bones and artefacts associated with skeletons of rhinoceros and mammoth. "There can be no doubt, that the human bones were buried at the same time and by the same cause as the other extinct species". His findings, however, were not considered seriously by his contemporaries.

The opposition to the case for the antiquity of man was argued partly from biblical authority but mainly on the ground that the remains might have become mixed together at some time after their original deposition, either by a subsequent flood or by the hand of man. That the opposition was so long-lasting was due to the authority of its supporters. Cuvier expressly denied the existence of early fossilised man. Buckland, even as late as 1836, argued that the presence of human bones among those of primitive animals could be explained by human burials in pits. Lyell (1832, *2,* pp.225-7) considered the questions carefully but concluded that the co-existence of man and extinct animals could only be proven if they were found together in stratified deposits. By 1833, however, he was wavering (Lyell, 1881, *1,* pp.401-2) having seen Schmerling's specimens which he said were found "under circumstances far more difficult to get over than any I have previously heard of."

Lyell, however, like others, was ultimately convinced by the results of the careful excavations in 1858-1859 in the newly discovered Windmill Hill Cavern, Brixham, sponsored by the Geological Society and carried out under the superintendence of Pengelly, Further confirmation was provided by the Kent's Cavern excavations which continued from 1865 to 1880.

Cave Art

Cave art was first recognised as prehistoric on pieces of carved bone. The first discovery was made in 1813 by F. Mayor who found a length of staghorn engraved with a design of birds in the Grotte de Veyrier in Haute-Savoie. Subsequent discoveries were made by Brouillet in the Grotte de Chaffaud between 1834 and 1845. It was Lartet (1861) who first recognised the significance and true antiquity of these finds and he himself made many other such discoveries.

Prehistoric wall paintings were seen in two caves before their significance was realised. De Belleforest (1575, p.198) wrote of "paintings in several places, and the traces or marks of large and small animals", in the Grotte de Rouffignac. About 1864 Garrigou saw some of the paintings in the Grotte de Niaux and wrote in his notebook "There are drawings on the wall; whatever can they be?" (Molard, 1908, p.185).

In 1878 Chiron discovered incised figures on the walls of the Grotte Chabot (Gard) and had them photographed, but his find aroused no interest. In 1879 Sautuola found the famous paintings in Altamira and claimed that they were of Palaeolithic age; this he argued on the basis of similarities between them and the decorated bone objects that were known to be prehistoric. A more conclusive proof of the antiquity of drawings on cave walls was obtained in 1895, when those in the Grotte de la Mouthe were revealed only when deposits of Palaeolithic age were removed. The great antiquity of cave art was still not widely accepted until 1902, when Cartailhac was converted from his previous scepticism.

FAUNA

An isolated but very early report of cave fauna was made by Trissino (1550) who, in a letter dated 5th March 1537, recorded what must have been a form of *Niphargus.* He noted that at the far end of the Covolo di Costozza in northern Italy there was a deep pool of clear water. "In this water no fish of any kind are found, except for some tiny shrimp-like creatures similar to the marine shrimps that are sold in Venice."

Apart from this, the first recorded observations of cave fauna were made in the 17th century but were limited to the larger creatures. When the intermittent lake of Cerknica in Yugoslavia filled with water each year, fish appeared in it from the caves below (Kircher, 1665, *1,* p.237). *Proteus,* the blind amphibian, was recorded by Valvasor (1689, *1,* p.597) and Von Löwengreif found the first underground specimen in Magdalena Jama in 1797 (Fitzinger, 1850, p.294).

In 1808 Schreibers discovered the first specimen of invertebrate cave fauna in Austria. More extensive collecting was done in the Postojna area by Hochenwart and others from 1831 onwards. It was there too that the earliest classifications of cave fauna according to habitat were proposed. Schiödte (1851, p.154) divided it into shade-animals, twilight-animals, animals of the dark zone, and animals living on stalactites. The classification into troglobites, troglophiles and "occasional cavernicoles" generally accepted now, was put forward by Schiner (1854, pp.239-40).

In the United States, important work continued intermittently from 1840. In that year the blind white fish of Mammoth Cave were first recorded by Davidson (1840, pp.54-5). Tellkampf (1844) described crustacea and other fauna from the Mammoth Cave and was followed by Cope, Packard and others between 1867 and 1880. Cope (1872, pp.417-8) worked out a food cycle for cave fauna.

Perhaps because of it relative scarcity, little knowledge was obtained about British cave fauna in the 19th century. Wright (1858) collected in the Mitchelstown Cave in 1857 and Carpenter and Jameson worked there between 1894 and 1897. Carpenter (1895) is notable for his early observation that some species ingest clay particles for nutrition.

In France the first cave fauna was found in 1857 by De la Rouzée and later work culminated in Bedel and Simon (1875) publishing a catalogue of all the species then known. Viré (1899) set up an underground laboratory in the catacombs of Paris so that he could experiment on the effects of light etc. on the evolution of cave species.

Modern biospeleology began with Racovitza, whose important essay (1907) reviewed the state of knowledge and discussed the main unsolved problems. With Jeannel, he founded the journal *Biospeologica* in 1907.

Cave fauna provided much evidence for the theory of evolution. Darwin (1859, p.138) argued that cave species were not separate creations but evolved from surface animals by modifications, from the effects of disease on some organs and the development of others by natural selection. Cope (1872) and Packard (1888) supported this with a mass of much more detailed evidence and Garman (1892) pointed out that potential cave species were already partially adapted to darkness as a result of their life under vegetation or stones.

Putnam (1872, pp.27-9) did not believe that the blindness and tactile acuteness of cave crustacea was the result of adaptation of surface species. It was more likely, he thought, that cave species consisted of those which survived a change from salt water, via brackish to fresh water life.

CAVE FLORA

The earliest reference to subterranean plants seems to be that of Lister (1674) who described a fungus growing some 14m underground in a Derbyshire lead mine.

Scopoli (1772) made the first serious study of vegetation underground, describing 75 species of fungi from caves and mines in northern Yugoslavia. Humboldt (1793) found green plants growing in the mines at Freiberg; he experimented on the influence of light on plant life and produced a large catalogue of underground algae and fungi. Welwitsch in 1836 and Pokorny in 1854 collected fungi in the Postojna cave.

An extensive study was carried out by Maheu (1906). He pointed out that heredity was not possible in cave flora except for certain fungi; although an individual plant might survive and even spread underground, retaining any modification it had developed, it did not normally fruit underground and so could not transmit these modifications.

October 1973.

Cdr. T. R. Shaw, R.N.,
Gateways,
11 Bewley Lane,
Lacock,
Wiltshire.

REFERENCES

Abel, O. & Kyrle, G. (1931) Die Drachenhöhle bei Mixnitz; Vienna [Speläologische Monographien, *7-9*]

Agricola, G. (1546) De Natura Fossilium; Basle

Albertus Magnus (1967) Book of Minerals; trans. D. Wyckoff; Clarendon Press

Aldrovandus, U. (1648) Mvsaevm Metallicvm; Bologna, B.Ferronius

Aubuisson de Voisins, J.F.d' (1819) Traité de Géognosie...; Strasbourg, F.G. Levrault

Barnes, J. & Holroyd, W.F. (1896) The Mountain Limestone Caverns of Tray Cliff Hill ...; Trans. Manchester Geol. Soc., *24,* (10): 215-252

Beaumont, J. (1676) Two Letters concerning Rock-Plants and their Growth. The Second Letter; Phil. Trans. Roy. Soc. *[11]* (129): 732-742

Bedel, L. & Simon, E. (1875) Liste générale des Articulés cavernicoles de l'Europe; Journal de Zoologie, *4*

Belleforest, F. de (1575) Cosmographie universelle de tout le monde; Paris, M. Sonnius

Binder, H. (1963) Die Anschauungen über die Zustehung unserer Höhlen im Wandel der Zeiten; Jahreshefte für Karst- und Höhlenkunde, *4:* 139-153

Birch, T. (1756-57) The History of the Royal Society of London ...; London

Bischof, C.G.C. (1847-51 [=1846-54]) Lehrbuch der chemischen und physikalischen Geologie; Bonn

Boodt, A.B. de (1609) Gemmarum et Lapidum Historia ...; Hanover

Borrichius, O. (1680) De Generatione lapidum in macro & microcosmo; p.184-196 *in* Bartholinus, T. (1680) Acta Medica et Philosophia Hafniensia, *5*

Bournon, J.L. de (1808) Traité de Minéralogie ...; London, W. Phillips

Brezina, A. (1890) Wie Wachsen die Steine?; Vortraege des Vereines zur Verbreitung naturwiss. Kenntnisse, Vienna, *30*

Brückmann, F.E. (1739) Sistens Antra Draconvm Liptoviensia; Epistola Itineraria 77 in Centuria Epistolarvm Itinerarivm; Wolfenbuttelae

Buckland, W. (1822) Account of an Assemblage of Fossil Teeth and Bones ... discovered in a cave at Kirkdale ...; Phil. Trans for 1822, pt. 1: 171-236

(1836) [On Certain Caves near Cork and Elsewhere (abstr.)]; Proc. Ashmolean Soc., Oxford, (9) for Nov. 1835: 6-8

(1840) On the Action of Acidulated Waters on the Surface of the Chalk near Gravesend [abstr.]; Rept. 9th Mtg. British Assoc. Adv. Sci. in 1839; Trans. of sections: 76-77

Buffon, G.L.L. de (1749) Théorie de la Terre; Histoire Naturelle ...; Paris, *1,* [63]-612

Carpenter, G.H. (1895) Animals found in Mitchelstown Cave; Irish Naturalist, *4*(2): 25-35

Catcott, A. (1761) A Treatise on the Deluge ...; London, M. Withers

Cheynier, A. (1936) Jouannet grand-père de la préhistoire; Brive

Choiseul-Gouffier, M.G.A.F. de (1782) Voyage pittoresque de la Grèce; Paris

Clave, E. de (1635) Paradoxes, or Traitez philosophiques des pierres et pierreries ...; Paris, Chevalier

Conringius, H. (1665) De Antiqvissime Statv Helmestadii et viciniae coniectvrae; Helmestad, H. Muller

Cope, E.D. (1872) On the Wyandotte Cave and its Fauna; Am. Naturalist, *6* (7): 406-22

Cuvier, G. [L] (1812) Recherches sur les Ossemens fossiles ...; Paris, Deterville

Daniel, G.E. (1950) A Hundred Years of Archaeology; London, Duckworth

Darwin, C. (1859) Of the Origin of Species by means of natural selection ...; London, J' Murray

Davidson, R. (1840) An Excursion to the Mammoth Cave ...; Lexington

Dawkins, W. Boyd (1874) Cave Hunting ...; London, Macmillan

De la Beche, H.T. (1835) How to Observe, Geology; London, C. Knight

Descartes, E. (1724) Les Principes de la Philosophie; Paris, G. Amaulry

Dupont, E. (1894) Les Phénomènes Généraux des Cavernes ...; Bull. Soc. Belge de Géologie ..., *7* for 1893, Mémoires: 190-297

Eaton, A. (1820) Index to the Geology of the Northern States; Troy (New York), W.S. Parker, 2nd edn (only)

Esper, J.F. (1774) Ausführliche Nachricht von neuendeckten Zoolithen ...; Nurnberg, G.W. Knorrs

Farey, J. (1811) General View of the Agriculture and Minerals of Derbyshire ...; London, *1*

Faventies, V. (1561) De Montium Origine; Venice, Academia Veneta; reprinted in Adams, F.D. (1938) The Birth and Development of the Geological Sciences: 348-57

Fitzinger, (1850) Über den Proteus anguinus; Sitz d. Kaiserlichen Akad. d. Wissenschaften. Math. - Naturwiss. Classe *5* (8): 291-303

Flamache, A. (1896) Sur la Formation des Grottes et des Vallées Souterraines; Bull. Soc. Belge de Géologie ..., *9* for 1895, Mémoires: 355-67

Frere, J. (1800) Account of Flint Weapons discovered at Hoxne in Suffolk (read 22 June 1797); Archaeologia, *13*: 204-205.

Garman, H. (1892) The Origin of the Cave Fauna of Kentucky ...; Science, N.Y., *20* (508): 240-241

Gesner, C. (1551) Historia Animalium, *1*, De Quadrupedis; Zurich, Froschoverum
(1555) Descriptio montis fracti, sive Montis Pilati ... juxta Lucernam in Helvetia; Zurich, A. & I' Gesner

Gruber, J.W. (1965) Brixham Cave and the Antiquity of Man; p.373-402 in Spiro, M.E. (ed.) (1965) Context and Meaning in Cultural Anthropology; New York, Free Press

Hain, J.P. (1673) De Draconum Carpathicorum Cavernis; Miscellanea Curiosa Medico-Physica Academiae Naturae Curiosum ..., Leipzig & Frankfurt, [Dec. I] Annus *3* for 1672: 314-317

Héréus, C.G. (1898) La Caverne de Ratelstein en Styrie; Spelunca, Bull. Société de Spéléologie, *4* (15): 98-106

Hill, J. (1748) A History of Fossils; London, T. Osborne

Hooke, R. (1705) The Posthumous Works; London; extract reprinted in Mather, K.F. & Mason, S.L. (1970) A Source Book in Geology 1400-1900; Harvard Univ. Press: 29

Horst, J.D. (1654) Observationum anatomicarum ...; Frankfurt

Humboldt, F.H.A. von (1793) Flora Fribergensis Specimen Plantas Cryptogamicas praesertim subterraneas exhibens; Berlin, H.A. Rottmann

Hunter, J. (1794) Observations on the Fossil Bones presented to the R[oyal] S[ociety] by ... the Margrave of Anspach; Phil. Trans. Roy. Soc. *84*: 407-417

H[utchinson], J. (1749) A Treatise on Mining *in* The Philosophical and Theological Works, *12*: [161]-258

[Hutton, J.] (1780) A Tour to the Caves, in the environs of Ingleborough and Settle ...; London & Kendal, Richardson & Urquhart

Jacob, H. (1652) Ookey-Hole, neere Wells in Somerset-shire, described at large A.1632; p.48-50 *in* Jacob, H. (1652) Philologiae ... Oxford H. Hall

King, E. (1768) An Attempt to Account for the Formation of Spas and Crystals; Phil. Trans. Roy. Soc. *57*, pt. i for 1767: 58-64

Kircher, A. (1665) Mundus Subterraneus; Amsterdam, J. Jansson

Kirwan, R. (1784) Elements of Mineralogy; London, P. Elmsly

Lang, C.N. [1705] Idea Historiae Naturalis Lapidvm Figvratorvm Helvetiae ...; Lucerne

Lartet, E. (1861) Nouvelles recherches sur la coexistence de l'homme et des grands mammifères fossiles...; Annales des Sciences Naturelles, Zool., 4th series, *15*: [177]-253

Launay, L. de & Martel, E.A. (1891) Note sur quelques questions relatives à la géologie des grottes et des eaux souterraines ...; Bull. Soc. Géol. de France, (sér.3), *19*: 142-165

Leibniz, G.W. (1859) Protogée ou de la formation et des révolutions du Globe; Paris, L. Langlois

Lister, M. (1673) An Account of two uncommon Mineral Substances, found in some coal and iron-mines of England; Phil. Trans. Roy. Soc. *8* (100): 6179-6181

Luc, J.A. de (1811) Geological Travels; London, F.C. & J. Rivington, *2*

Lyell, C. (1832) Principles of Geology ...; London, 1st edn', *2*

Lyell, K.M. (1881) Life, Letters, and Journals of Sir Charles Lyell ...; London, J. Murray

Magni, C. (1692) Quanto di Piu'Curioso ... Turchia; Parma, *2*

Maheu, J. (1906) Contribution à l'étude de la flore souterrain de France; Paris, Masson [Thèses ... 1233]

Martel, E.A. (1896) Applications Géologiques de la Spéléologie ...; Annales des Mines, July:[5]-100
(1897) Irlande et Cavernes Anglaises; Paris, Delegrave

Molard (1908) Les Grottes de Sabart (Ariège) Niaux et les dessins préhistoriques; Spelunca. Bull. et Mém. de la Soc. de Spéléologie, *7* (53): [177]-191

Packard, A.S. (1888) The Cave Fauna of North America ...; Mem. Nat. Acad. Sciences, *4* (1) 3-156

Palissy, B. (1564) Recepte veritable ...; La Rochelle

Parandier, N.A. (1833) Notice sur les causes de l'existence des cavernes ...; Académie des Sciences, Belles-Lettres et Arts, de Besançon, Séance publique du 28 Jan 1833:59-85

Pengelly, W. (1869) The Literature of Kent's Cavern' Part II; Trans. Devonshire Assoc., *3* (1): 191-382

(1881) Notes on Recent Notices of the Geology and Palaeontology of Devonshire, pt. VIII; Trans. Devonshire Assoc., *13*: [359]-402

Penn, G. (1825) A Comparative Estimate of the Mineral and Mosaical Cosmologies ...; London, J. Duncan, 2nd edn. (only)

Phillips, J. (1853) The Rivers, Mountains and Sea-Coast of Yorkshire; London, J. Murray

Putnam, F.W. (1872) The Blind Fishes of the Mammoth Cave and their allies; Am. Naturalist, *6* (1):6-30

Racovitza, E.G. (1907) Essai sur les problèmes biospéologiques; Biospeologica I, Archives de Zoologie Expérimentale et Générale (sér.4), *6*:[371]-448

Ray, J. (1692) Miscellaneous Discourses concerning the dissolution and changes of the world ...; London, S. Smith

Salzer, H. (1936) L'Esplorazione delle Grotte e del Carso Carniolico del matematico Giuseppe Antonio Nagel; Le Grotte d'Italia, (ser. 2), *1*:106-119

Schiner, J.R. (1854) Fauna der Adelsberger, Lueger und Magdalener-Grotte; p.[231]-272 *in* Schmidl, A. (1854) Die Grotten und Höhlen von Adelsberg, Lueg, Planina und Loos; Vienna, Braunmüller

Schiödte, J.C. (1851) Specimen Faunae Subterraneae ...; Trans. Entom. Soc. London, NS, *1* (4):134-144 & (5):145-157

Schmerling, P.C. (1833-34) Recherches sur les Ossemens Fossiles découvertes dans les Cavernes de la Province de Liége; Liége

Schmidl, A. (1857) Die Höhlen des Ötscher; Sitz. d. Kaiserlichen Akad. d. Wissenschaften. Math.-Naturwiss. Classe, *24* (2):180-230

Scopoli, J.A. (1772) Plantae subterraneae descriptae & delineatae; p.84-120 *in* Scopoli, J.A. (1772) Dissertationes ad Scientiam Naturalem, pt.1; Prague, W. Gerle

Sennert, D. (1632) Epitome Naturalis Scientiae; Oxford, I Lichfield

Serres, P.M.T. de (1836) Essai sur les cavernes a Ossemens et sur les causes qui les y ont accumulés; Montpellier, J.M. Ainé

Steinberg, F.A. von (1758) Grundliche Nachricht von dem in dem Inner-Crain gelegenen Czirknitzer-See ...; Laybach, A.E. Reichhardtin

Sturmy, S. (1678) *in* Hooke, R. (1678) Lectures de Potentia Restitutiva ...; London, J. Martyn 40-41

Tellkampf, T. (1844) Beschreibung einiger neuer in der Mammuth-Höhle in Kentucky aufgefundener Gattungen von Gliederstieren; Wiegm. Archiv. für Naturgeschichte, *10* (1):318-322

Tournefort, J.P. de (1741) A Voyage into the Levant ...; London

Trissino, G.G. (1550) [letter dated 5 March at Cricoli], f.420v in Alberti, L. (1550) Descrittione di Tutta Italia ...; Bologna, A. Giaccarelli

Valvasor, J.W. (1689) Die Ehre dess Hertzogthums Crain ...; Laybach

Viré, A. (1899) Essai sur la Faune Obscuricole de France ...; Paris, J.B. Baillière

Virlet, T. (1834) [Sur la formation des cavernes]; Bull. Soc. Géol. de France, *4*:345-347

(1834[=1835]) Observations faites en Franche-Comté, sur les cavernes et la théorie de leur formation; Bull. Soc. Géol. de France, *6*:154-164

Vollgnad, H. (1676) Draconibus Carpathicis et Transylvanicis; Miscellanea Curiosa Medico-Physica Academiae Naturae Curiosum ..., [Dec.I], Annus *4* & *5* for 1673 & 1674 : 226-227

Wallace, W. (1865) On the Growth of Flos Ferri, or Coralloidal Arrangonite; Quart. J. Geol. Soc., London, *21* (1):413-421

Whitehurst, J. (1786) An Inquiry into the Original State and Formation of the Earth ...

Willems, J. (1894) Compte Rendu de la session extraordinaire de 1893 ... Etude de la circulation de l'eau dans les calcaires et visite des grottes de la Lesse; Bull Soc. Belge de Géologie ..., *7* for 1893, Mém.: 298-377

Williams, D. (1834) MS. Notebook, *5*:ff.2b,35b (Somerset Archaeological and Natural History Society archives, box R/7)

Wright, E.P. (1858) Notes of a Visit to Mitchelstown Caves [abstr.]; Rept. 27th Mtg. British Assoc. Adv. Sci. in 1857; Trans. of sections 108-9

Young, G. (1828) A Geological Survey of the Yorkshire Coast ...; Whitby, R. Kirby, 2nd edn (only)

Trans. British Cave Research Association. Vol. 1. No. 1. pp.15-28 January 1974

THE GENESIS AND CLASSIFICATION OF LAVA TUBE CAVES

by Christopher Wood

Summary

An attempt is made to resolve the current conflicts in vulcano-speleology which result from the difficulties found in reconciling the complex three-dimensional lava tube networks with traditional models of speleogenesis in lavas. The important observations and models of lava tube cave genesis are described and discussed. It is found on observational and speculative grounds that the models may be reduced to two: the crusting of open lava channels and the chilling of a shell around flow units or pahoehoe toes. The popular theory of laminar flow and shear plane development as a pre-requisite for the evolution of complex tube forms is discussed and rejected. Instead, it is suggested that caves of a more complicated form may result from the crusting of braided channel flow or the coalescence of drainage channels carried in flow units or toes. Multi-level lava tube caves may be developed in a similar way and result from stacked conduits or flow units. In the light of these discussions it is seen that a genetic classification of lava tube caves is not practicable, for one cave may result from a combination of speleogenic processes. A descriptive classification is therefore proposed which is based on cave form as measured by the cave survey.

Current conflicts in vulcano-speleology result from difficulties found in reconciling the often extremely complex three-dimensional lava tube cave networks with traditional models and observations of speleogenesis in basaltic lava flows. For some, the principal hypotheses on lava tube genesis lack credibility, for no one theory will suitably explain the wide range of lava tube morphologies encountered in the field. Others are attracted, somewhat blindly, to a single all-embracing theory of laminar flow and speleogenesis intimately linked with the formation of shear planes in lava, as an explanation for the origin of diverse morphologies, though they provide little evidence in support. The cause of this conflict, which has flavoured all recent discussions, appears to stem from the infant nature of vulcanospeleology, and results from unsystematic terminology, poor fieldwork, inadequate documentation, a general acceptance of unproved theories and, as yet, little observation of actively forming lava tubes. Conclusions have been drawn in the past without the foundation of sound descriptive material. This paper then, is an attempt to resolve the conflict. The information already available on speleogenesis in lavas will be summarised; much of it is, because of the obscure publications in which it is found, still unknown to the general worker. Proposed models of lava tube cave genesis will be reviewed in the light of known behavioural characteristics of basalt lava flows.

Models and observations of speleogenesis in lavas

General descriptive works on lava tube caves have in the past been numerous, but relatively little important evidence was cited which would contribute to a discussion on the origin of these features. The widely accepted traditional model which involved the simple crusting of a lava flow and its subsequent drainage did little to explain the often extremely complex forms of lava tube caves. Clearly, speleogenic processes at work in basalt flows were much more complicated. It was only recently, within the last few years, that important fieldwork was carried out both in ancient flows and in active extrusive volcanism. These observations are outlined below, together with the more important older contributions.

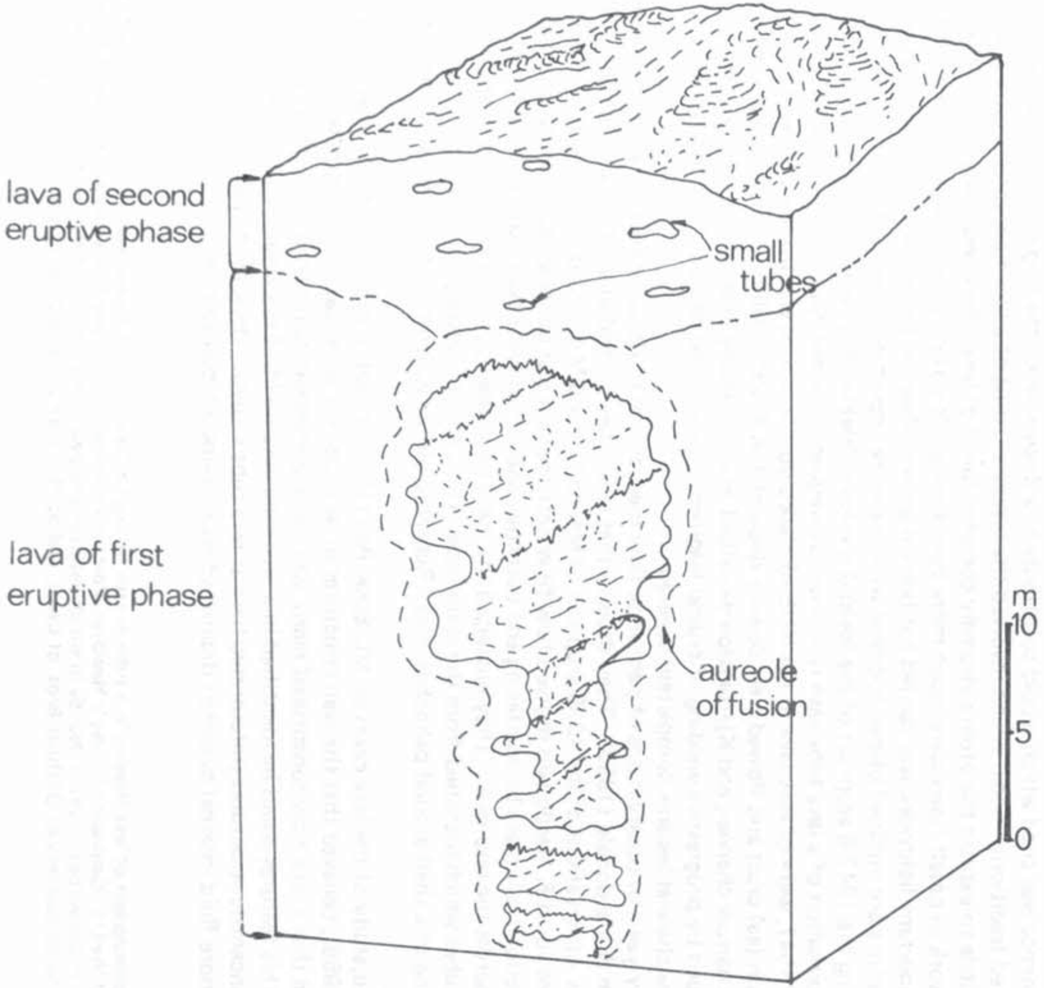
During the 1947-8 eruption of the Icelandic volcano 'Hekla', Kjartansson (1949) was fortunate to observe the formation of a lava tube cave which was subsequently named Karelshellir. His observations in December, 1947, were of new lava to the NNE of Haskuldbjalla, which was being extruded from beneath a flat apalhraun (aa) crust and flowed west down a slope of 1 in 8 with a velocity of 20cm/sec. The lava was confined to a narrow channel, and Kjartansson described how it partially crusted over and how marginal levees developed by progressive welding of crustal fragments towards the centre of the channel until, ultimately, the channel became completely covered.

Many years of observations of pahoehoe flow mechanisms in Hawaii were similarly summarised by Wentworth & Macdonald (1953). They showed that lava tubes formed under two contrasting situations. Citing Stearns' observations of the 1935 eruption of Mauna Loa and Macdonald's observations of the 1942 eruption, Wentworth & Macdonald showed how flow near the vent was confined to a narrow channel. Here, levee construction took place by spattering and overflow, and a roof was developed by the jamming of crustal slabs across the lava river. They envisaged the margins of the flow to be fed by a myriad of small distributary tubes which branched from the main tube. Thus, an alternative process of tube construction was the chilling of a shell around pahoehoe toes. Repeated outbursts lengthened the toes and small tubes were formed.

In his study of the lava caves on Mt. Etna, Poli (1959), possibly stimulated by Rittmann's speculations (Rittmann, 1958), believed that the wall structures in lava tube caves indicated laminar flow. The hypothesis was presented that a lava flow constituted many successively enclosed cylinders of lava whose viscosity increased externally. This features could be identified in a lava tube cave on Mt. Etna where the walls were composed of layered concentric structures (interpreted here as lava tube crusts). Thus, at the cessation of eruptive activity the more fluid internal cylinders drained of lava leaving a tube-like cave.

* The cover photograph of lava flowing in a tube as seen through a "skylight" on Hawaii was kindly supplied by D.W. Petersen, of the U.S. Geological Survey's Hawaiian Volcano Observatory. It is reproduced by permission of the editor of "Studies in Speleology" (Vol. 2. No. 6) in which Petersen and Swanson's account of this phenomenon is presented. Colour blocks by courtesy of Gilchrist Bros. of Leeds, and by Hawaiian Volcano Observatory.

FIG.1



STRUCTURAL FEATURES OF 'CUEVA DE LOS VERDES' AFTER BRAVO (1964)

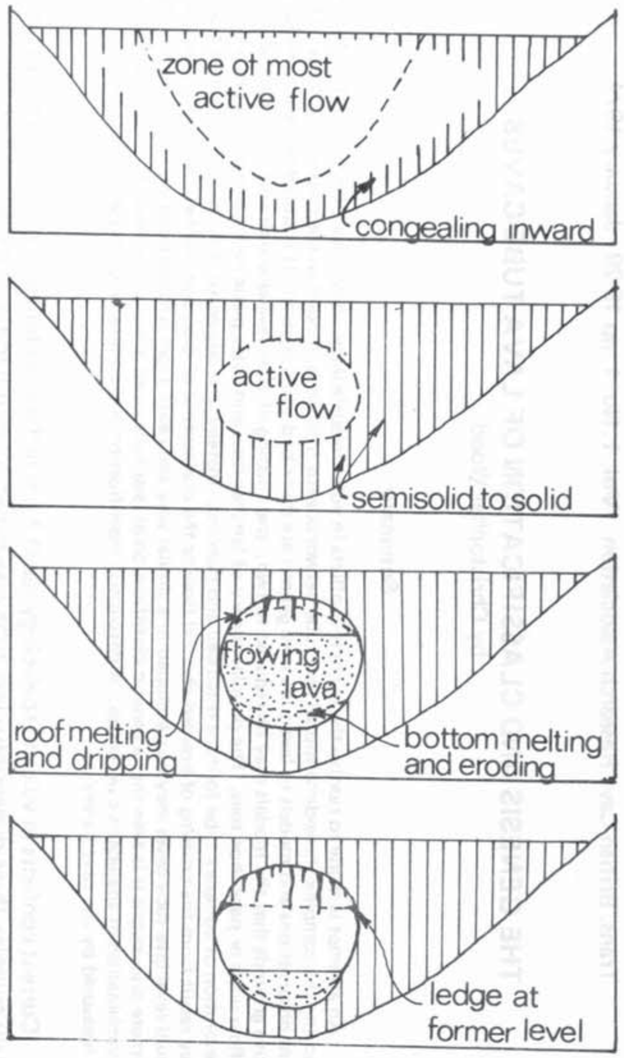
FIG.2

A. A lava flow (confined to a valley) develops a thin crust and starts to freeze inward from the edges, but the centre remains hot and continues to flow.

B. The active movement becomes restricted to cylindrical pipelike zone near axis of flow.

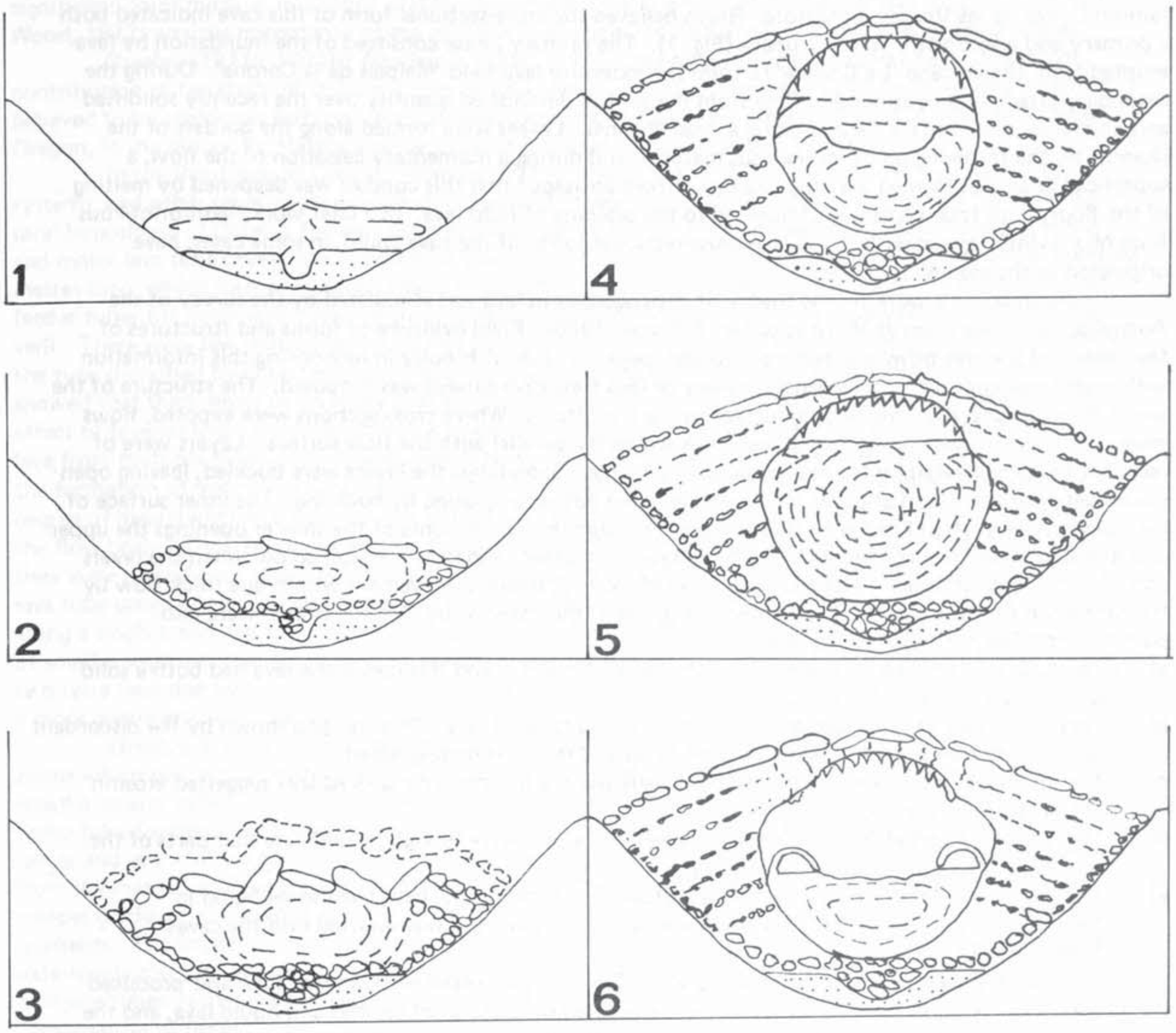
C. Supply of liquid lava diminishes and no longer entirely fills pipe. Burning gases heat roof and causes it to drip.

D. Further diminution of supply lowers liquid level – congeals to form tube floor.



MODEL OF SPELEOGENESIS IN LAVA AFTER MACDONALD (1970)

FIG.3



1 Thin pahoehoe lava flow in an open channel. Surface spatter caused by steam from trapped water.

2 Formation of slab pahoehoe. Slabs form, jostle and sink. Carpet of scoriaceous rubble.

3 Pulses in lava supply produce thin, layered levees.

4 Decrease in supply forms tube, shelves, and benches with gutters against the walls.

5 Temporary increase in supply, and therefore heat, engulfs previous forms and enlarges the diameter of tube - thermal erosion.

6 Rapid decrease in supply causes rolls of plastic lava to arch down. Festoon ridges on floor.

MODEL OF SPELEOGENESIS IN LAVA AFTER KERMODE (1970)

Another European study which followed traditional lines was carried out by Bravo (1964) on the famous Cueva de los Verdes, Lanzarote. Bravo believed the cross-sectional form of this cave indicated both a primary and a secondary volcanic phase (Fig. 1). The primary phase consisted of the inundation by lava erupted from the volcano 'La Corona' to form the extensive lava field 'Malpais de la Corona'. During the secondary phase, lava continued to flow from the vent in diminished quantity over the recently solidified and, in places, still hot lava field, eroding a deep channel. Levees were formed along the borders of the channel by the throwing up of scoriaceous material, and during a momentary cessation of the flow, a superficial crust was formed over the channel. Bravo envisaged that this conduit was deepened by melting of the floor, until total cessation of flow led to the draining of fluid lava. In a later work, Montoriol-Pous & de Mier (1969) agreed with Bravo that cross-sectional forms of the cave could, in some cases, have originated in the manner described.

An important work on the theory of speleogenesis in lava was stimulated by the survey of the Australian lava tube caves at Victoria (Ollier & Brown 1965). Field evidence of forms and structures of the caves and the lava flows was summarised and, because of the difficulty in reconciling this information with traditional concepts, a new general theory of lava tube cave genesis was proposed. The structure of the basalt flows around the caves was important to the hypothesis. Where cross-sections were exposed, flows were divided into layers up to several feet thick which lay parallel with the flow surface. Layers were of compact basalt separated by trains of vesicles or partings. Sometimes the layers were buckled, leaving open spaces between them, and at other times partings were not accompanied by buckling. The inner surface of the openings were often lined with stalactites and stalagmites, and in some of the smaller openings the upper and lower surfaces were connected by vertical threads of basalt, apparently stretched out when the layers parted. This 'layered lava', it was thought, resulted from differential movement within one thick flow by the formation of shear planes. The following arguments put forward by Ollier & Brown were also particularly relevant to their point of view:

a) The existence of caves indicated the withdrawal of magma, and this meant the lava had both a solid and a liquid phase within the same flow.
b) Cave shape suggested an abrupt passage from liquid to solid lava. This was also shown by the discordant contact between the inner lining of some caves and the surrounding basalt.
c) The discordance between the curved cave walls and the horizontally layered lava suggested erosion of the layered material.
d) The 'treacle' effect at partings between layers in the lava were thought to indicate that parts of the layered lava was still sticky at a late stage.
e) The 'hands' of stalactites in some caves indicated that there must have been some liquid in the interstices of the layered lava which was under pressure and was squirted into the caves from the walls.

Ollier & Brown believed the layering of the lava was connected with laminar flow and produced by its partial congelation. Individual layers were separated by partings of vesicles and liquid lava, and the thickness of the layers increased with increasing viscosity. It was said that when layered lava formed, the more congealed lava went into layers while the more liquid lava was concentrated between laminae. The liquid lava then became further segregated and came to occupy tubes running through the layered lava. Mobile lava eventually became concentrated in a few major channels, and these were a continuing source of heat and could erode some of the earlier layered lava. The end result was cylinders of liquid lava flowing through tubes cut in virtually solid layered lava.

A simpler model which summarised in diagrammatic form the processes which led to the formation of a lava tube cave in a flow confined in a narrow valley, was presented by Macdonald & Abbott (1970). This is reproduced in Fig. 2. It was common, they also noted, for minor tubes to develop at flow margins in pahoehoe toes.

In a slightly later work on lava tube caves in New Zealand, Kermode (1970) produced a similar model to that of Macdonald & Abbott's for flow confined in a valley (Fig. 3). Kermode, however, envisaged progressive enlargement and thickening of the flow, so that definite stratigraphical horizons could be identified, and tube enlargement took place by thermal erosion.

Interesting fieldwork was carried out by the writer (Wood 1971) in the Icelandic lava tube cave Raufarhőlshellir. The smallest type of tube was generally found above lavafalls in the extremities of the cave and had a form consisting of a flat floor and an arched roof. A second type of tube, into which the first type passed below the lavafalls, carried three lateral benches, one of which was found above a lateral shelf and was continuous with the single lateral bench of the first tube type. A third type of tube was the joint controlled, rectangular, breakdown tube, and a fourth type was composed of a series of irregular forms of large size which constituted the main tube. Cross-sections of the lava flow were rarely observed in the smaller tubes, but it was observed that because of the natural weaknesses at flow unit contacts, ropy surfaces were sometimes exposed. By the identification of successive contacts, therefore, the relationship between flow structure and tube forms could be understood. It appeared that the smallest tubes represented the drained cores of single flow units, and that each flow unit represented a potential 'primary tube unit'. Larger tubes were seen to be constructed of multiples of this single unit, due to erosion and remelting of the crusts of the original flow units by the lava stream. The second type of tube, therefore, was observed to be made up of two flow units or primary tube units (Fig. 4), one situated above the other, whose dividing crust had been eliminated. Similarly, although evidence was stated to be difficult and inconclusive, it was envisaged that the main tube was made up of multiple, superimposed and adjacent units, due to the formation of an enlarged lava stream by the confluence of liquid lava carried in the tributary tubes. A further significant point made in this study, and by the same author in a note on Vidgelmir lava tube cave (Mills & Wood, 1972) was the importance of the pre-flow topography in influencing the draining of these tubes.

Greeley (1971a, 1971b; Greeley & Hyde, 1971) made a recent large, if somewhat inconsistent, contribution to the study of lava tube cave genesis, due to a special interest in lunar sinuous rilles which were believed to be analogous features. An impressive amount of fieldwork was carried out in the Bend area of Oregon, in the Mount St. Helens area (with Hyde), and on Kilauea volcano, Hawaii.

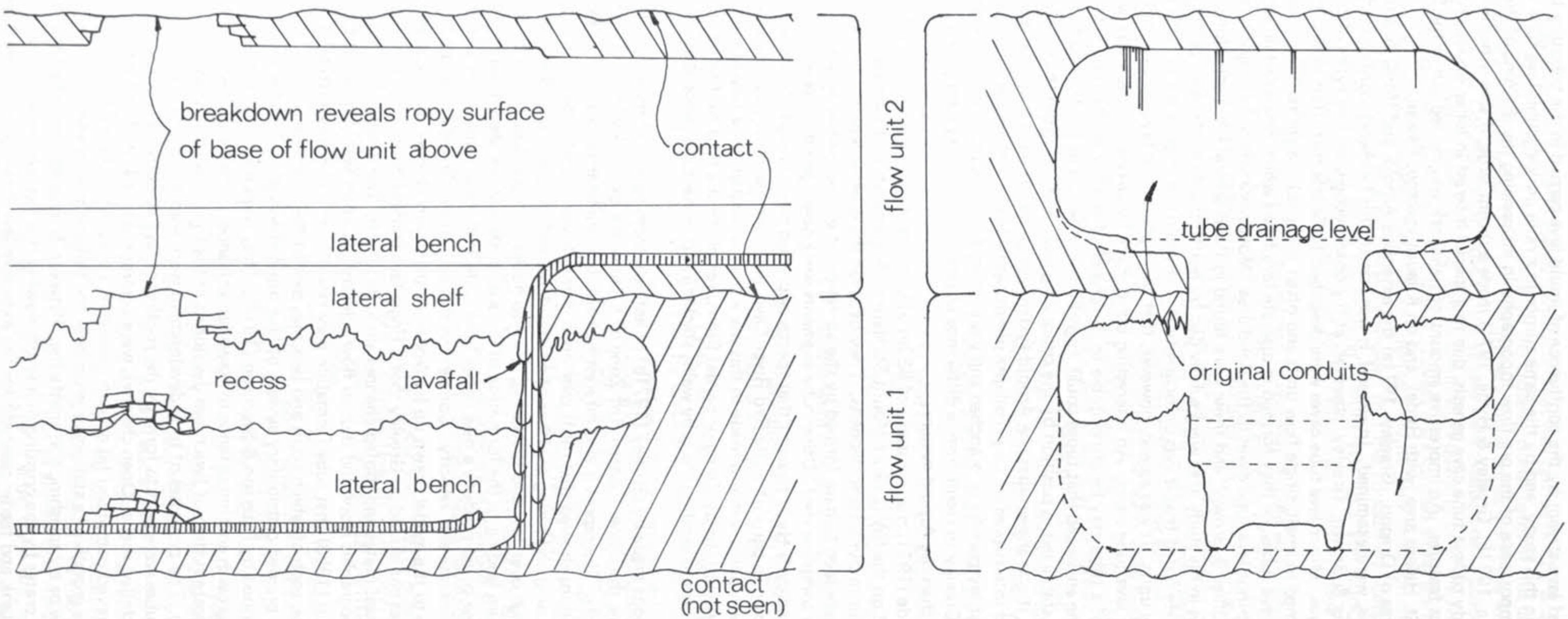
In the Bend area of Oregon, (Greeley, 1971a) the extensive Arnold- and Horse lava tube cave systems, and other caves, were examined. In general, it was stated, this fieldwork confirmed the 'layered lava' hypothesis of Ollier & Brown. Greeley, however, at the onset recognised two types of tubes: minor and major lava tube caves. Minor lava tube caves were described to be less than 10m wide and a few hundred metres long, which formed in small, single flow units and often occupied the entire flow. They were often feeder tubes for larger lava tubes, or they formed in discrete lava flows which emanated directly from the vent. There were few minor lava tube caves in the Bend area. Most were said to be major lava tube caves 'of the type described by Ollier & Brown', and these were found in flows several kilometres long. Greeley showed that thick flows in his study area were subdivided by horizontal discontinuous partings giving the effect of layered lava. He noted that it was unfortunate that it was often impossible to distinguish layered lava from multiple flow units. It was agreed, however, that shear planes and layered lava were essential to the formation of major lava tube caves. An interesting point made by Greeley in the study was that the degree of meandering of a tube may be attributable to the degree of fluidity of the mobile conduit within the flow body. Thus, he envisaged that tubes could migrate from one side of the flow to the other, until they were more firmly stabilized in position by the congealing lava. Further, from the surveys of the two lava tube cave systems, it was shown that the Arnold system comprised of large lava tube segments oriented along a single trend and interrupted by large collapse ponds, while Horse system was seen to be composed of smaller segments that lay parallel or branched and were often disconnected. The difference between the two were regarded by Greeley to result from a difference of gradient. Horse system formed in a flow with a more gentle gradient than the Arnold system.

Greeley & Hyde (1971) made a study of 833m of lava tube cave in the Cave Basalt, a pahoehoe basalt which originated on the SW flank of Mount St. Helens, Washington, and extended southward for 11km down a stream valley cut in pyroclastic deposits. They believed the cave system had two modes of formation. Some tube segments were seen to have formed by the accretion of spatter leading to the formation of arched levees and eventually a complete roof. Other tube segments were developed in layered lava and resulted from laminar flow. Greeley & Hyde thought that spatter accretion was a product of more turbulent flow on a steeper gradient, as shown in parts of Little Red River Cave, while laminar flow was a product of lesser gradients. The important point was also made in this work that subsequent lava flows could modify quite extensively the first formed tube by filling or partial filling, remelting the tube roof to form vertically elongate tubes, reshaping and eroding the tube walls, stacking additional tube levels above the first, or any combination of these.

The observations made by Greeley (1971b) of actively forming lava channels and lava tubes during the 1970 eruption along the Upper Eastern Rift Zone of Kilauea, are extremely important to the discussion on lava tube cave genesis. The report is also interesting because it summarises previous observations in Hawaii. Greeley's own observations showed that roofs over open channels were constructed by simple crusting procedure, by the jamming and fusing together of crustal slabs, and by levee formation resulting from accretion of lava through overflow and spattering. He also noted multiple flow along rifts and suggested this may be a mechanism leading to the formation of unusual cross-sections seen in some lava tube caves. Here, each flow or surge could produce a new upper level, with individual dimensions and characteristics dependent upon flow volume and velocity. Concerning this procedure, Greeley produced a diagram (Fig. 5) which bore similarities to the model drawn up by Wood for the origin of more complicated tube forms in Raufarhólshellir. It was concluded by Greeley that a single lava channel could display braided channel flow, open flow, mobile crustal plates and roofed channel along its length. The difference in type appeared to be related, in part, to topographic slope and thus to flow velocity. Support was also found for the hypothesis put forward by Baldwin (1953) that tube formation may result from a complex system of overlapping and coalescing lobes of lava, each of which cools and becomes part of the tube roof.

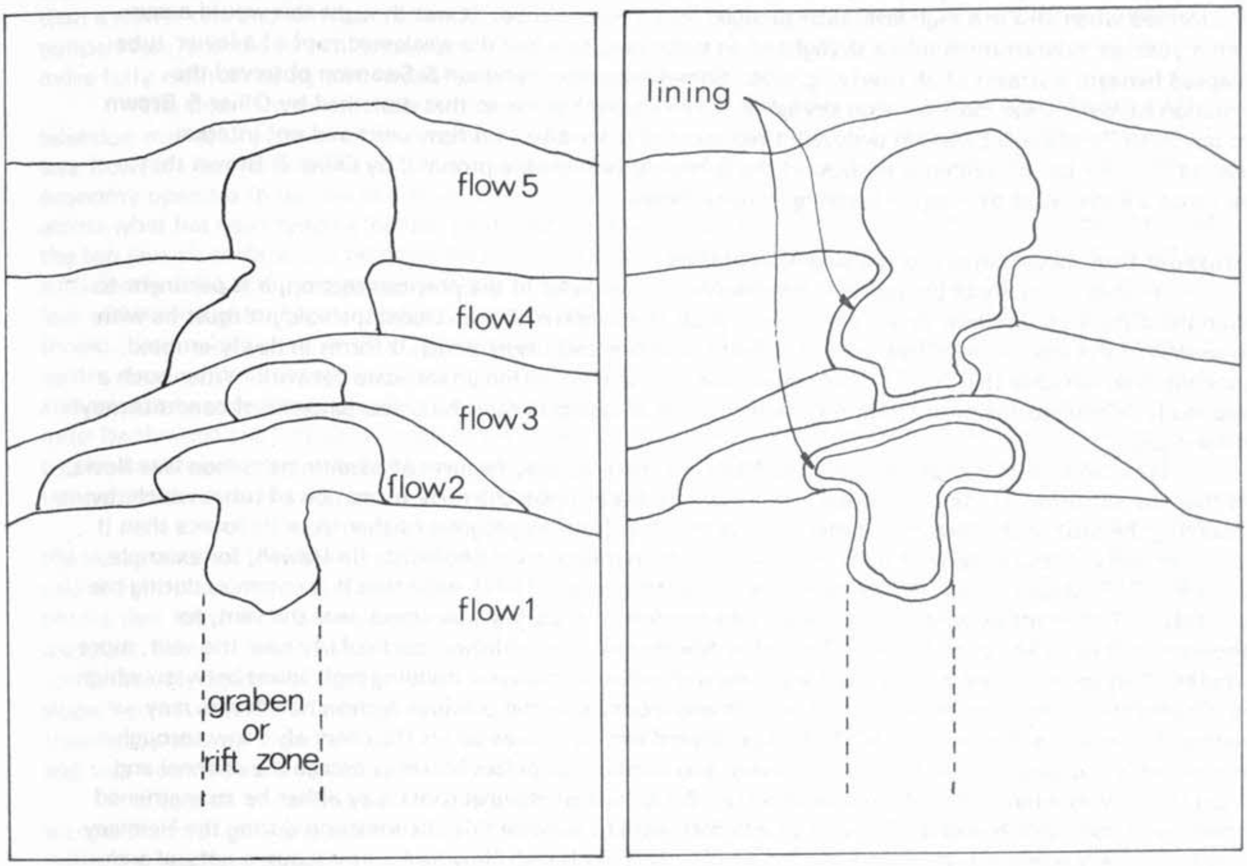
The complex braided distributary system of lava tubes observed by Greeley on Kilauea during 1970-1 were also described by Peterson & Swanson (1974). They were impressed at the considerable role lava tubes play in the growth and importance of Hawaiian volcanoes. Frequent observations were made of the extensive and intricate system of lava tubes developed in the thin flows that slowly advanced down the south flank of Kilauea. The processes of tube development were seen to vary with distance from the source vents, but in general tubes were seen to form by the roofing of lava streams and by advancing lava toes becoming encased in chilled shells. Open channels were common near the vent and the various methods of roof construction observed comprised (a) growth inward of a crust from the banks, (b) the jamming together of crustal slabs, (c) the growth of a stationary crust over the flowing stream and (d) the growth of levees by accretion and overflow or by splashing and spattering. Peterson & Swanson described the formation of a master tube into Alea crater by the crusting of a south flowing channel, and showed how Alea became an underground holding tank and feeder reservoir for the extensive lava flows lower on the flank. Further away from the vent and below Alea crater, processes of tube formation were seen to be similar to those near the vent, though they were slightly modified because of different flow characteristics. Small, narrow channels

FIG.4



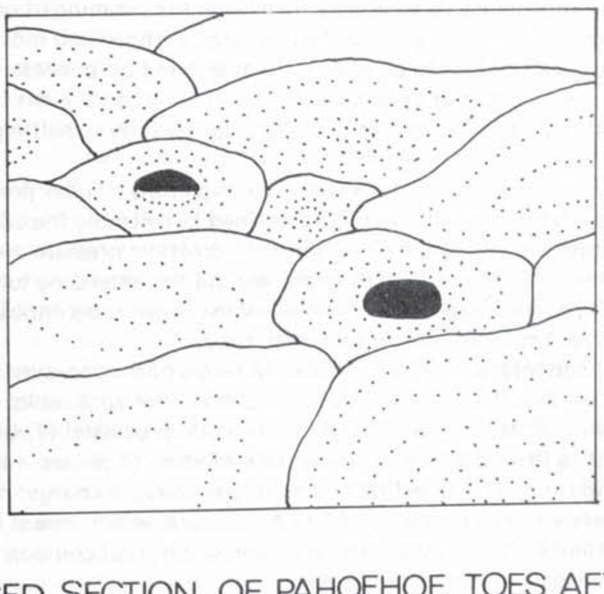
EVIDENCE OF STACKED CONDUITS IN RAUFARHÓLSHELLIR
AFTER WOOD (1970)

FIG.5



FORMATION AND MODIFICATION OF LAVA STRUCTURES AS A RESULT OF SUBSEQUENT LAVA FLOWS AFTER GREELEY (1971b)

FIG.6



IDEALISED SECTION OF PAHOEHOE TOES AFTER MACDONALD (1967) were seen to develop though they were only 1-3m across, and from the main channel ran a complex of distributaries in a braided pattern. Tubes developed at the front by chilling of a skin around pahoehoe toes. Sometimes, by looking through 'skylights' (collapsed portion of a tube roof), underground lavafalls could be seen, formed when lava in a high level tube plunged into a deeper tube. It was thought this would occur when a younger tube emptied into a skylight of an older one, or when the weakened roof of a lower tube collapsed beneath a stream of an overlying tube. Sometimes, also, Peterson & Swanson observed the formation of lower level roofs beneath skylights. Layered lava similar to that described by Ollier & Brown was seen, but Peterson & Swanson believed it represented successive thin flow units and not internal shearing. "... we saw no evidence to support the currently fashionable proposal by Ollier & Brown that lava tubes are the result of internal shearing of thick flows'.

Discussion: flow mechanisms and speleogenesis in lavas

In order to evaluate the models and observations outlined in the previous section, it is pertinent to divide the discussion into two parts. In the first place, the concern of the vulcanospeleologist must be with the genesis of the simple, primitive form of conduit, and the laws under which it forms in newly erupted pahoehoe lava, whether that form be the whole cave or branches within an intricate network. When such a basic model is realised the mechanism for the formation of complex morphological patterns of conduits may be discussed.

It has long been recognised that lava tubes are characteristic features of basaltic pahoehoe lava flows, and that the extrusion of the flow depends to a marked degree upon the early formation of tubes which, by conserving the heat of the lava river within, allows the flow front to progress further from its source than it would normally. Observations of surface phenomena by numerous vulcanologists (in Hawaii, for example, by Jones, 1937; Jagger, 1947; Macdonald, 1967; Swanson et al., 1971) show that it is common during the early stages of an eruption when discharge is often greatest, and during later stages near the vent, for pahoehoe to flow in an open channel. Here, after the channel is established, particularly near the vent, more turbulent flow causes splashing and spattering along the channel margins, building high levees between which the stream flows commonly several feet down. It was recorded in the previous section how levees may become arched and a firm roof established under special circumstances across the channel. Flow through the channel is not generally uniform but pulsates, and during high pulses lava may escape the channel and spread laterally as minor units which cool quickly. Early formed channel roofs may either be strengthened or destroyed during such pulses. The author was fortunate to observe this phenomenon during the Heimaey eruption in the Vestmannaeyar Islands during April, 1973. Although flow here was viscous, a natural arch was seen to develop between two high pulses across part of a lava channel which was under observation. Once established, the arch was overriden by lava of subsequent pulses and appeared to be considerably strengthened by accretion above and below. This continued through six or seven large changes in lava level, until an extra large surge of lava swept away the apex of the arch.

Further from the vent the lava has cooled and degassed quite significantly, and the surface is observed generally to darken and to crust. The nature of the crust appears to vary from a thin grey skin, to pahoehoe slabs, or to irregular scoriaceous blocks, according to flow characteristics and viscosity. Numerous Hawaiian observers attached great importance to tube genesis through the jamming of crustal slabs. Blocks and slabs were seen to develop on Heimaey when the discharge dropped and movement generally slowed, and these were later swept downstream to be piled onto a roof and onto levees. Due to the nature of the lava on Heimaey, however, blocks did not become welded, but lay upon the channel as unconsolidated moraine-like material, as froth piles up at a weir, and this was strengthened by remelting and accretion beneath.

Near the flow front channel type flow changes to tongue type flow. Tubes predominate, and the flow front advances in a spasmodic fashion which has been described to resemble the advance of an amoeba 'by the protrusion of successive lobate toes'. Mobile lava, under hydrostatic pressure, may burst forth from the front and chill quickly with the result that a shell develops around the extending tongue. These become buried by later tongues. Cliff and roadside exposures in Hawaii often reveal superimposed pahoehoe toes (Fig. 6), some of which may be over 1m thick and contain small tubes.

Is it possible that these phenomena may be explained in terms of thermo-dynamic considerations? The argument has been put forward that thermo-dynamic principles are not applicable; 'Thermo-dynamics deals with equilibrium systems only; it cannot consider dis-equilibrium processes' (Tubbs, 1972, p.9). Practically all lava in a state sufficiently fluid to flow at all, must consist of a mixture of phases – bubbles of gas and solid crystals suspended in a liquid melt. It is true that lava is subject to rapid changes of temperature, is low in conductivity and inadequately mixed in relation to its dimensions, which means that it is unlikely to approach homogeniety in temperature, density, viscosity, pressure, or physical composition. However, certain valid conjectures may be made and speculated upon.

In the early stages of an eruption, very hot and fluid lava flows out from the vent over a cold surface. This is a situation that does not represent a steady condition, for there is a sharp transition between the newly erupted lava and the cold surface, and this is subject almost immediately to a rapid widening of the temperature slope and a corresponding decrease in its steepness. Flow of heat to the outer parts of the lava tends powerfully towards congelation resulting in a narrowing of the channel. Ultimately a restricted lava channel is formed which represents a condition where the velocities of flow and of heat delivery by the stream are nearly equal to the heat loss through the channel sides and to the air, and is sufficient to keep temperatures nearly constant. Thus, in a given lava channel there is a steady state of thermal and flow conditions.

The mobility of the lava appears to depend on the maintenance of high temperatures. It is important to consider that the internal transfer of heat by conduction is probably insignificant compared with convection, and there must therefore be a relationship between movement and the relationship of heat. If the moving lava is losing heat to the air and the ground, the faster flow will suffer a smaller temperature drop than a slower one and will more effectively maintain a higher mobility. Since mobility increases with temperature, and the rate of movement will increase with higher temperatures, the temperature, in turn, is more fully maintained by an increase or maintenance of movement.

The flow fails to overflow its margin and movement ceases, therefore, through lack of heat, and selection may take place amongst the several flow routes away from the vent. The great initial widths of lava flows are not maintained and, in the course of continued flow, something like a principle of thermal economy operates to narrow and thicken the flowing tongue. The hot liquid is cooled by heat transfer across what has been called a 'heated perimeter' (analogous to 'wetted perimeter' of flowing water) between the top lava-air surface and between the walls and floor. It is thought that solid channel walls which are sufficiently solid to stay in place are likely to be about 700°C, and the adjacent outer parts of the moving lava will have slightly higher temperatures, but these will be lower than the more rapidly moving central thread. In any lava channel, then, there must be a zone of transition of temperature and viscosity from the centre outwards and downwards to the wall rock. This transition of temperature may be as much as 200°C and take place over something like 1m of thickness. In maintained open channel flow greatest heat loss must be through the lava-air contact, but it appears at this stage that the velocity of flow and heat delivery by the stream keeps temperatures nearly constant. In this type of flow the maximum velocity and highest temperatures are at the top and in the centre of the channel.

As velocity and corresponding thermal delivery drop, perhaps because of the greater distance from the vent source or the slowing of the extrusive activity, the thread of maximum temperature and maximum velocity drop below the surface of the flow. The top now gradually becomes covered by solidified crustal blocks that move with the most rapid flow. Gradually, the increase in the continuity of crusting and the increased viscosity results in a decrease of top velocity. It is at this point that a channel may become completely bridged, while fairly rapid flow continues beneath in a lava tube. Thus, there is a change down-slope from channel flowto tongue flow. The subcrustal movement of lava results when the rate of thermal transfer by channel flow falls below the rate of thermal loss through the sides and bottom of the channel and loss from the surface of the lava to the air.

Thus, on observational and speculative grounds simple conduit formation in basalt lava flows is acceptable through the crusting of open channels and the chilling of a skin around pahoehoe toes. Additional models, such as those provided by Bravo, Poli, Macdonald and Kermode, are but variations upon a similar theme. The processes of conduit genesis in basalt flows may be summarised:

1. by the crusting of open lava channels;
   a) by spatter accretion
   b) by simple, wholesale crusting
   c) by the jamming and welding of crustal slabs
2. by the chilling of a skin or crust around
   a) thick, rapidly emplaced lava flows or lava flow units
   b) pahoehoe toes.

It must be remembered that each process is dependent upon particular flow conditions which may be a function of the physical properties of the basalt, the distance from the vent, and the nature of the topography over which the lava flows.

These conclusions are important, for they provide the foundation upon which the evolution of complex morphologies in lava tube caves may be understood. In order to account for such complicated lava tube cave systems as the Mt. Hamilton Lava Cave, Ollier & Brown proposed an hypothesis of layered lava. In seeking an explanation for these fantastic forms, they related lava structures to tube morphology. Unfortunately, their observations and conjectures may be flawed on a number of points. Their hypothesis hinges upon the concept of laminar flow and the development of shear planes. The writer has argued elsewhere (Wood, 1971) that the description provided by Ollier & Brown of layered lava would compare well with a description of a flow composed of thin, superimposed flow units. Peterson & Swanson also reached the same conclusion. The six accompanying photographs illustrate the range of lava structures found around lava tube caves in Iceland. They are shown here because the author believes 'layered lava' structures cannot be unique to Victoria or, indeed, the Bend area of Oregon, and if this structure be a pre-requisite to lava tube cave genesis, then it should be identifiable at all cave entrances and collapses. Instead, in Iceland, two basic structures are observed: multiple flows and a type of piled slab lava. Most typical is the structure of Plate 1., which is similar to that shown by Greeley (1971a) in Figs. 4a & 4b of 'layered lava' structures in Idaho and Washington. The extensive cave systems of Surtshellir/Stephanshellir, Vidgelmír and Raufarhólshellir are formed in this type of lava, and in all cases buried, oxidised, ropy surfaces are identifiable at regular intervals throughout the vertical section, indicating flow unit contacts. Plate 2 shows such a contact at the roof collapse of the lava tube cave Borgarhellir. It is interesting to compare Plates 1 & 2 with the description of 'layered lava' given by Ollier & Brown. The alternate banding of compact lava and trains of vesicles can be shown to exist in superimposed flow units. Buckles were held to be important also by Ollier & Brown. Buckles are seen in Plate 1 and are the obvious result of movement below an already congealed and quite solid crust. Where flow units are buried by subsequent units, the buckles are preserved as shown in Plate 2. Commonly, the roof of cavities below crustal upwarpings are adorned by lava stalactites,

1. Entrance to Surtshellir showing lava structures.

2. Contact of flow units in west wall of entrance to Borgarhellir.

3. Lava showing structures resulting from laminar flow, Stephanshellir.

4. Structure of "slab-lava", Gullborghraun.

6. Three superimposed flow units in the west wall of the entrance to Borgarhellir.

5. Mouth of buried lava channel at entrance to Borgarhellir.

and the cavities lie in a transverse direction to the lava flow. Partings identified by Ollier & Brown which show a 'treacle effect' may be small cavities formed by the coalescence of vesicles (see Plate 4). Lava which may be interpreted as resulting from laminar flow is shown in Plate 3. This shows narrow bands of highly vesicular lava and, in some places, fractures which might be interpreted as shear planes. This lava was seen at an entrance collapse of Stephanshellir, and formed part of the compact central mass of the uppermost flow unit. No cavities were found relating to this particular structure and it obviously played little parts in speleogenesis here.

The second type of lava structure observed about lava tube caves in Iceland is that shown in Plate 4, and perhaps these are more suited to the name 'layered lava'. A structure very similar to this was observed by the author forming by means of unloading and overthrusting of thin crustal slabs onto levees by a lava stream during the Heimaey eruption. Plate 5 shows piled crustal slabs bordering a partially drained and buried lava channel. Plate 6 shows large thicknesses of slabs forming the upper part of three superimposed flow units at the entrance collapse of Borgarhellir. It is obvious here that cooling of a surface crust on units was sporadic and the crust continually broke up through movement of the mobile mass and through surges.

It appears that these two structural types in Iceland are a function of the viscosity of the lava. The lava of Heimaey fell intermediate between Hawaiite and Mugearite, was erupted at low temperatures, (1030°c), and was estimated to contain some 47% crystals at the time of the eruption. This lava has affinities with the Snaefellnes lavas from which Plates 4, 5 & 6 are taken. Lavas of interior Iceland were generally more fluid and show more typical flow unit structures as in Plate 1.

Another objection to the theory of lava tube genesis by means of shear plane development, is that the lava during its passage through the congealed layers must lose much of its heat and therefore its capacity to erode. Once movement of lava through a given opening tends to slow down, there must be a powerful 'feedback' effect which, by diminishing temperatures, will tend towards cessation of movement altogether. Only an external addition of heat, such as increased temperature of lava passing through, or heating of the whole mass from outside, can lead to increased movement. As a further objection, it is difficult to envisage a horizontal arrangement of laminae and shear planes in relation to the lava tube, rather than a concentric one proposed by Poli, unless erosion has considerably enlarged the conduit through several flow units.

Greeley's support for the hypothesis proposed by Ollier & Brown is inconsistent. The flow structures observed at Bend appear to be similar to well-jointed, thin, flow units. In addition, his concept of the hypothesis changes, so that there is little difference between his diagrammatic model shown in the Mount St. Helens paper and the model outlined by Macdonald.

In the light of recent observations, the hypothesis put forward by Ollier & Brown does not seem credible and in accordance with field evidence. Perhaps more reasonable models which could account for the genesis of more complex morphologies are to be found which treat individual tube segments as simple conduits formed under the laws and principles outlined above. Any lava tube cave segment, therefore, under this principle, developed either by the crusting of an open channel, or by the rapid chilling of a skin around a flow unit or smaller pahoehoe toe. Both are directly applicable to the genesis of complex tube patterns, either separately or combined. Greeley and Peterson & Swanson described how the Kilauea lava streams assumed intricate, braided networks, any of which if crusted and drained would form extremely complex lava tube cave systems. Greeley, Peterson & Swanson and the writer have all pointed to the importance of coalescing drainage channels carried in stacked conduits or flow units. It could be that complicated three-dimensional tube patterns are a combination of both processes. Here is scope, then, for improved field techniques in ancient flows, so that unit flows and tube segments may be identified and isolated.

Discussion: Classification of lava tube caves

In the light of the preceeding discussion, it would seem ridiculous and pointless to attempt a classification of lava tube caves based upon genetic considerations, for it is obvious that throughout the length of a single lava tube cave numerous speleogenic processes may have been at work. Attempts have been made to classify lava tube caves, however, and these are reviewed here in the hope that some basis for a descriptive classification may be drawn up which will facilitate observation recording and further research on lava speleogenesis.

A descriptive classification of lava tube caves was found necessary by Halliday (1963) to compare morphologies of the caves of Washington. He found it necessary to refer to the planimetric and longitudinal form of the caves. They were either described as simple/unitary (unbranched) or complex (branched). Both types of cave could be vertically complex, and the complex varieties could possess re-entrant, confluent or effluent passages, or a combination of these. Greeley (1971a), however, agreed with Hatheway & Alika (1970) that there were two basic types of lava tube caves, minor and major caves, differentiated by their genetic characteristics. These have been outlined above. A vague, hypothetical genetic classification was presented by Harter & Harter (1970) which was based on wall stratification and thermodynamic principles. They found 5 basic classes of lava tube caves: surface tube, true trench, semi-trench, rift cave and interior tube.

Owing to the present limited knowledge of speleogenesis in lava any genetic classification is premature. We have already found difficulty with the concept of major and minor lava tube caves as described by Greeley, and the classification proposed by Harter & Harter is to a large extent hypothetical, bearing little comparison with examples in the field. Points of criticism of the latter classification have been published by Tubbs (1972), though Tubbs himself appears to be a little misguided over flow mechanisms prevalent in basalt lava flows.

Yet a means is needed to differentiate basic lava tube cave varieties, so that unified descriptions can be made and progress achieved towards an understanding of their origin. Halliday has shown that caves may be categorised on the basis of descriptive fact which becomes available on the measurement (survey) of the cave. Such solid facts as the planimetric and longitudinal morphologies form a sound basis for classification and there is no reason why Halliday's system should not be taken up. Vulcanospeleologists should beware, however, that the morphology of the lava tube cave described is not the result of modifications of the original conduit formed during its draining, but is the form developed during the extrusive phase of volcanic activity. Multi-level caves may result, for example, from the formation of stacked conduits or from the formation of false floors and roofs during the draining of the conduit. Secondary features are extensively described in the literature and are easily identified by the experienced lava tube caver.

Thus, it is proposed here that lava tube caves be described as simple/unitary or complex. Simple or unitary lava tube caves should be unbranched, sinuous, elongated and uni-level in character. Perhaps they represent the simple conduit described above? Complex lava tube caves should bear predominantly ingressive tubes or more complicated anastomosing tube patterns. A preliminary examination of lava tube surveys in the literature suggests that eggressive patterns may be rare. Gradations between eggressive, ingressive and anastomosing forms most probably exist. Complex tube types may be formed at a common level or they may be multi-level. Multi-level caves are easy to identify in practise from caves divided by secondary features because of the occurrence of lavafalls.

It may be found that unitary forms develop in single, thick, rapidly emplaced and cooled lava flows. Tubes of more complex morphology in Iceland, such as the confluent Raufarhó lshellir and the more complicated anastomosing Surtshellir/Stephanshellir are found considerable distances from the vent (10km and 26km respectively), and obviously result from more complex flow mechanisms. It is of paramount importance, therefore, that cave forms be related to flow structure and the topographical situation in which lava tube cave genesis is induced.

Conclusions

The current conflicts in vulcanospeleology resulting from the difficulty found in reconciling complex cave forms with traditional models of lava tube cave genesis can now, in the light of recent observations, be resolved. Observational and speculative considerations show that models on speleogenesis in lava may be reduced to two: (a) the crusting of open channels by spatter accretion, by wholesale crusting, and by the jamming and welding of crustal slabs or (b) the chilling of a shell around flow units or pahoehoe toes. Complex lava tube caves do not appear to result frcm laminar flow and the development of shear planes, but are most likely the result of crusted braided flow, or coalescence of drainage channels carried in flow units or smaller toes. Multi-level tubes may be the product of the last mechanism and may represent stacked conduits.

Genetic classification of lava tube caves does not appear to be a worthwhile exercise at the present time, for a single cave may be the product of more than one vulcanospeleogenic process. Grounds may be found for supporting a descriptive classification of tube forms based upon cave surveys, as used by Halliday in the 'Caves of Washington'.

25th July, 1973.

Christopher Wood,
12 Kenton Gardens,
St. Albans,
Hertfordshire.

References

Bravo, T. (1964) 'En volcan y el malpais de la Corona. La 'Cueva de los Verdes' y 'los Jameos'; Publicaciones des Cabildo Insular de Lanzarote, Arrecife. 32pp.

Greeley, R. (1971a) 'Geology of selected lava tubes in the Bend Area, Oregon'; State of Oregon Dept. of Geology and Mineral Industries, Bull. 71, 47pp.

(1971b) 'Observations of actively forming lava tubes and associated structures, Hawaii'; Modern Geology, Vol. 2, pp.207-223.

Greeley, R. & Hyde, J.H. (1971) 'Lava tubes of the Cave Basalt, Mount St. Helens, Washington'; NASA Technical Memorandum, NASA TM X-62, 022, 33pp.

Halliday, W.R. (1963) 'Caves of Washington'; Washington Dept. of Conservation, Div. of Mines and Geology, Inf. Circ. No. 40, 132pp.

Hatheway, A.W. & Alika, K. (1970). 'The Bandera lava tubes of New Mexico, and lunar implications'; Commun. Lunar and Planetary Lab., Univ. Arizona, Vol. 8, Pt. 4, No. 152, pp.299-327.

Harter, J.W. & Harter, R.G. (1970) 'Classification of lava tubes'; Northwest Caving, Vol. 3, No. 1, p.7-13.

Jagger, T.A. (1947) 'Origin and development of craters'; Geol. Soc. America, Memoir 21.

Jones, A.E. (1937) 'The formation of basaltic lava flows'; Jour. Geol. Vol. 45, pp.872-880.

Kermode, L. (1970) 'Lava Caves, their origins and features'; New Zealand Speleol. Bull., Vol. 4, No. 76, pp.441-465.

Kjartansson, G. (1949) 'Nyr hellír i Hekluhrauni'; Natturufraedingurinn, Vol. 19, pp.175-184.

Macdonald, G.A. (1967) 'Extrusive basaltic rocks' *in* 'Basalts, the Polderwaart Treatise on Rocks of Basaltic Compositions', ed. H.H. Hess & A. Poldervaart, Interscience Publ., New York, pp.1-63.

Macdonald, G.A. & Abbott, A.T. (1970) 'Volcanoes in the sea: The Geology of Hawaii'; Univ. Hawaii Press, Honolulu.

Mills, M.T. & Wood, C. (1972) 'A preliminary investigation of Vidgelmir lava cave, Mid-West Iceland: A case for cave conservation'; Journ. Shepton Mallet Caving Club, Ser. 5, No. 4, pp.3-17.

Montoriol-Pous, J. & de Mier, J. (1969) 'Estudio morfogenico de las cavidades volcanicas desarrolladas en el malpais de la Corona'; Karst, Ano VI, No. 22, pp.524-562.

Ollier, C.D. & Brown, M.C. (1965) 'Lava caves of Victoria'; Bull. Volcanologique, Vol. 28, pp.215-229.

Peterson, D.W. & Swanson, D.A. (1974) 'Observed formation of lava tubes during 1970-71 at Kilauea volcano, Hawaii'; Studies in Speleology, (Vol. 2, Pt. 6).

Poli, E. (1959) 'Genesis e morfologia di alcune grotte dell'Etna; Boll. della Societa Geographica Italiana, Ser.8, Vol. 12, pp.452-463.

Rittmann, A. (1958) 'Appunti di vulcanologia'; Catania Inst. di Vulcanologia dell'Universita.

Swanson, D.A. et al. (1971) 'Mauna Ulu eruption, Kilauea, volcano'; Geotimes, Vol. 16, No. 5, pp.12-17.

Tubbs, D. (1972) 'Alternate views on lava caves'; Northwest Caving, Vol. 3, No. 1, pp.9-10.

Wentworth, C.K. & Macdonald, G.A. (1953) 'Structures and forms of basaltic rocks in Hawaii'; U.S. Geol. Survey Bull., 994, pp.1-90.

Wood, C. (1971) 'The nature and origin of Raufarhólshellir'; Trans. Cave Res. Gr. G.B. Vol. 13, No. 4, pp.245-256.

(1973) 'Actively forming volcanic structures observed during the Heimaey eruption, Spring, 1973'; Report of the Univ. of Leicester expedition to Heimaey, April, 1973, (manuscript), 20pp.

Trans. British Cave Research Association. Vol. 1. No. 1. pp.29-42. January 1974.

SUBTERRANEAN COURSES OF THE RIVER ALYN, INCLUDING OGOF HESP ALYN, NORTH WALES.

by Peter Appleton

Summary

The development of the surface course of the River Alyn is described. The limits of karstic drainage associated with part of the river's course is established and discussed in terms of the local geology. The recent cave discovery of Ogof Hesp Alyn is described and an attempt made to place it in the context of the known hydrology of the area.

Introduction

This paper has been written in an attempt to create as clear a picture as possible of the karstic drainage associated with the River Alyn in north east Wales. It is also intended as a general introduction to the area, in the light of a new cave discovery, Ogof Hesp Alyn.

Much information has been obtained from literature concerning lead mining as, during the working of the mines, fissures connecting with the underground course of the river were intersected. The river was eventually completely 'short circuited' by deep drainage tunnels leaving the original resurgences dry, except perhaps in the highest of floods. The river enters the mine workings at a point about 1½ miles from the main group of swallets. The form of the underground channels has hitherto been unknown, and although the Alyn valley has received a passing mention in speleological literature no serious attempt had been made to enter the inferred cave system until the Spring of 1973, when, encouraged by a strong draught, a shaft was sunk by the North Wales Caving Club on the site of one of the former resurgences. Open passages were entered at a shallow depth and they have been followed for about 1500 metres horizontally, and to a depth of about 65 metres below the 'pre-mining' water table.

With further exploration and study the cave may yield solutions to long standing problems of water movement and also provide an opportunity to examine shallow and deep phreatic zones of a cave system with a virtual guarantee that there have been no modifications by vadose streams.

The area of present interest extends from the Loggerheads Inn in the south to Rhydymwyn in the north. It is likely that all the karstic water in this area belongs to a single complex system of drainage, although this has been drastically modified by lead mining operations.

Evolution of the Surface Course of the Alyn

The river Alyn rises a mile or two south of the village of Llandegla in eastern Denbighshire flowing northwards in a wide valley between the Clywedian hills to the west and steep limestone hills to the east, (Fig. 1). In the vicinity of the Loggerheads Inn on the Mold to Ruthin road, the river flows more swiftly and occupies a narrow, thickly wooded valley alongside steep limestone cliffs. Further north at Cilcain, the river turns abruptly across the limestone outcrop through the Alyn Gorge. At Rhydymwyn there is another sharp turn, the river then flowing south westwards through Mold, eventually joining the river Dee near Wrexham.

Reference to a relief map of the area clearly shows that the present surface course of the Alyn is not the original one, as a dry valley can be seen continuing northwards beyond Cilcain. Embleton (1957) has shown quite convincingly, from analysis of data of the long and cross profiles of the Alyn valley and the Wheeler valley to the north, that at different periods the Alyn in fact occupied two distinct north westerly courses. The earlier course, indicated in Fig. 1, entered the sea near Prestatyn. Remnants of a wide shallow valley can still be seen both intact north of Caerwys and represented as terraces on the sides of the present valley to the south. At a later date this river was captured by a stream cutting back into what is now the Wheeler valley, probably initially drawing water from the original Alyn via underground channels. Terraces corresponding to this later course can also be identified at a lower level on existing valley slopes.

Embleton has termed these two river courses the Higher and Lower Terrace Alyn respectively and concluded that they were both graded to a sea level some 500 to 520 feet (150-156m) above present sea level, coinciding with a situation thought to exist in late Tertiary times.

The final diversion of the river through the Alyn Gorge is generally considered to have occurred during Glacial times, the latest evidence suggesting that this channel was initiated by the action of sub-glacial streams and not by overflow of meltwater from an ice-dammed lake as was earlier thought (Embleton 1964). It is likely, however, that if this were the case, then the excavation of the rock channel took place before the onset of the last glaciation, since there exist deposits of boulder clay in the present valley floor, upstream of the gorge, through which the present river is still downcutting.

Evidence of Karstic Drainage from the Upper and Lower Terrace

Courses of the Alyn.

Fig. 1 indicates that nearly all of the earlier river courses and a large proportion of the present river's course is over limestone. This implies that there has been at least potential for karstic circulation of river water since the 'Upper Terrace' stage. Definite evidence of such circulation is not available although several presently active drainage systems do occur along these former river courses. The most extensive is that resurging at the powerful spring of Ffynnon Asaph above Dyserth, but a number of smaller springs flow from the limestone into the Wheeler valley both from the north-east and from the south. Should any

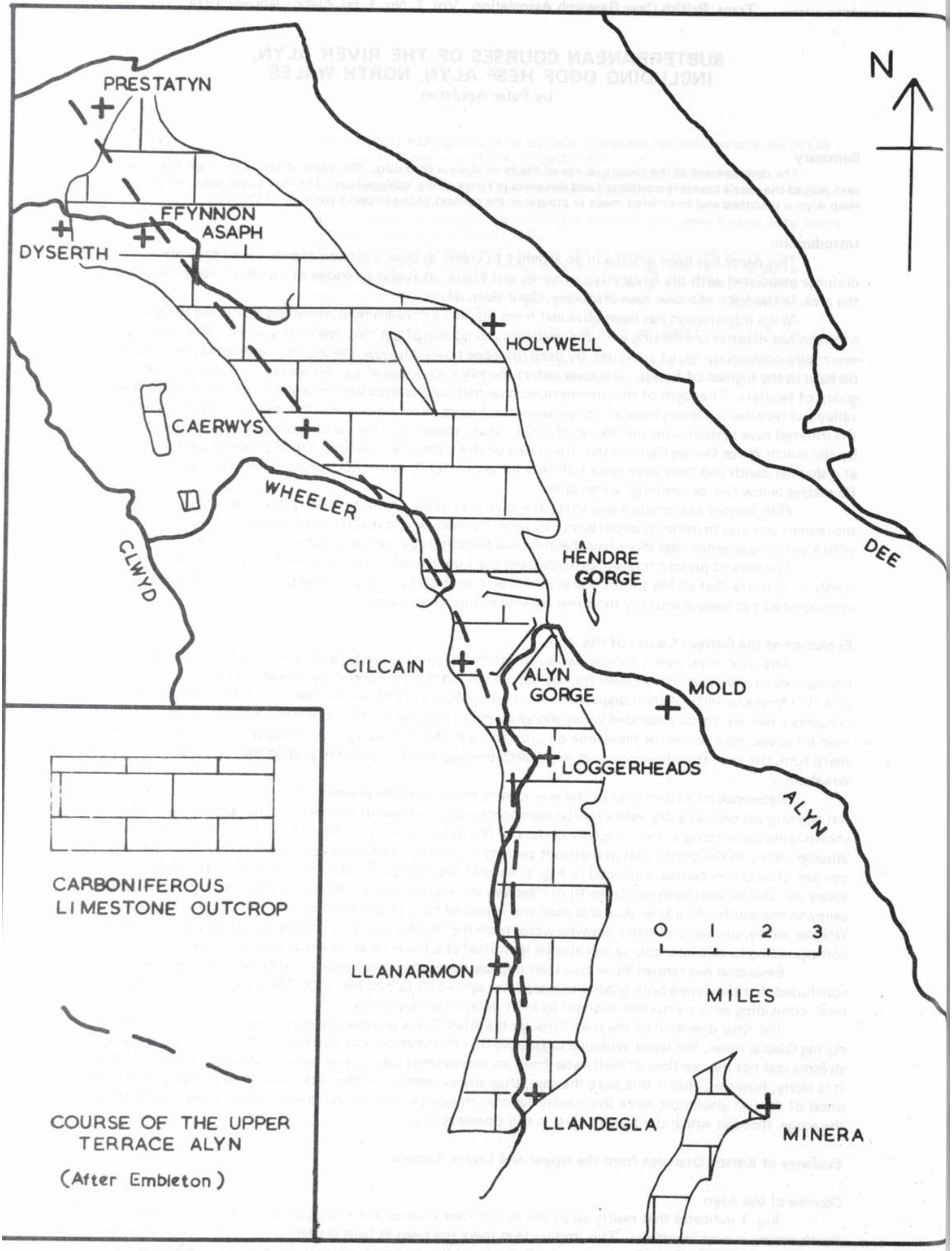


FIG. 1. PRESENT AND FORMER COURSES OF THE RIVER ALYN.

cave systems associated with these springs be entered in the future, it would be interesting to speculate that they have evidence of development by these old rivers.

South of Cilcain the course of the river appears to have been the same since the Upper Terrace stage, thus it is not easy to ascribe evidence to individual stages in the river's development. It has been recorded, however, (Strahan 1890) that during mining operatings east of the present river and one mile north of Loggerheads, 'cavities' were found in a north-south joint, which contained tufa and pebbles of Wenlock shale, a rock outcropping to the south and west. These cavities were above the present river but below the level of the Upper Terraces. It is likely therefore that the pebbles were deposited by streams resulting from leakage from the Upper Terrace Alyn and since other and larger caverns are known in this vicinity at similar altitudes, it would seem that a widespread karstic drainage system was well development by the end of the Upper Terrace stage.

Upstream from the Loggerheads Inn are several springs and cave sites, but the river at present draws water from the limestone and this was likely the case at earlier stages of the river's development.

Geology

Before describing the present underground drainage from the River Alyn in the area between Loggerheads and Rhydymwyn it is essential to have some appreciation of the local geology. Useful accounts are given by Strahan (1890), Smith (1921) and Schnellmann (1939).

The succession of strata is shown in Fig. 2, where it will be seen that the Carboniferous Limestone rests unconformably on Silurian rocks. These are hard shales of Wenlock age and form the Clywedian range of hills to the west of the limestone outcrop. The limestone has been described as forming a segment of a dome, the direction of dip varying from northerly in the north of Flintshire to south-easterly where the outcrop passes into Denbighshire in the south. In the centre of the area, adjacent to the cave, the dip is to the east and averages about 15 degrees.

The lowest beds of the Carboniferous Limestone are termed the Lower Brown Limestone, being somewhat argillaceous in nature. They reach 130 metres in thickness and merge upwards into a pure, crystalline and massive limestone, the White Limestone. This subdivision is about 500 metres in thickness and it is in this rock that the bulk of the karstic water flow is confined. The White Limestone is succeeded by the Upper Grey Limestone, the contact between the two sometimes presenting an eroded appearance, and containing a thin layer of shale. The lowest 30 metres of the Upper Grey Limestone, termed the Intermediate Limestone by Schnellmann, is a dark, crystalline and well-bedded rock. It is followed by two shale beds, the Lower and the Upper Shale, each about 3 metres thick, and separated by 25 metres of rock similar to the Intermediate Limestone. The lower shale has been shown to have an important effect in restricting the upward extent of mineralization in the many lead/zinc veins of the area. It has been mapped by the Halkyn District United Mines and found to be continuous over several square miles. The limestones above the Upper Shale are impure, thinly bedded and have frequent shale partings. They are succeeded by quartzites, sandstones and shales of Millstone Grit age.

Structurally the limestone area is complex, being fractured by two distinct sets of faults of east-west and north-south orientations, which are dip and strike faults respectively. In addition there is the major dislocation of the Nant Figillt Shear Zone, throwing down the strata about 300 metres to the south west in the vicinity of Rhydymwyn, and effectively separating our area from that of Halkyn Mountain to the north-east.

The E-W faults are usually mineralised and their exploitation has in past years supported a lead mining industry. They are considered to be tension fractures and their vertical component of movement is greater than the horizontal. Generally the E-W faults or 'veins' have been found to have a northerly downthrow in the area south of and including the Pant y Buarth vein, but north of and including the Pant y Mwyn vein, they have a southerly downthrow. The area between these two veins therefore represents a local structural trough.

The N-S faults are thought to be of compressional origin and have a large horizontal component of movement. Where examined they are generally found to consist of wide zones of crush breccia. Mineralisation in the area under consideration is said to be infrequent, but sometimes large deposits of vein calcite have been found and worked. Due to their rather 'open' nature these N-S faults or 'cross-courses' offer easy routes for water movement. Smith (1921), in describing cross-courses, stated that 'they are often empty or in communication with large empty caverns or 'vughs', and appear to form the principal underground water channels'.

A structure contour map of Schnellmann (1939) indicated four cross-courses in the Alyn Gorge area, having a nett downthrow to the west of about 200 metres. The E-W width of the limestone outcrop has thereby been greatly increased by successive uplift of strata to the east.

It will be appreciated that the overall system of fracturing gives the appearance of dissecting the area into a series of large blocks. Smith (1921) compared this situation with a child's box of bricks 'in which some of the faces of contact are cemented together and some left open'. He used this analogy to describe what he termed 'chessboard' and 'staircase' drainage. 'If such a box were given a slight oblique tilt, water poured in at an upper corner would make its way by devious routes to a lower corner. The eastward travel of water down dip would be facilitated by the numerous E-W veins and the northward travel by cross-courses. Water could also cross certain bedding planes in the downward direction. This interpretation of the effects of structure on drainage implies an essentially vadose situation with little concept of the well known deep phreatic flow in the area.

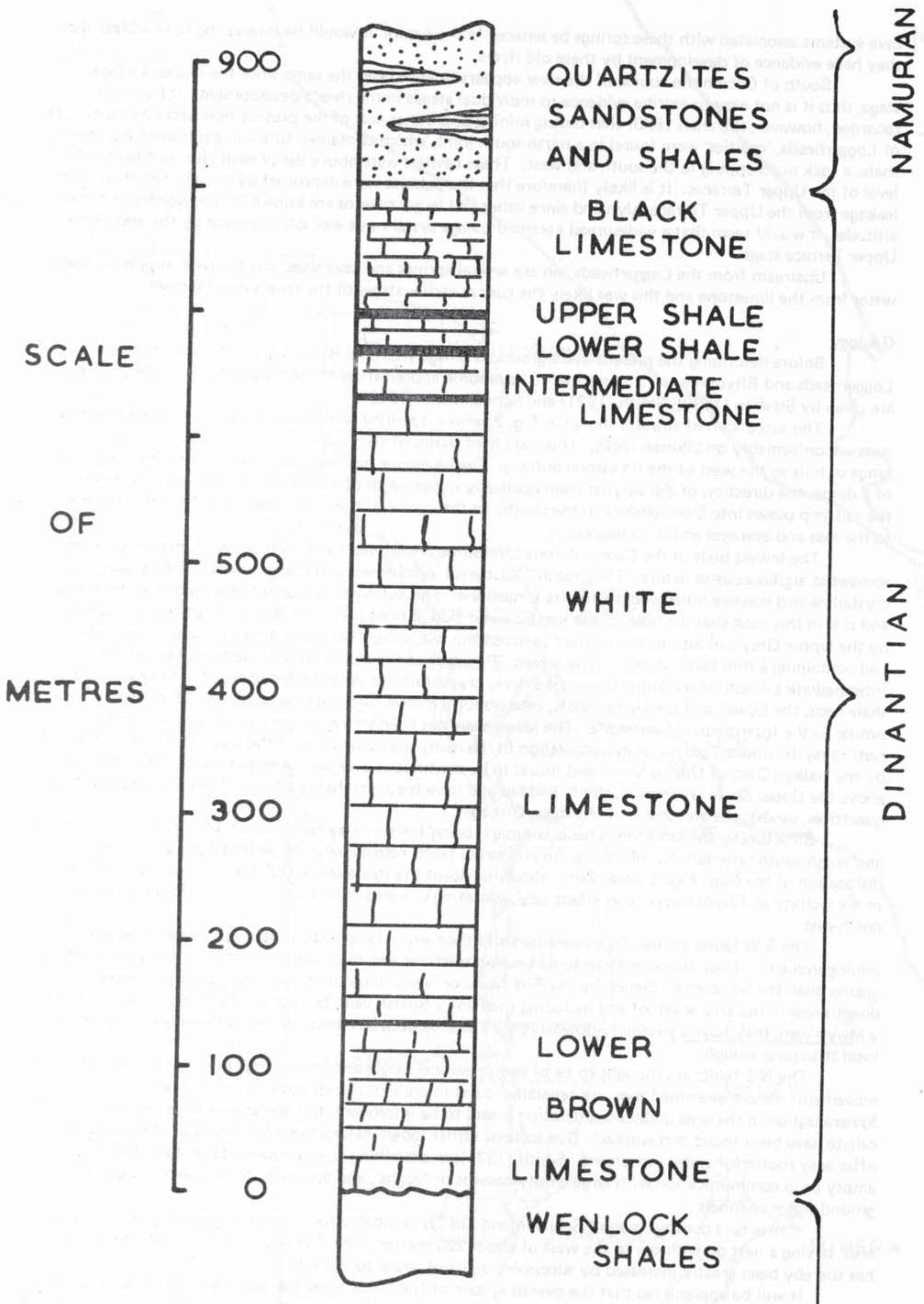


FIG. 2. STRATIGRAPHICAL COLUMN.

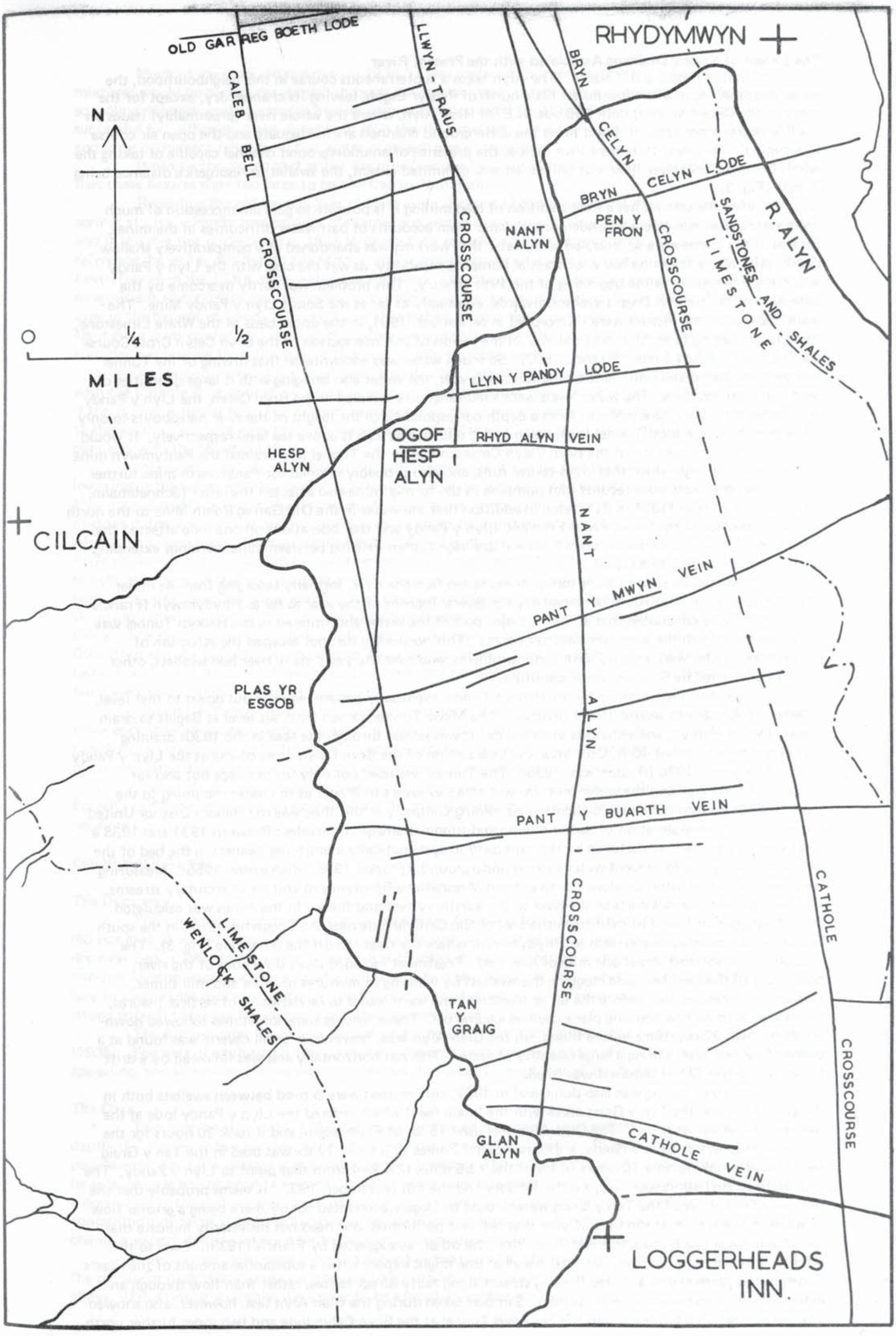


FIG. 3. THE MIDDLE ALYN VALLEY AND ITS GEOLOGY.

The Extent of Karstic Drainage Associated with the Present River

Strahan (1890, p.34) stated, 'The Alyn takes a subterraneous course in this neighbourhood, the water disappearing in a swallow hole a little north of Plas yr Esgob, leaving its channel dry, except for the entry of the Cilcain stream, until 200 yds. N.E. of Hesp Alyn, where the whole river (presumably) issues on the line of a cross-course. In flood times the underground channels are inadequate and the open air course is occupied'. This clear statement thus defines the presence of an underground channel capable of taking the whole of the normal river flow, but only in an area of limited extent, the swallet to resurgence distance being ½ mile (Fig. 3).

Since the district has a long tradition of lead mining it is possible to gain an impression of much more widespread movement of underground water from accounts of past water difficulties in the mines. Several of the mines were so troubled with water that working was abandoned at a comparatively shallow depth, even where the mine had a substantial pumping capability, as was the case with the Llyn y Pandy and Pen y Fron mines at the beginning of the 19th century. This problem was partly overcome by the extension of the Halkyn Deep Level southwards, eventually as far as the South Llyn y Pandy Mine. The main 'feeders' of the district were intercepted in November, 1901, in the upper beds of the White Limestone, the flow increasing to an 'immense volume' in the region of the intersection of the Bryn Celyn Cross Course and the Llyn y Pandy Lode. (Francis 1902). So much water was encountered that driving of the Tunnel was seriously hampered until June of the following year, the water also bringing with it large quantities of sand and even boulders. The water levels were simultaneously lowered in the Bryn Celyn, the Llyn y Pandy and the South Llyn y Pandy Mines, from a depth corresponding to the height of the river hereabouts to only a few feet above the local Tunnel level, being about 440 ft. and 255 ft above sea level respectively. It would appear that the intersection of the Bryn Celyn Cross-Course by the Tunnel also drained the Pantymwyn mine to the south, through which that cross-course runs, and also probably drained the Panybuarth mine further south, it being known from records that pumping in the former mine also affected the latter (Schnellmann, 1955, p.472). Smith (1921, p.81) stated in addition that the water in the Old Garreg Boeth Mine to the north was in connection with that of Pen y Fron and Llyn y Pandy and that operations on one lode affected the other two. The above evidence infers a natural drainage system existing between mine workings extending for two miles in a N-S direction.

After the draining of these mines it was noted that the river, formerly resurging from its underground course near Hesp Alyn, remained dry for several months of the year as far as Rhydymwyn (Francis 1938). It may be concluded that at least a major part of the water encountered in the Halkyn Tunnel was water captured from the subterranean river course. This possibility had not escaped the attention of earlier miners, who were plagued with water problems, and over the years many river bed swallets, other than that recorded by Strahan, were identified.

Since the mines drained by the Halkyn Tunnel eventually became worked out down to that level, it became necessary to secure deeper drainage. The Milwr Tunnel, driven from sea level at Bagillt to drain mines N.W. of Halkyn, was extended southwards. It was driven through the area in the 1930s draining the mines there to about 40 ft. O.D. after the intersection of the Bryn Celyn cross-course at the Llyn y Pandy lode in September 1936 (Richardson, 1936). The Tunnel was used not only for drainage but also for underground haulage and the water problem was often so severe in Winter as to render tramming to the main shaft at Halkyn extremely difficult. The mining company at this time was the Halkyn District United Mines, being an amalgamation of earlier mining and tunnel drainage companies. Between 1931 and 1938 a great deal of work was undertaken by this company in systematically identifying swallets in the bed of the river and attempting to prevent water sinking underground, (Francis 1938; Richardson 1955). Measuring weirs were set up at intervals along the river from Maeshafn to Rhydymwyn and on all tributary streams. The leakage from various parts of the river to the karstic system and thence to the mines was calculated. Severe leakage was found to exist from the area of the Cathole lode near the Loggerheads Inn in the south and at various points down-stream to Rhydymwyn, where the river ran off the limestone (Fig. 3). The 'bad stretches' totalled about one mile of river bed. Treatment included short diversions of the river, concreting of the river bed, and clogging the swallets by washing in mixtures of ashes and mill slimes. Swallets were cleaned out before the latter treatment and were found to be networks of vertical fissures, sometimes with narrow bedding plane cavities leading off. These fissures were sometimes followed downwards for over 20 feet (6m) before filling. In the Glan Alyn area, however, a 'small cavern' was found at a depth of 22 feet (7m) taking a large quantity of water. This ran horizontally and was followed by a drift for about 70 feet (21m) before it was filled.

Some dye testing was also done, and in 1937, connections were proved between swallets both in the Glan Alyn and the Tan y Graig areas with the 'main feed' which entered the Llyn y Pandy lode at the western end of the workings. The Glan Alyn test used 15 lb. of Fluorescein, and it took 20 hours for the colour to reappear at Llyn y Pandy, a distance of 1.72 miles (2.6 km). 17 lb. was used in the Tan y Graig test, the water taking only 10 hours to travel the 1.55 miles (2.4 km) from that point to Llyn y Pandy. The tests were carried out respectively on the 1st July and the 4th November, 1937. It seems probable that the relatively faster flow of the Tan y Graig water would be largely accounted for by there being a greater flow of water in the system at the time of year that test was performed, and need not necessarily indicate that this channel was much more free and direct than the other, as suggested by Francis (1938). Even so the rates of flow are both relatively fast and are what one might expect when a substantial amount of the river's underground journey was as a free flowing stream along fairly direct routes, rather than flow through an extensive and deep seated phreatic system. Samples taken during the Glan Alyn test, however, also showed positive coloration from feeds into the Sea Level Tunnel at the Bryn Celyn lode and two lodes further north.

Much of the work on the river in 1936-37 was undertaken in the belief that the ashes and slimes mixtures would be sucked far enough through the complicated surface network of fissures to be deposited, so sealing the presumed few major fissures communicating with the Llyn y Pandy lode. This was not successful for, although it was possible to stop the flow through individual swallets, others soon opened up and little permanent relief from the 'water problem' was obtained.

It can be concluded that either the mixtures used did not penetrate as far as the main 'fissures' or that these fissures were too large to be blocked by that method.

Regarding the old springs N.E. of Hesp Alyn, Francis (1931) mentioned that the flow from the springs at Llyn y Pandy (presumably the same) amounted sometimes to several thousand gallons per minute and that a dye test undertaken in 1931 to prove their source had been inconclusive. This is the last reference the writer can find to the springs, and it would appear that with the continued driving of the Sea Level Tunnel in the 1930s more water was captured from the natural system reducing the springs from intermittent to complete inactivity, for, to the writer's knowledge, the springs today do not become active even in the highest of floods. It is probable that before mining there were also river bed springs where the Nant Alyn cross-course runs through the valley, as nowadays, with the lowered water table, there is considerable leakage from the river in this area, on those occasions when the river flows so far.

The present limit of the Sea Level Tunnel is the Cathole lode, which is intersected at its junction with the Cathole cross-course. A 'fairly large' feed of water issues here, but it is not known to the writer if this is river water or not. It is known, however, that the water standing in the Maeshafn Mine, one mile to the south of Cathole, often falls to many yards below its adit level, and that the Cathole cross-course also connects with the Maeshafn Vein.

Interpreting the above information, with confidence it can be said that, even before the drastic lowering of the water table by mining operations, there was a single interconnected system of karstic water flow extending at least from the Garreg Boeth lode in the north to the Cathole lode in the south, a distance of three miles (5 km). The major contribution of water to this system has been from swallets in the river Alyn from Loggerheads downstream to Cilcain. The stretch of the river's course between Cilcain and Rhydymwyn can be considered to have been an area of resurgence of water from various limbs of the system, even though leakage occurs at present, when the river is flowing, due to the artifically lowered water table. It is also clear that water sinking from the river in the west ran eastwards down the dip of the limestone until meeting one or other of the cross-courses where it flowed northwards to resurge in the Alyn Gorge. The system is probably largely phreatic, due to low relief between the furthest group of swallets at Glan Alyn and the old resurgences at Hesp Alyn, a drop of from 590 ft. (177m) to only 470 ft. (141m) respectively over a distance of two miles (3.2 km), and further indicated by the great depths at which water feeds were encountered during mining.

What has hitherto remained a mystery is the form the underground channels take. From the large flows encountered during mining one assumes they are fairly substantial, but one gains, from the available literature, an impression of high narrow fissures, perhaps filled with breccia and communicating with the occasional large but isolated cavern at the intersection of vein and cross-course.

There would appear to be no connection between the 'Alyn System' and the large flow from Powell's Lode at Rhosesmor, as samples taken from this water, during the dye testing described, were all negative.

OGOF HESP ALYN

The Discovery

The entrance to the cave system of Ogof Hesp Alyn was found by chance in April, 1973; in fact it did not look at all like a cave entrance but more like a small patch of gravel amongst the grass, above the dry river bed. Closer examination revealed a noticeable draught alongside a small rock outcrop. A few minutes feverish excavation produced a hole about two feet deep, the few inches of roots and topsoil giving way to clean loose rocks and gravel. The draught was tested with lighted newspaper and was found to be strong enough the draw the flames completely underground.

The site was later found to coincide with one of the old springs indicated in the report of Francis (1938). The idea of exploring a cave system downwards from the resurgence end, albeit now dry, was most appealing, and so serious digging was commenced that week by members of the North Wales Caving Club.

The Cave

Two months later, after a lot of digging in fissured limestone, the bottom fell out of the dig at a depth of 7 metres, into a narrow, flat-roofed chamber of 'Standing' height. Its silty floor sloped steeply downwards into a low passage and another larger chamber. The walls of this cavity were mostly angular, large fragments having been broken off at some period and now seen lying as silt-covered boulders blocking a downward rift which ran the length of the floor. 'Older' areas of wall displayed the large rounded concavities typical of limestone solution in slow-moving phreatic waters. There was no other exit from the chamber except the rift, where a route through the boulders could not be found.

The chamber must once have functioned as the top of a 'phreatic lift', water flowing upwards from the rift under hydrostatic pressure, and out to the surface via the springs in the river bank some 10 metres above. Many similar examples were later to be identified within the cave.

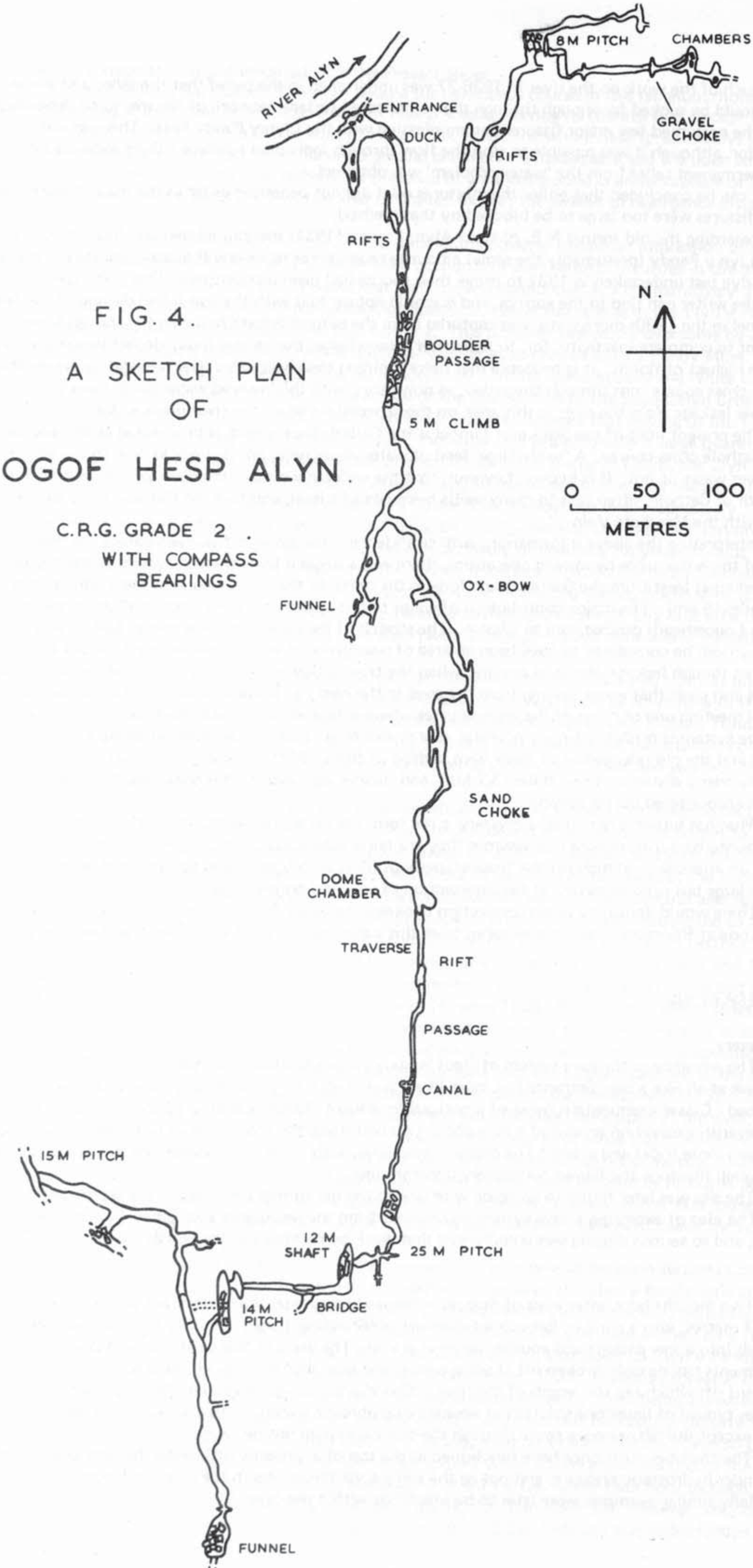


FIG. 4.

A SKETCH PLAN OF

OGOF HESP ALYN.

C.R.G. GRADE 2 . WITH COMPASS BEARINGS

Back in the low passage from the entrance chamber, the source, of the now outward draught, had been found in a low downward-sloping passage floored with coarse sand. The roof soon dipped lower and a pool was met having only a few inches of airspace; later it was stirred up into liquid mud consistency (Plate 1). Beyond, the roof lifted and the passage continued at crawling height for about 50 metres after which it was possible to walk. The floor was an even firm silt, with no sign of a stream channel, and its gentle undulations along the passage reflected the profile of the roof. The silt was apparently deposited by a slow-moving phreatic stream. The walls were gently contoured except where joints crossed the passage giving rise to a succession of small solution chambers. As the passage become higher, both narrow vertical solution tubes and rifts occurred, the latter extending upwards for about 10 metres. These features were developed along N-S joints parallel to the passage, which was here being followed southwards.

At a distance of about 100 metres from the entrance a much larger passage was entered, extending both to the north and south.

Southwards from that point the cave descends steeply over a large boulder pile, covered in the usual silt displaying runnel and ridge markings. Above an enormous boulder, jammed across the passage, the roof can be seen to descend through different beds of limestone in a series of large inverted steps.

The passage at the foot of the boulders is most interesting as its upper part is clearly typical of a large phreatic tube, while the lower part of its cross section can only be described as a 'vadose' trench (Plate 2).

Distinct scalloping in the tube section indicated a rapid, upward and outward movement of water. Staining on the upper walls followed the upward inclination of the passage and since it cannot therefore represent a 'static' tide mark, must have been made under conditions of flow. The trench part of the passage has no scallops, but the walls do show some evidence of vertical fluting similar to that seen in some surface river channels which have been abraded by the churning or 'potholing' effect of pebbles. In a few further metres of passage the roof dips from about 5 metres to a low archway only 1 metre high. On the entrance side of this arch is a heap of pebbles washed through from within the cave. After the low arch the roof quickly lifts to about 3 metres. The archway, being a constriction in the passage, has clearly resulted in a local increase in water velocity. The writer therefore believes that the floor trench was abraded by the sediment borne at relatively high velocity by the outward phreatic stream, and has not resulted from down-cutting by a vadose stream.

Soon the passage divides, one branch meandering down to a chamber, the floor of which slopes down to a boulder-choked 'funnel' in the centre. The only ways on are a series of small narrowing tubes, and it seems fairly clear that the 'funnel' operated as a phreatic lift similar to the chamber near the entrance.

The other passage at the 'divide' is more or less tubular in cross section with the same silty floor, but here much silt has been removed and blocks of this material are in various stages of slumping into the passage.

The passage, now about 3 metres in diameter, meanders gently uphill generally in a southerly direction, until a high rift-like portion is entered. Beyond this section a floor trench is again found.

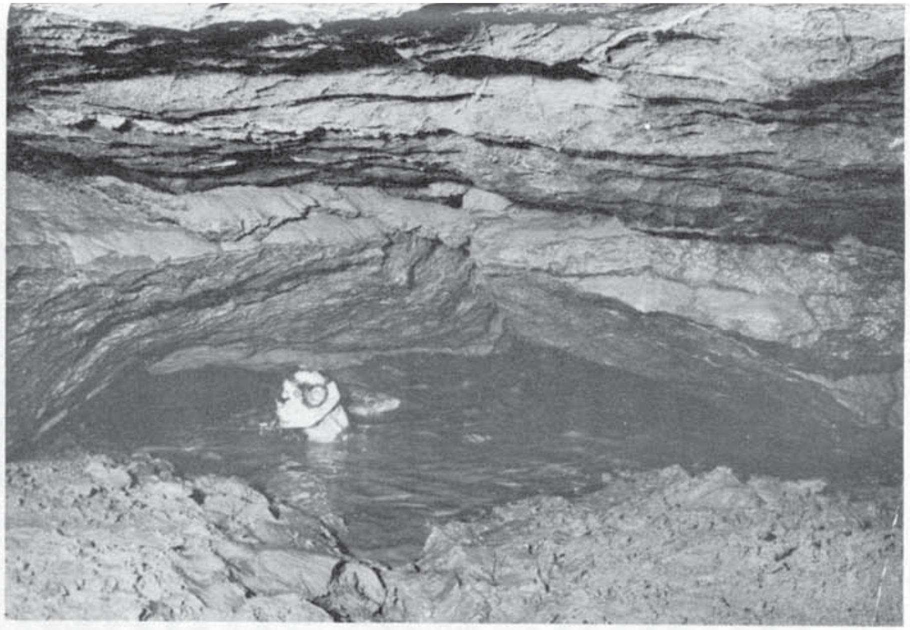
A little further on rounding a corner, one is confronted by a sudden steep wall of rock at the top of which is a lenticular shaped window through which one can see the passage beyond. The passage proper winds sharply up and around as a well-formed tube, cutting back on itself in what must be a solutional analogy to an 'ox-bow' in a surface river (Plate 3). The 'ox-bow' has been formed along a small fault which has thrown down the strata about 2 metres to the north. The tubular cave passage has also developed with a vertical displacement of this amount, being developed along the same bedding plane in the limestone on each side of the fault.

The passage continues for perhaps 200 metres from the junction, occasionally opening into short high rifts and sometimes descending under low archways where heaps of stones or coarse sand on the outside indicate past water flow from within the cave. A feature of this passage and many other passages in the cave are numerous dark stained areas in shallow roof bells, changes in the colour appearing as concentric rings, being pale at the outside and nearly black in the centre, (Plate 4). These must correspond to past airbells, the colour probably being carbonaceous and possibly derived from gaseous decomposition products of vegetable matter in the washed in sediment. In addition faint horizontal tide marks can be detected, all of which tends to indicate draining and re-flooding of the cave system. The passage eventually turns downhill, and behind a large heap of coarse sand the roof and walls close right in to a narrow tube. The outward draught still persisting, the tube was excavated for about 10 metres before the roof lifted only to close down again after a short distance. A little more digging was required before it was possible to crawl through a now steeply uphill passage to emerge in the bottom of a large domed chamber about 10 metres high (Plate 5). Along the lower wall of the chamber runs a channel containing clean washed stones. On the far side of the chamber the roof has been dissolved into a remarkable series of rock pendants and deep solution cavities, with staining from black to reddish brown and creamy yellow, (Plate 6).

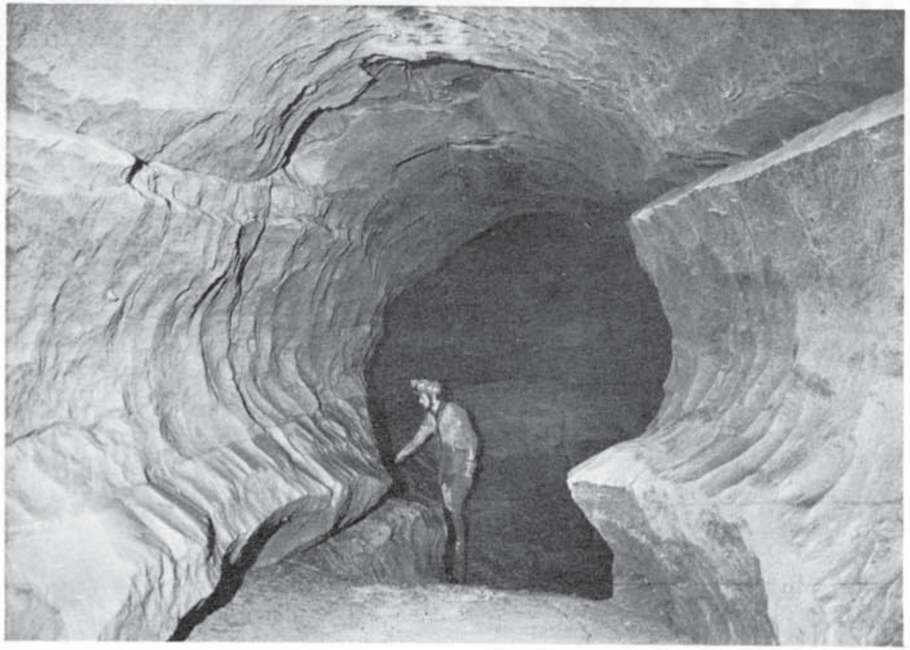
Beyond this chamber the character of the cave changes, being now essentially a long rift passage, sometimes 10 metres or so high and still following a southerly course (Plate 7). Although following a major series of N-S joints the rift passages have also been influenced in their development by one or two bedding planes which generally appear as a conspicuous shelf about halfway up the passage cross section.

Beyond a short but quite deep canal the passage takes more the form of a narrow winding fissure, being conspicuously smaller in cross section than hitherto, and without the usual covering of silt, in fact washed clean. This is a high point in the cave, and, although scalloping of the walls is indistinct, it may, during the later stages of the cave's development, have functioned as a short vadose zone between ascending and descending arms of a phreatic loop.

OGOF HESP ALYN

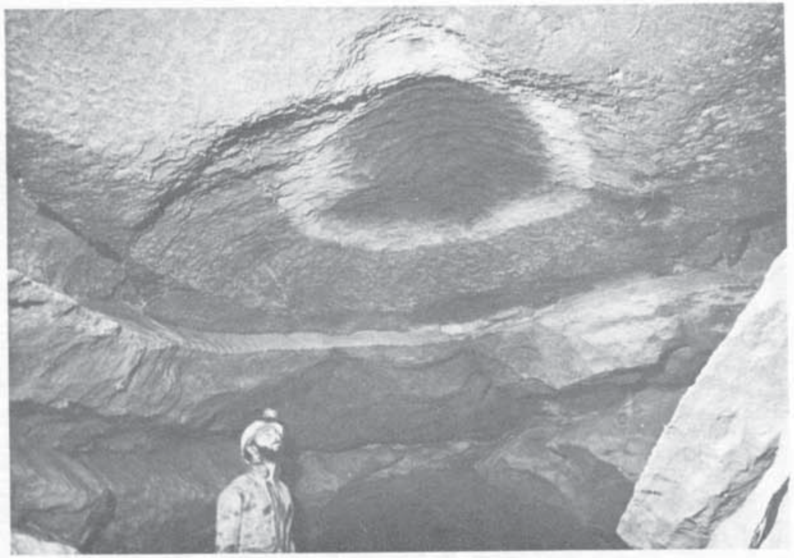


1. The 'Duck' in the entrance passage.

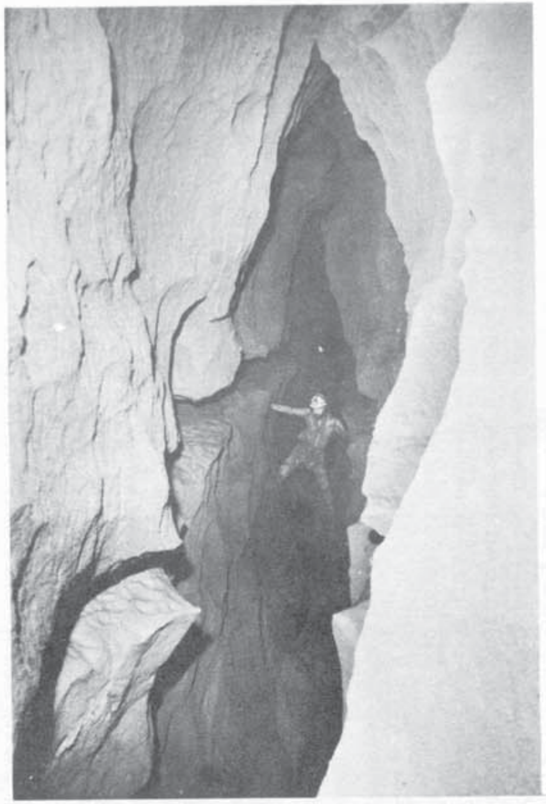


3. Tube passage above the 'ox-bow', with evidence of 'tide marks'.

2. Boulder passage, showing the upper scalloped tube and the floor trench. (Looking towards entrance)

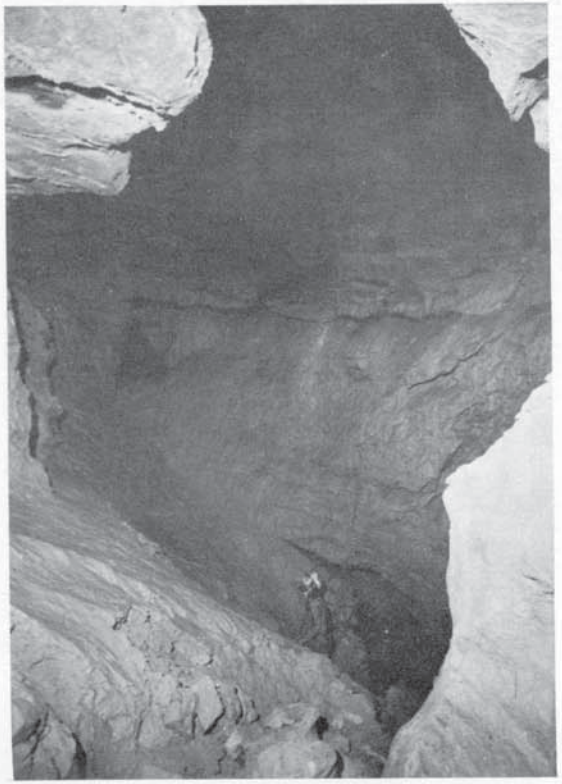


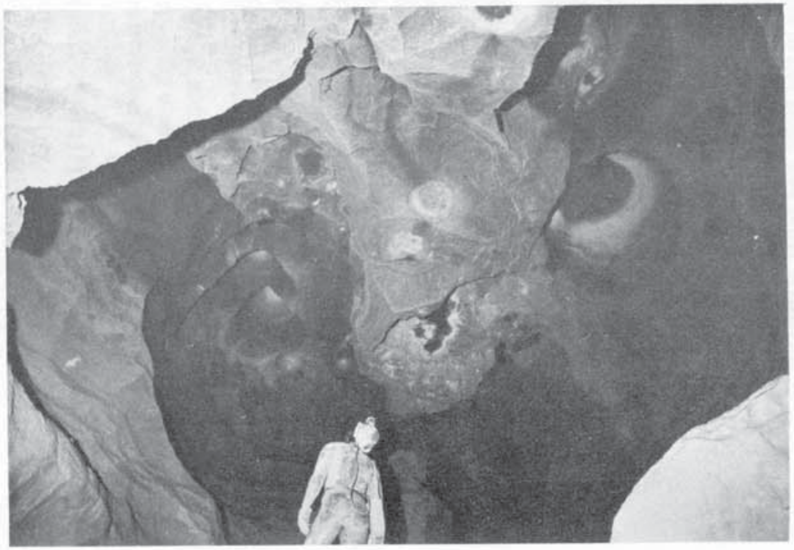
4. Small roof dome with staining from re-flooding of the cave.



7. Rift passage with bedding plane enlargement.

OGOF HESP ALYN





The fissure passage eventually winds its way out into a wide chamber strewn with large slabs which have fallen from the now flat roof. The limestone here is more thinly bedded and may represent the lowest beds of the 'Intermediate Limestone'. Passing the blocks to more clean-washed floor, beyond a slight hump, the passage is descending once again. After one or two metres the silt is met again, and a little further on an area of fissures is entered; one of these opens into the top of a narrow 25 metre shaft (25m ladder and lifeline required) formed at the intersection of two joints.

Silt is found in thick layers on ledges right the way down the shaft and in the small chamber at the bottom. It is only under a rain of drips from the roof that some silt has in places been washed away, there being no evidence that any stream, vadose or otherwise, has flowed down the shaft. In fact the shaft always has and probably still does in time of flood, function as a phreatic lift, inferring that the cave behind and below this upward limb of the phreatic loop becomes full of water. The water would rise slowly from below, eventually overflowing the top of the shaft washing out the phreatically deposited sediment from those portions of the passages above the shaft which descend towards the cave entrance. It must be appreciated that this 'vadose' process can only have taken place since the at least partial draining of the cave system by mining operations. Such events have taken place at least twice since the Spring when the cave was opened, resulting in the partial refilling of the excavated sand passage and obliteration of footprints on the floor back to the boulder passage. The floodwater on the second occasion rose to the duck near the entrance but no further. This poses the question of the point of disappearance of the water within the cave, which will be discussed later.

From the foot of the shaft a wide opening leads into a steeply descending passage falling away into another shaft about 12 metres deep (handline useful). A feature of this shaft is the presence of many delicate horizontal fins of rock indicating solution in a slowly moving upward water flow. The shaft has been developed in an area of strong N-S jointing with many near vertical calcite ribs. The calcite ribs being less soluble stand out in relief from the limestone walls and pieces of calcite, having been completely freed from their limestone matrix, lie as irregular flat plates on the floor below.

The lower part of the shaft contains a boulder choke with rocks of frightening size. Treating this area with some respect one can enter a flat elliptical passage below, which, after a few metres, drops away into twin holes about 5 metres deep (ladder required), with a narrow rock bridge in between leading to a low rising passage. This passage ends abruptly after a further 20 metres on the brink of a 14 metre shaft (ladder and lifeline required) followed immediately by another large descending rift full of boulders. From this rift it is possible to enter at two levels a parallel passage, from which in a south-easterly direction, a low wide tunnel meanders down to a large 'funnel' chamber, the downward continuation of which is blocked by boulders. In a westerly direction an interesting passage rises steeply with the dip of the beds to end suddenly after about 120 metres at the top of a 15 metre pitch (ladder and lifeline required) into a large passage below. This is the limit of exploration of the cave in this area at the time of writing.

Most of these lower passages lack the smooth contours of the passages in the higher parts of the cave, and the impression one gets of water movement, is a slow flow through a complicated network, with ascending portions of phreatic loops developed at strong vertical N-S joints, and horizontal or descending portions developed at two or three distinct bedding planes.

Returning now to the boulder passage near the entrance, this can be followed northwards for about 150 metres eventually entering a boulder choke. At intervals along this passage small holes communicate with a lower passage under boulders.

Two upward rifts can be climbed from this passage, one on the east side containing a thick broken layer of stalagmitic calcite which has been partly re-dissolved. This is the only stalagmitic deposit so far found in the cave and occurs in and below a narrow chimney. It is covered with silt but higher up the chimney the silt is absent. The point at which the silt finishes must represent the height of the last resurgence and the water level within the cave. The fact that thick stalagmite has been found below this level and has partly re-dissolved indicated a lower water level in the cave at one time, probably of the order of 3 to 4 metres.

At the boulder choke a rift can be descended by ladder for 8 metres at the foot of which a recent stream has produced a clean washed channel through silt covered rocks. A couple of short drops are followed by a narrow crawl, soon emerging into a low steeply descending bedding passage. The floor of the passage is unusually flat and smooth and could indicate a plane of movement in the strata. Against the walls a section of previous fill can be seen consisting of silt, with a layer of small pebbles resting on the floor. Lower down, the bedding passage levels off, and was blocked with a steep bank of pebbles, all highly polished. They appear to have been derived from the fill by a stream flowing down the bedding passage. The pebbles have been excavated and found to occupy a 'step up' in the passage, beyond which two chambers were entered. These contain the usual boulder blocked holes in the floor and must originally have functioned as phreatic lifts being very near to the old springs. Beyond the chambers a 20 metres shaft has been found, which at the time of writing has not been descended, (ladder and lifeline will be required). The source of recent water could be the stream which flows up from the south end of the cave in flood, flowing under the floor of the boulder passage to seek out another route into the mineworkings below.

In many passages near the river, stream pebbles may be seen where the silt has been removed. A trench to drain the 'duck' near the entrance also revealed a layer of pebbles under about 25 cm of silt and just below a thin layer containing the remains of vegetation. It seems unlikely that pebbles would be washed up from a deep phreatic zone through large passages, so they must have resulted from local leakage from the river into the system. This infers a lower resurgence at one time.

Summary of Hydrology

Pre-Mining

Ogof Hesp Alyn and the neighbouring spring sites east of Hesp Alyn Farm, without doubt, represent the last natural point of resurgence for the river Alyn system of karst drainage. There is evidence to suggest that the water table within the known cave area was lower at one time and that water flowed into Ogof Hesp Alyn from the present entrance area. This infers a lower resurgence which was probably in the region of the intersection of the Nant Alyn cross-course with the Alyn Gorge. This would explain the convergence of present water flow in this area indicated by the massive leakage into the mine workings at the Llyn y Pandy lode. The reason for the development of the Hesp Alyn springs in preference to springs at Nant Alyn is not clear, but it would appear that the Alyn valley was deeper at one time and is now partly filled with boulder clay, which could have choked the lower resurgence.

The present river swallets, between Loggerheads and Cilcain, seem to be very recent in origin consisting of leakage through innumerable fissures over long stretches of river bed. Water probably leaks into an older system of channels existing at a fairly shallow depth beneath the present river bed, the older swallets which once fed them now being blocked by boulder clay.

The writer proposes the following scheme for the evolution of the drainage system:–

1. Widening of bedding planes, joints and fault planes by percolation water and concentration of flow down dip and along strike to the north to resurge near the convergence of the Nant Alyn and Bryn Celyn cross-courses near Rhydymwyn, in a valley to the west of the Nant Figillt Shear Zone, and pre-dating the formation of the Alyn Gorge.
2. Progressive leakage from both the Upper and Lower Terrace Alyn resulting in the development of a deep and extensive phreatic system, probably with a comparatively limited vadose zone due to the only slight relief between swallets and resurgence and great depth of limestone with 'open' fissuring.
3. Clogging of swallets during earlier periods of glaciation.
4.(a) Formation of the Alyn Gorge at some time before the last major glaciation, probably initially by sub-glacial streams, then by a major meltwater river, resulting in dissection and draining of the upper parts of the phreatic system, isolated parts of which have been encountered during mining.
(b) Short term invasion of 'sub-river' phreatic loops and deposition of gravels therein.
(c) Development of exposed channels, as resurgences in the lower Alyn gorge, and swallets in the upper Alyn gorge but with a very shallow vadose zone.
5. Re-glaciation with partial filling of the Alyn Gorge and valley with boulder clay and finally with gravelly deposits.
6. Partial re-excavation of the valley and development of the present swallets. Development of springs at Hesp Alyn as the main point of resurgence for the Karstic drainage from the present-day river swallets.

Post-Mining

It is likely that the system described was first partially drained during working of the Llyn y Pandy and Pen y Fron mines in the latter half of the 18th century, when extensive pumping was carried out by water wheels and later by pumping engines. A depth of about 50 metres below river level was drained, Walker (1791). After about 1805 working ceased and the area was not again unwatered until the Halkyn Tunnel reached the area in 1901. This resulted in a permanent change to the flow in the Alyn system the resurgences becoming intermittent, indicating that the fissures connecting with the mine were large enough to take the normal flow but not the flood flow in the system. With the driving of the Sea Level tunnel into the area the springs apparently ceased to function altogether, although backing up still occurs in the natural system as confirmed by exploration in Ogof Hesp Alyn and by the fact that flood pulses in the Sea Level tunnel are considerably longer than in the surface course of the river.

Relation of the Alyn System to Geology

Clearly the most important geological factor in the development of the Alyn drainage system is the presence of N-S cross-courses, which are often continuous over several miles of country. Evidence from Ogof Hesp Alyn suggests that water flow is not necessarily confined to these fault fissures although the direction of water flow is clearly influenced by them. It seems fairly certain that the main Karstic flow is confined to the White and Intermediate limestones below the lower Shale. The latter bed appears to act as a stratigraphical barrier to the upward movement of phreatic water, similar to its effect in controlling the upward extent of ore shoots in the E-W mineral veins. It is likely that percolation water above the shale beds is collected into a few major channels and enters the main system through breaks in the shale beds afforded by faulting.

Since the strata are thrown down in a trough between the Pant y Mwyn and Pant y Buarth veins, which are between the swallets and the former resurgences, it is likely that this is a low point in the cave system also. The rapid increase in depth of passages in the southern end of Ogof Hesp Alyn therefore, is probably due to the proximity of the Pant y Mwyn vein, which has a downthrow of about 100 metres to the south.

It is reasonable to suppose that the explored extent of Ogof Hesp Alyn is typical of the karstic drainage channels in the area as a whole. The present vertical extent of flow in this system is about 180 metres from the river bed at the swallets, to feeders entering the Sea Level Tunnel. Of this about 130 metres would be below the pre-mining water table, and indicates a system of deep phreatic flow as described in the theory of W.M. Davis (1930).

The form of passages in Ogof Hesp Alyn suggests a pattern of water movement similar in some respects to that of parts of the Mendip Hills as described by D.C. Ford (1968). Tubular passages have been developed along bedding planes, but with the strong influence of N-S faults and jointing, water flow has been along strike in addition to down dip. Joint chimneys are much in evidence, and in the resurgence part of the cave so far explored, they form the 'lifting' portions of phreatic loops, linking bedding plane tubes. Floor trenches occur in the crests of several higher loops, but appear to indicate, in this case, abrasion by a stream load in rapid flow conditions near the top of a phreatic zone, rather than isolated vadose trenches.

The amplitude of phreatic looping so far encountered is over 60 metres, but could well exceed 100 metres in the area of the structural trough described previously

Conclusion

It would be unwise of the writer to draw a series of detailed conclusions on the development of the Alyn System as so much information is lacking which may soon be available. An accurate survey of Ogof Hesp Alyn is being made and of course exploration is continuing. The flooding problem is being treated with respect and is likely to hamper work in the further parts of the cave during the Winter months.

Although some of the ideas expressed in the paper are rather tentative, it is hoped that they will stimulate discussion of an area which has a lot to offer to the serious speleologist.

Acknowledgements

The author wishes to thank fellow members of the North Wales Caving Club whose hard work has made possible the exploration of Ogof Hesp Alyn, and also Mr. A.W. Boustred of Halkyn Mines for his friendly and helpful interest.

27th October, 1973

Peter Appleton,
St. Jude,
Minera,
Wrexham,
Denbighshire.

N.B. This cave is very liable to flooding and low sections may take 2 weeks or more to drain after a flood.

References

Davis, W.M. 1930. Origin of Limestone Caverns. Bull. Geol. Soc. Am. Vol. 41. pp.475-628.

Embleton, C. 1957. Some Stages in the Drainage Evolution of North East Wales. Trans. Inst. Brit. Geog. Vol. 23. pp.19-35.

1964. Sub-Glacial Drainage and Supposed Ice Dammed Lakes in North-East Wales. Proc. Geol. Assn. Vol. 75. Pt. 1. pp.31-38.

Ford, D.C. 1968. Features of Cavern Development in Central Mendip. Trans. Cave Res. Gp. G.B. Vol. 10. No. 2. pp.11-25.

1971. Geologic Structure and a New Explanation of Limestone Cavern Genesis. Trans. Cave Res. Gp. G.B. Vol. 13. No. 2. pp.81-94.

Francis, J.L. 1931. Notes on Water Problem. Correspondence with C.L. Budd of Halkyn Mines and an addendum to the 1938 report of Francis. In private hands.

Francis, J.L. & Thompson-Jacob, J. 1938. An Attempt at Sealing Natural Water-Holes or 'Swallows' in the River Alyn. Report of Halkyn District United Mines Ltd.

Francis, M. 1902. Half yearly managers reports of the Halkyn District Mines Drainage Company. (Flints. Record Office D/DM/219/29.)

Richardson, J.B. 1936. A Revival of Lead Mining at Halkyn, North Wales. Trans. Instn. Min. Met. Vol. 46. pp.339-461.

1955. Attempts at Sealing off River Water from Underground Workings in North Wales. Trans. Instn. Min. Met. Vol. 64. pp.211-

Schnellmann, G.A. 1939. Applied Geology at Halkyn District United Mines Ltd. Trans. Instn. Min. Met. Vol. 58. pp.585-650.

1955. Discussion of 'Richardson 1955', p.471.

1958. Lead-Zinc Mining in the Carboniferous Limestone of North Wales. A symposium of Inst. Min. Met. on the Future of Non-Ferrous Mining in Great Britain and Ireland. pp.235-246.

Smith, B. 1921. Lead and Zinc Ores in the Carboniferous Rocks of North Wales. Special Report by the Geological Survey on Mineral Resources. Vol. 19.

Strahan, A. 1890. The Geology of the Neighbourhood of Flint, Mold and Ruthin. Memoirs of the Geological Survey.

Walker, D. 1791. Survey of the Manor of Mold. (Flints. Record Office, D/KK/267.)

Trans. British Cave Research Association. Vol. 1. No. 1. pp.43-53. January 1974.

THE HYDROLOGY AND MORPHOLOGY OF A KARST AREA IN SWEDISH LAPLAND

by Ulf Helldén

Summary

In the period 1970-72 a karst area on Artfjället in the Caledonian Mountain Range in southern Lapland, Sweden, was investigated. Mainly hydrological and morphological data are presented in this paper together with a summary of the Sotsbäcks Cave, the biggest known cavern of Sweden.

According to Köppen's classification the climate belongs to the type Et, tundra climate. The precipitation is 1009 mm/year and the mean annual temperature is -2.2°C.

The water discharge at the greatest swallets and at the karst spring U_1 is recorded. Some of the underground connections have been proved with dyes.

The morphological forms of the landscape were systematized and then processed morphometrically mainly according to the method introduced by Williams (1969, 1971).

The results indicate that the landscape has high permeability in connection with a highly developed vadose underground drainage system. In the vicinity of the springs, however, marked groundwater horizons may appear.

Considerable parts of the Sotsbäcks Cave are supposed to be of sub-glacial origin.

Introduction

As a stage in the investigation of the properties and effects of the groundwater and chemical processes in arctic and subarctic environments with a bedrock rich in carbonate, a karst area on Artfjället (Fig. 1) has been investigated for morphology, hydrology and chemical processes during the period 1970-72. Mainly hydrological and morphological data are presented and a summary is made of the Sotsbäcks Cave, the biggest known cavern in Sweden.

Geology

The bedrock is a part of the low-grade metamorphic series of the Seve-Kölinappe, which borders the high-grade metamorphic bedrock of the Rödingfjeld nappe. The former is mainly composed of micaceous schists, phyllites, greenstones, migmatites, quartzites and limestones (Kulling 1955). The karst belt, which is 2.4 km^2 in area, is built up of partly crystalline folded limestones, with beds varying in thickness from a few cm to more than 0.5 m. The limestone is probably of Ordovician age. The karst belt is surrounded by migmatitic greenschists interspersed with winding bands of quartz. The contact zone between the limestone and greenschist consists of calcareous and quartziferous phyllite.

The chemical composition of the limestone varies considerably in this are and the bedrock is sometimes dolomitic. The table below gives analyses of two samples. The analyses were carried out by Zoltan Solyum at the Institution of Mineralogy and Petrology, University of Lund, Sweden.

Sample	%Cao	%Mg0	%CO_2	%$Fe_2 0_3$+Fe0	Miscellaneous
1.	40.0	4.9	35.8	0.9	18.4
2.	31.1	18.1	43.6	0.1	7.1

$Si0_2$, $Na_2 0$ and $A1_2 0_3$, in the first place can be referred to the category "miscellaneous". The density is measured at 2.6 g/cm^3.

The top parts of the succession strike in a north-easterly direction but at the level of the tree-line they turn off towards west-northwest in the form of a giant fold. As the strata are highly folded, the dip fluctuates and its values vary from about 10°-50° having a mean value of about 35°W. The joints strike north-northwest to northeast.

During the maximum of the last glaciation the inland ice moved from east to west or west-northwest in this region, situated to the west of the ice-divide. As the thickness of the ice-sheet gradually decreased owing to melting at the close of glaciation, the highest summits were laid bare above the ice surface and acted as barriers deflecting the ice flow. At a more advanced stage of deglaciation the ice is thought to have been channeled by the main valleys and to have formed valley glaciers. These gradually retreated towards the east and thereby created the pre-requisites for the formation of large ice-dammed lakes in the valley. This late-glacial stage left many traces round Lake Över-Uman, which was an integral part of the ice-dammed complex of Gäuta Icelake (Gavelin 1910) which had an area of 550-600 km^2. The shorelines of the icelake at Över-Uman lie about 20 m above the present water level and are for the most part formed in glaciofluvial material. Conspicuous engorged eskers* and delta formations adjacent to the investigated karst area indicate that the supply of subglacial meltwater was copious.

The till cover within the limestone zone has a depth varying from zero to about 30 cm above the treeline and between 30 and 40 cm below this limit. The till is sandy and somewhat washed out because of slope processes. About 75 per cent of the area above the treeline is covered with soil while the area below is almost entirely covered. Large parts of the area below 20 m. above present lake level consists of glaciofluvial material, especially the promontories to the west of the brook Sotsbäcken and Gertrudsviken.

* Engorged esker, Swedish "Slukas", is an esker which can be found in the Caledonian Mountain Range. The eskers are usually found on steep slopes and their long axes are perpendicular to the contours of the slopes (Mannerfelt 1945). They are believed to have formed in gorges cut in the ice.

Climate

The nearest weather station is situated at Hemavan about 25 km to the south-west of the investigated area, in the valley of the Ume River, 450 m above sea level. The station has continuous observations listed from 1965. The annual mean temperature for the period 1965-72 is -0.8°C and the annual mean precipitation amounts to 685 mm. The distribution of temperature and precipitation over the year is evident from the table below. In order to obtain values valid for the investigated area the temperature was adjusted to the altitude of 750 m above sea level in accordance with Ångström's (1958) estimations. The table below gives mean monthly values for 1965-72.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
temperature Hemavan	−14.9	−13.0	−6.7	−2.2	3.7	10.4	11.0	10.4	5.3	3.0	−6.4	−7.8	−0.8°
temperature 750m asl	−16.0	−14.3	−8.1	−3.9	2.0	8.6	9.2	8.6	3.7	3.7	−7.0	−8.5	−2.2°
precipitation Hemavan	50	36	69	35	29	41	98	54	65	81	63	64	688mm

It should be noted that only 5 months in the year are frost-free and, accordingly, only in this period can corrosional processes take place on the ground surface. The subterranean drainage, however, continues all the year round, although to a minimal extent in the six winter months. The annual precipitation of the investigated drainage area, 3.68 km^2, was calculated on the basis of the water discharge measurements that were carried out twice a day in May-August and once a day during one week in December in 1971. During the winter months the water discharge was roughly estimated about once a month. The annual value 1000 mm (1009 mm) was the result of these calculations. The evaporation has been assessed at 150 mm per annum (155 mm) with the help of Tamm's formula (Ångström 1958) $E=30xt + 221$. E=evaporation in mm, t=annual mean temperature in °C.

From the values presented it is evident that the climate of the area belongs to type Et, tundra climate, according to Köppen's classification (Köppen 1936). However, it should be noted that no permafrost exists in this region.

On June 11, 1971, about 5 per cent of the ground surface below the treeline was covered with snow and 65 per cent above this limit. About June 25 nearly all snow had melted away.

Morphology

The karst zone has partly been formed through selective glacial erosion. Under the action of corrosion and frost weathering a karst landscape has developed, characterized by pronounced karst depressions, karren and a highly differentiated subterranean drainage system. The limestone solution intensity in the area has been calculated at 28 mm/1000 years (Helldén 1973). No less than 67 per cent of the annual total $CaCO_3$ transport from the area takes place in the period May-July.

The depressions can be divided into five classes on the basis of their genesis and morphology: swallets, solution dolines, snow dolines (kotlici), joint dolines and collapse dolines.

1. **Swallets** are depressions into which streams disappear underground. If the stream is swallowed by a solution doline, joint doline or collapse doline, the swallet is named solution swallet, joint swallet or collapse swallet respectively.
2. **Solution doline** is a type of depression formed by rain and meltwater trickling down through joints and fissures and dissolving the limestone. The result is a closed depression with fairly even floor and gently sloping sides. The doline is covered with a thin layer of soil with an accumulation of residual and washed down material on the floor.
3. The **snow doline** (kotlici) is in part filled with snow almost all the year round. The development of snow dolines is dependent on frost shattering and the snow meltwater which is supposed to be rich in CO_2. The sides are very steep and sometimes strewn with loose frost-shattered blocks and boulders.
4. The **joint doline** is formed along a joint or along a bedding plane in the limestone. The length generally exceeds the width by two and a half times.
5. **Collapse dolines** are depressions that have developed because parts of the subterranean drainage system have caved in. The largest collapse doline, "Devil's Crater", has a diameter of about 50 m and is directly connected with the stream passage in the inner part of the Sotsbäcks Cave, situated 34 m below the surface.

Common to all the karst depressions is the fact that they function as channels draining the landscape, the swallets by engulfing surface streams and the dolines through the absorption of the remaining water.

Karren furrows are not very frequent. The number of karren can be assessed at about one hundred which are concentrated on a few bare rock surfaces all located above the treeline. The most frequent types are, according to Bögli's (1960) classification: Rillen-, Rinnen- and Rundkarren.

Hydrology

None of the allochthonous streams that reach the karst belt flow over more than c.100 m limestone before they disappear in a swallet. The whole drainage pattern is subterranean except during the snow melt period at the end of May and beginning of June, when autochthonous meltwater can give rise to small brooks. Of the swallets marked on the map (Fig. 2) S_1, S_2 and S_3 absorb at least 95 per cent of the allochthonous water discharge. The rest of the swallets are more or less intermittent and mainly function

Fig. 1.
Location of Artfjället

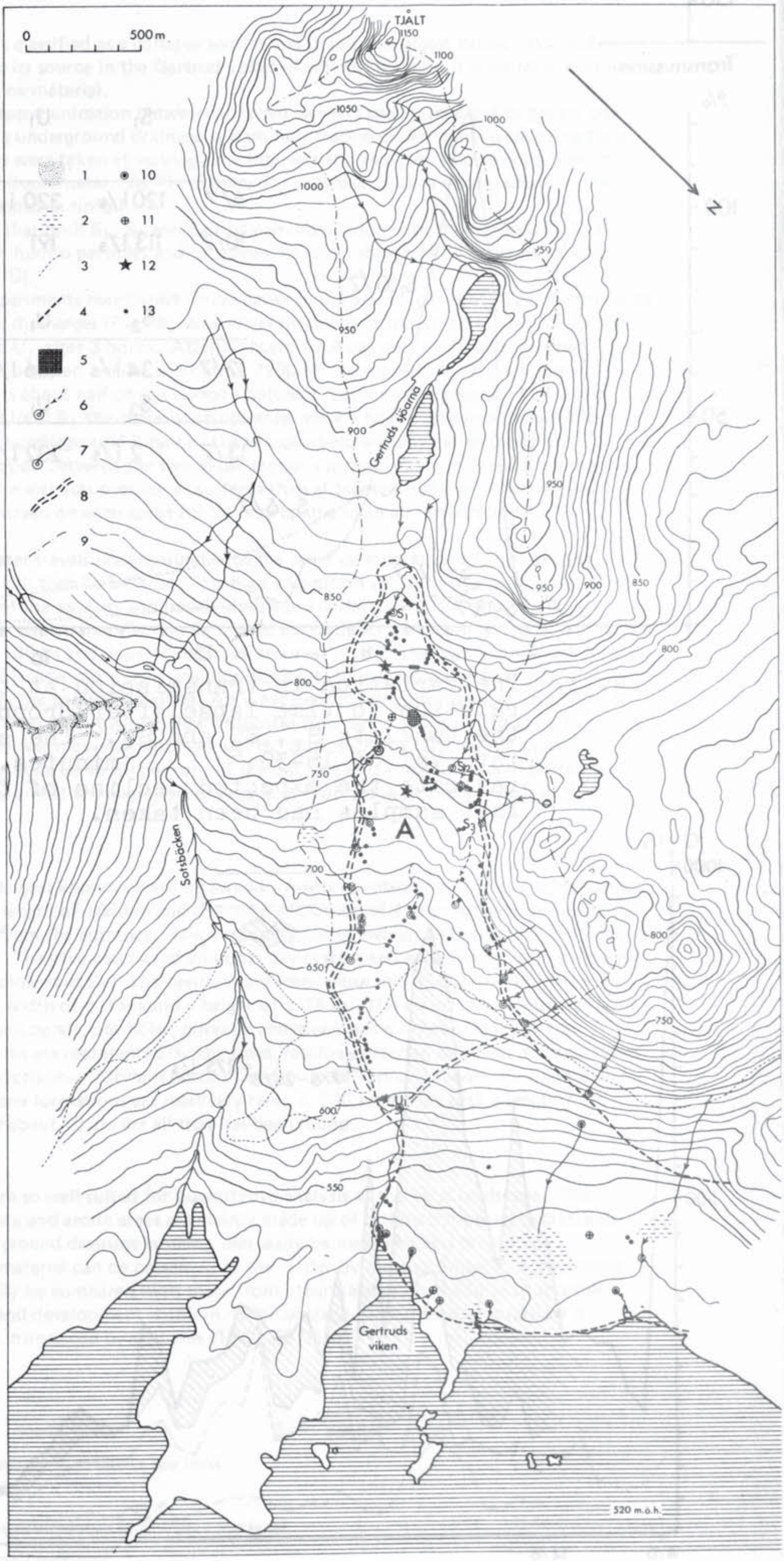


Fig. 2. Artfjället karst area. 1, engorged eskers. 2, peat-moss. 3, tree-limit. 4, limestone border. 5, "Devil's Crater". 6, intermittent stream with swallet. 7, permanent stream with swallet. 8, limestone area A. 9, the drainage are of A. 10, karst spring. 11, intermittent karst spring. 12, fossil karst spring. 13, karst depression.

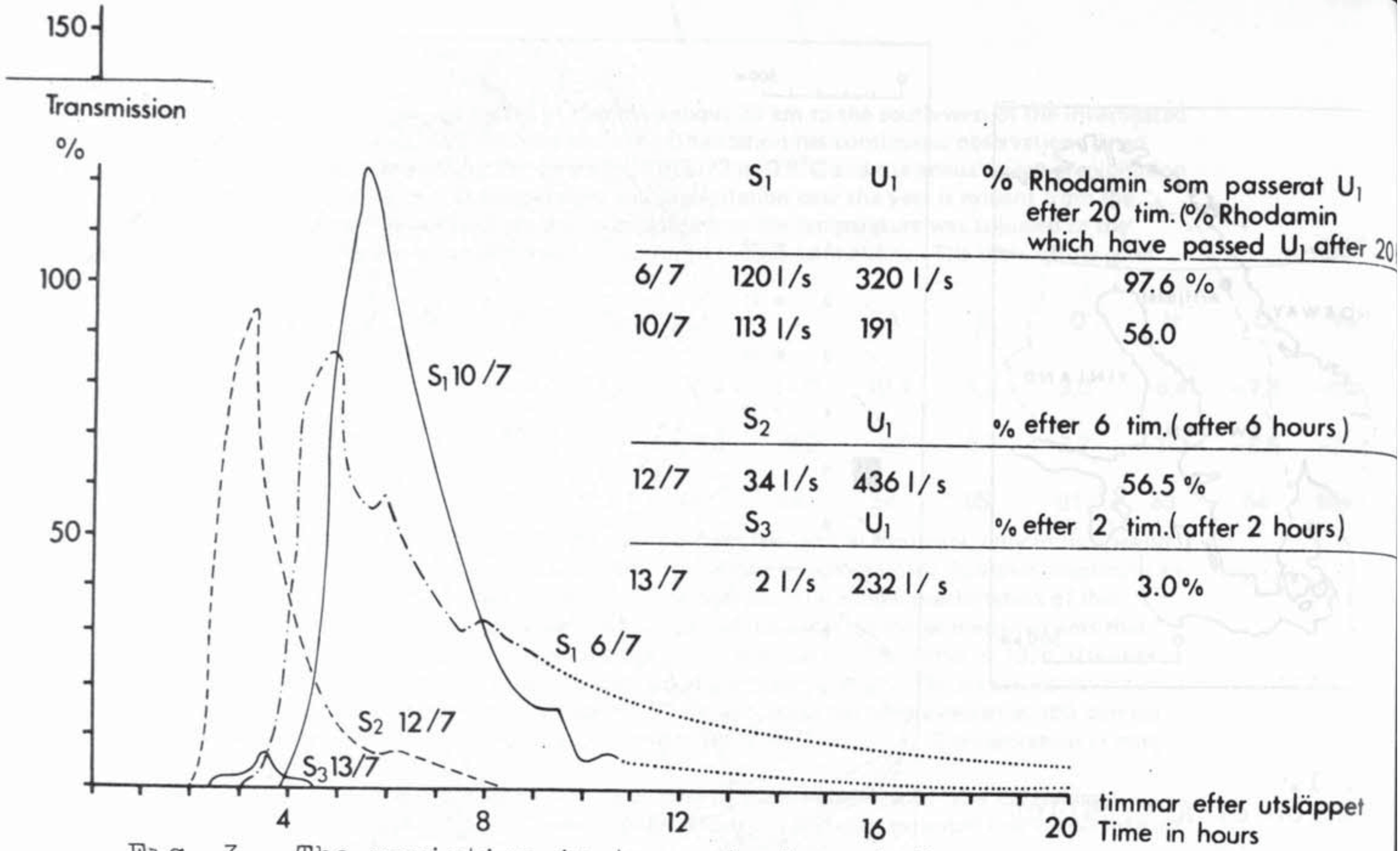


Fig. 3. The variation in transmission at the karst spring U_1 in relation to time lapse after dropping the tracer into the swallets S_1, S_2 and S_3. The samples are drawn with an interval of 15-30 minutes. The dotted lines indicate the expected decline of fluorescence after the last samples had been taken.

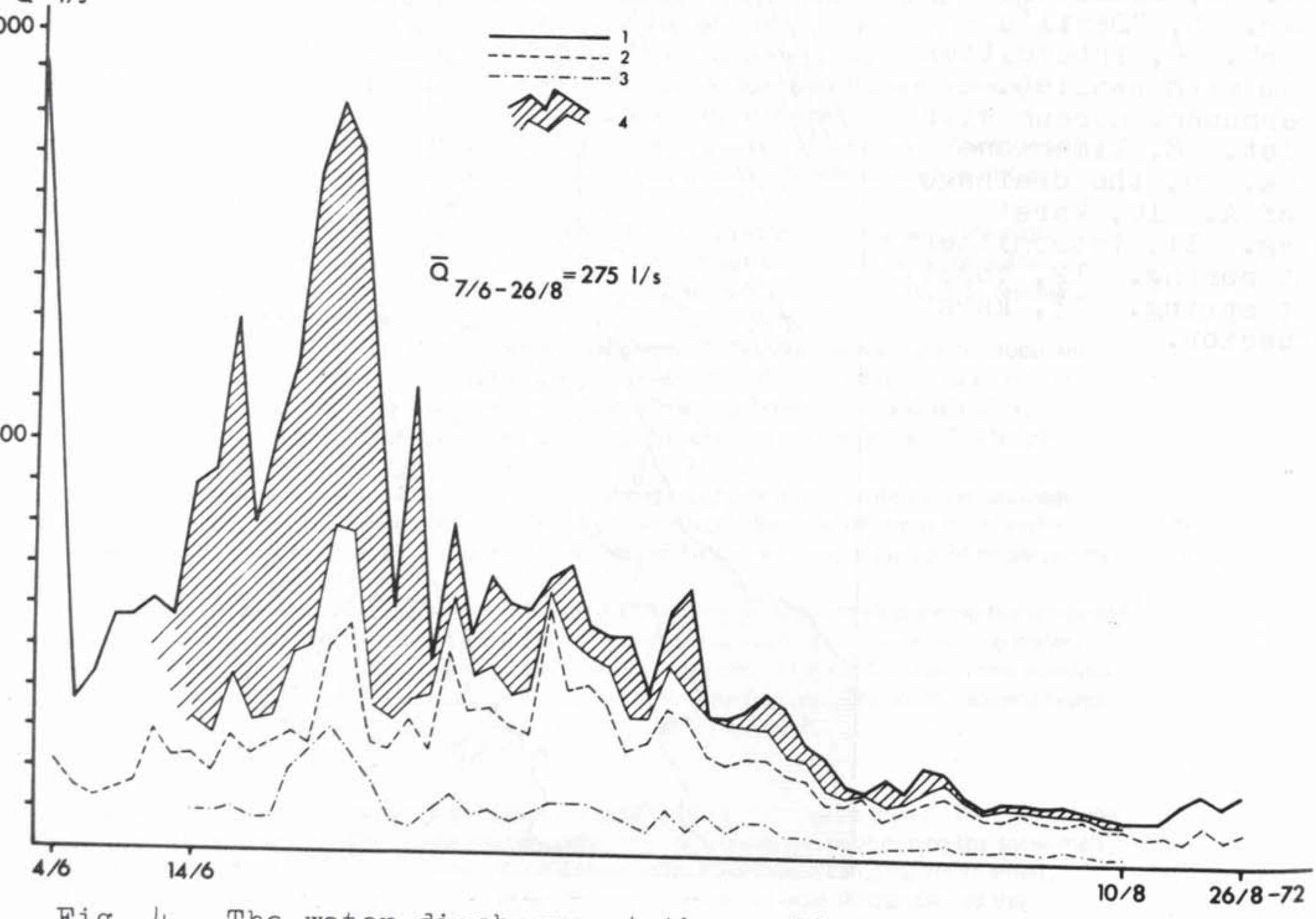


Fig. 4. The water discharge at the swallets S_1 and S_2 and at the karst spring U_1. In the snow melting period at the end of May and the beginning of June up to 60 per cent of the outflow at U_1 consists of percolation water.
1, discharge at U_1. 2, discharge at S_1. 3, discharge at S_2. 4, percolation water.

during the snow melt period, S_1 is classified as a collapse swallet and drains the largest brook that reaches the limestone belt. This brook has its source in the Gertrud Lakes of which the upper is situated in a cirque and the lower is dammed by moraine material.

In order to establish the communication between different swallets and springs and to get an idea of the characteristic features of the underground drainage system four tracing experiments were carried out with Rhodamine B. Water samples were taken at varying time intervals and analysed two months later in an Aminco-Bowman Spectrophotofluorometer. As Rhodamine B is sensitive to ultra-violet radiation, the sample bottles were stored up wrapped in tinfoil.

The experiments showed that both S_1, S_2 and S_3 had communication with the outlet U_1. The adsorption of the dyestuff on clay, humus particles and limestone has been shown to be appreciable under some circumstances (Knutsson 1970).

The adsorption at the experiments mentioned varied between 0.4 and 97 per cent. Two experiments were made at S_1 at different water discharges (Fig. 3). At a water discharge at the spring U_1 of 320 l/s and at S_1 of 120 l/s the colour reached U_1 after 3 hours. After 20 hours 97.6 per cent of the dyestuff had passed through. The least distance between swallet and outlet, 2200 m, corresponds to an underground water velocity of 0.23 m/s, which is about half of the velocity before it reaches the entrance. At a water discharge of 191 l/s at U_1 and 113 l/s at S_1 the corresponding values were 4 hours, 56 per cent and 0.17 m/s. In this case, too, the water velocity underground is half of the velocity before the water arrives at the entrance. The difference in adsorption between the two experiments is probably due to the fact that at the lower water discharge each litre of water acts over larger surfaces than at higher discharge. The two small secondary maxima that can be observed on each curve for S_1 may be due to small ramifications in the drainage network.

If we suppose that the water travels underground with the same velocity as on the surface, the drainage path between S_1 and U_1 will then be 5400 m. The high adsorption values of dye in S_2 and S_3 may be caused by the small discharges of the swallets and poorly developed underground drainage channels.

The water discharge at the two swallets S_1 and S_2 and at the outlet U_1 is shown in Fig. 4. U_1 has a calculated annual mean value of 105 l/s and delivers water, all the year round. During the one week long measuring period in December 1971, after more than one month's frost, an average water discharge of 50 l/s was recorded. The average in the period September-April has been roughly estimated at 25 l/s which is thought to be a minimal value. Most of this winter flow originates from snow and ice melting in the contact zone between the relatively warm cave atmosphere and the zero isotherm. During the snow melt at the end of May and beginning of June up to 60 per cent of the outflow at U_1 may consist of percolation water. This value decreases rapidly and at the beginning of August it is only one or two per cent of the outflow.

The Sotsbäcks Cave

The Sotsbäcks Cave, the largest known cavern of Sweden, forms an integral part of the subterranean drainage system. It has a mapped length of 1650 m and a vertical amplitude of 110 m between the entrance S_1 and the innermost part 520 m from the entrance. The distance between swallet and outlet (U_1) is 2200 m horizontally and 250 m vertically. The cave consists of an upper dry system and an active lower system which is drained by the brook that is swallowed at S_1. The cavities vary from those too small to penetrate to chambers with a length of 20 m, a width of c. 15m and a height of c. 15 m. The abundance of erosive forms is great with water falls, rapids, small ponds, pot-holes, phreatic and meandering tunnels, scallops and cave karren. The accumulative forms are represented by collapses, residual material, sediment accumulations and different types of $CaCO_3$ precipitation. Certain portions of the upper tunnel network are filled with thick well stratified sands. Dripstone formations are relatively rare; c. 200 stalactites with a length from up to 10 cm and one stalagmite of about 10 cm are all that has been found.

Morphometry

Few types of landscape are so well suited for quantitative analysis as the karst landscape. The landscape forms, which in temperate and arctic areas are mainly made up of different types of depressions, karren, springs, swallets and underground drainage systems, can easily be measured and processed statistically. Precise, summarised material can be presented to the reader by means of mean morphometric parameters and the results can easily be compared with those from other karst areas. In spite of this the quantitative method is little used and development is still in its initial stage. The presentation below is mainly based on the methodology introduced by Williams (1969, 1972).

Drainage system

Abbreviations:

A = the area of the limestone zone in km^2. S = swallet

$\bar{H}_s$ = average altitude of the swallets in m above sea level.

K_r = karst resurgence

$\bar{H}_r$ = the average altitude of the resurgences in m above sea level.

L = the length of the brooks on limestone

L_u = the horizontal distance between a swallet and its nearest karst spring.

i = intermittent. p = permanent. f = fossil. σ = standard deviation.

Definitions:

1. **Swallet density $D_s = \frac{\Sigma S}{A}$ gives a measure of how many swallets occur per unit of limestone.**

2. **Rising density $D_r = \frac{\Sigma K_r}{A}$**

3. **Swallet/rising ratio $R_{sr} = \frac{\Sigma S}{\Sigma K_r}$ gives an indication of the extension and ramification of the** subterranean drainage system. A vadose system might be expected to have values greater than one while **well developed phreatic systems might have to have values less than one.**

4. **Mean shortest distance of underground flow $\bar{L}_u$ is the average horizontal distance between each** swallet and its resurgence. If **the communication with the resurgence is not known, the distance to nearest** resurgence applies.

5. **Rising coefficient $V_{hr} = \frac{\sigma H_r \times 100}{\bar{H}_r}$** where σH_r **is the standard deviation of the sample. The rising** coefficient is a measure of the altitude variation of the karst springs and can be interpreted as a measure of the uniformity of the ground water table. It can thereby give an idea of the development and extension pattern of the underground drainage system. Low values of V_{hr} indicate a uniform ground water table while high values might indicate that no ground water table exists. The karst springs have been grouped at three different altitude levels $\bar{H}_{ra}$, $\bar{H}_{rb}$ and $\bar{H}_{rc}$. There are no indications of existing perched water tables. The rising coefficient is stated separately for each of the mentioned groups.

6. **Stream density on limestone $D_1 = \frac{\Sigma L}{A}$ is a measure of the length of surface drainage channel per** unit of area, accordingly, an indirect measure of the permeability of the karst zone.

Results:

	p	σ	i	σ	f	σ	p+i+f	σ
S	11.0	–	9.0	–	–	–	20.0	–
K_r	9.0	–	4.0	–	2.0	–	15.0	–
$\bar{H}_r$	564 m	76.6	586 m	14.5	778 m	56.6	598 m	111.4
$\bar{H}_{ra}$	750 m	0.0	775 m	0.0	778 m	56.6	770 m	35.4
$\bar{H}_{rb}$	595 m	0.0	–	–	–	–	595 m	0.0
$\bar{H}_{rc}$	522 m	2.4	522 m	4.0	–	–	522 m	2.7

The distribution of the springs over the three levels $\bar{H}_{ra}$; $\bar{H}_{rb}$ and $\bar{H}_{rc}$:

	p	i	f	p+i+f
$\bar{H}_{ra}$	1	1	2	4
$\bar{H}_{rb}$	2	0	0	2
$\bar{H}_{rc}$	6	3	0	9

The values of already mentioned characteristics of the drainage system (of area 2.4 km^2) are evident from the table below:

	p	i	f	p+i+f
1. D_s	4.5/km^2	3.7/km^2	–	8.2/km^2
2. D_r	3.7/km^2	1.6/km^2	0.8/km^2	6.1/km^2
3. R_{sr}	1.2	2.3	–	1.5
4. $\bar{L}_u$	0.9 km	1.1 km (1)	–	1.1 km
5. V_{hr}	13.6	2.5	7.3	18.6
V_{hra}	0.0	0.0	7.3	4.6
V_{hrb}	0.0	–	–	0.0
V_{hrc}	0.5	0.8	–	0.5
6. D_1	0.6 km/km^2	0.5 km/km^2	–	1.1 km/km^2

(1) between intermittent swallets and nearest resurgences

The distribution of the swallets over the three types mentioned earlier is evident from the table below. The values in brackets denote the percentage of the total of swallets.

	p	i	p+i
Solution swallets	–	2(10%)	2(10%)
Collapse swallets	8(40%)	5(25%)	13(65%)
Joint swallets	3(15%)	2(10%)	5(25%)

The material presented here gives an overall picture of the drainage structure of the whole karst zone. Through the dividing of the zone into smaller units and treating each unit according to the above method further information can be obtained.

To sum up, it can be stated, according to the low stream density on limestone (D_1) the high swallet density (D_s) and the high rising density (D_r), that the zone has high permeability with a well-developed underground drainage system.

The springs are found at three different levels; $\bar{H}_{ra}$, $\bar{H}_{rb}$ and $\bar{H}_{rc}$. The low values of the rising coefficient (V_{hr}) for the springs of the levels $\bar{H}_{rb}$, and $\bar{H}_{rc}$ indicate that the ground-water is firmly tied to these levels.

The values of the swallet/rising ratio (R_{sr}), being higher than one, point towards the fact that the system as a whole is vadose with no uniform ground-water table with the exception of the spring areas around the levels $\bar{H}_{rb}$ and $\bar{H}_{rc}$.

Karst depressions

Further information about the landscape and its karstification rate has been secured through an analysis of the closed depressions (swallets, solution dolines, collapse dolines etc) which include all the types of drainage holes developed owing to karst processes.

Abbreviations:

C_d = closed depression. A_{cd} = area of depression. L_{cd} = length of the depression.
W_{cd} = width of the depression. H_{cd} = maximum relief of the depression (difference between the highest and the lowest point).
R_{de} = length/width ratio. $\bar{1}_o$ = average orientation of longitudinal axes.
$\overline{Str.}$ = average strike of the limestone. $\bar{J}_o$ = average joint orientation.
d_s = solution doline. d_c = collapse doline. d_j = joint doline.
n = number of observations. A = area of limestone.

Definitions:

1. **Mean length of depressions** $\bar{L}_{cd} = \frac{\Sigma L_{cd}}{n}$
2. **Mean width of depressions** $\bar{W}_{cd} = \frac{\Sigma W_{cd}}{n}$
3. **Closed depression density** $D_{cd} = \frac{C_d}{A}$, i.e. number of depressions per unit area.
4. **Mean area of depressions** $\bar{A}_{cd} = \frac{A_{cd}}{n}$, states the approximate ground surface area (horizontal plane) occupied by the depressions.
5. **Mean depression relief** $\bar{H}_{cd} = \frac{H_{cd}}{n}$
6. **Index of pitting** $R_p = \frac{A_{cd}}{A}$, states the fractional part of the surface of the landscape which is interrupted by depressions. When R_p is close to 1, the landscape is almost completely broken by depressions. When R_p is close to zero there are almost no depressions.
7. **Mean elongation ratio of depressions** $\bar{R}_{de} = \frac{R_{de}}{n}$, states the measure of depression symmetry. The more $\bar{R}_{de}$ deviates from 1, the greater the asymmetry.
8. **The orientation indices** $\bar{R}_{OJ} = \frac{\bar{1}_o}{\bar{J}_o}$ and $\bar{R}_{O.Str.} = \frac{\bar{1}_o}{\overline{Str.}}$ give the ratios of the mean orientation depression long axes with the mean joint orientation and mean strike of the limestone respectively. They give a measure of the dependence of the depressions on joint orientation and strike respectively. Only joints more than 2 m long have been measured. The strike and the joint orientation of the limestone together with the orientation of the longitudinal axes are also represented in the rose diagrams figs. 5-8.

Results:

The swallets are referred to the depression type concerned. The values in brackets give the standard deviation if nothing else is stated.

	d_s	d_j	d_c	$d_s+d_j+d_c$
n	64 (46.0%)	37(26.6%)	38(27.4%)	139(100%)
1. $\bar{L}_{cd}$	8.0 m(9.2)	5.0 m(2.9)	11.2 m(4.3)	8.1 m(8.0)
2. $\bar{W}_{cd}$	5.5 m(5.2)	2.2 m(1.2)	8.1 m (4.1)	5.3 m(5.8)
3. D_{cd}	26.2/km^2	15.2/km^2	15.6/km^2	57.0/km^2

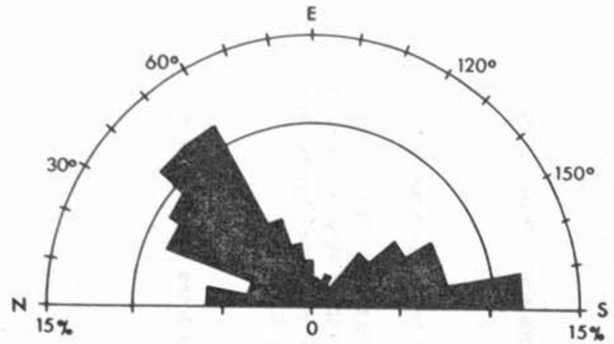


Fig. 5. The orientation of the joints in per cent of the number of measurements made. The material is divided into 10°-classes. n = 152.

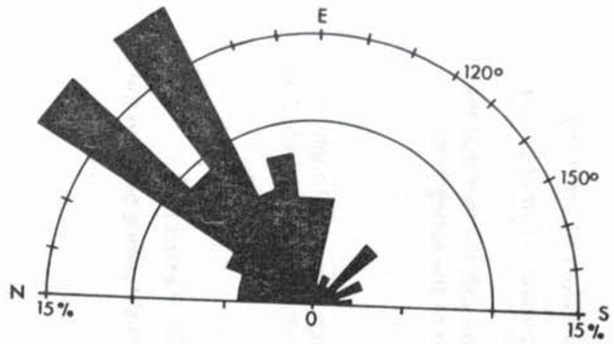


Fig. 6. The orientation of the longitudinal axes in per cent of the total length of the axes. The material is divided into 10°-classes. n = 139.

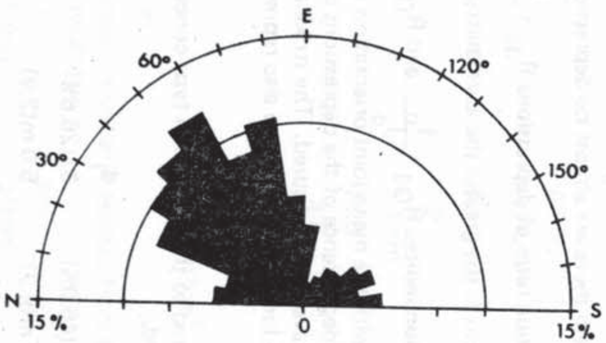


Fig. 7. The orientation of the longitudinal axes in per cent of the number of measurements made. The material is divided into 10°-classes. n = 139.

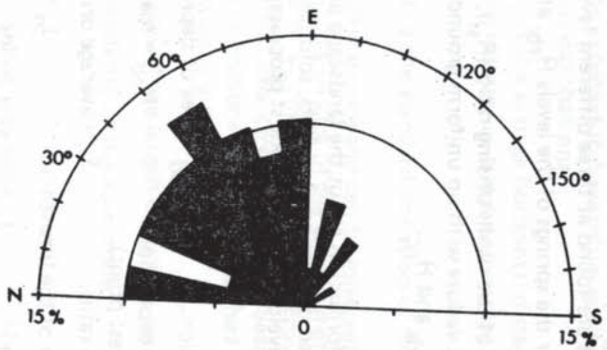


Fig. 8. The strike of the limestone in per cent of the number of measurements made. The material is divided into 10°-classes. n = 50.

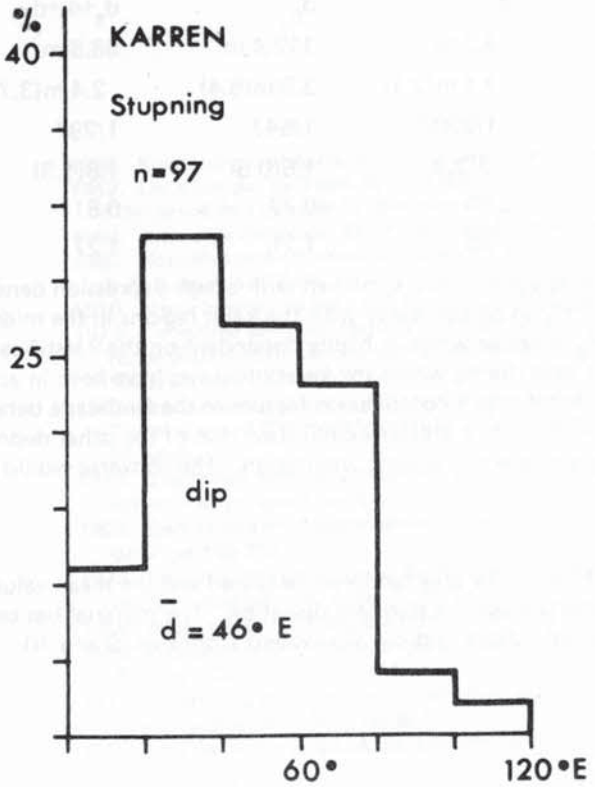


Fig. 9. The variation in dip in per cent of the number of measurements made. The dip of the karren furrows is divided into 20^{o}-classes. n = 97.

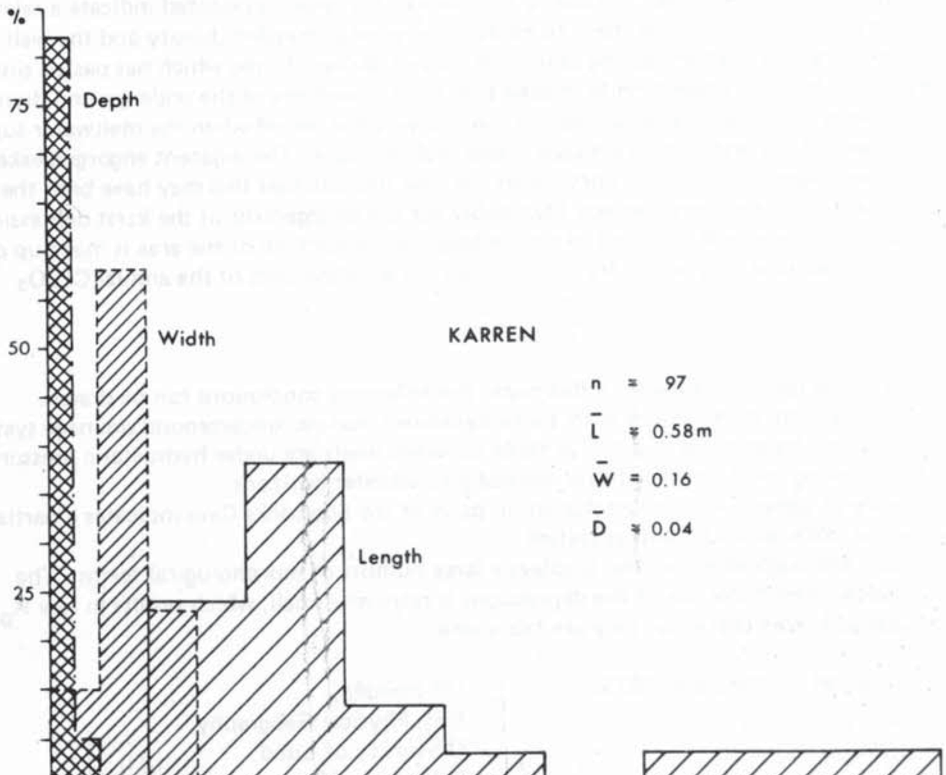


Fig. 10. The variation of the karren furrows in depth, length and width in per cent of the number of measurements made.

	d_s	d_j	d_c	$d_s+d_j+d_c$
4. $\bar{A}_{cd}$	53.2 m^2	8.3 m^2	117.4 m^2	58.8 m^2
5. $\bar{H}_{cd}$	1.6 m(1.3)	2.1 m(2.1)	3.9 m(5.4)	2.4 m(3.7)
6. R_p	1/716	1/8000	1/547	1/297
7. $\bar{R}_{de}$	1.4(0.6)	2.8(2.2)	1.5(0.5)	1.8(1.3)
8. $\bar{R}_{OJ}$	0.84	0.80	0.77	0.81
$\bar{R}_{O.Str}$	1.32	1.25	1.21	1.27

To sum up, the landscape is strongly karstified with a high depression density. The size of the depressions, however, is relatively small compared with the karst regions in the middle latitudes. The small size results in low values of R_p, a factor which is highly dependent on the karstification intensity, the age of the landscape and the time span during which the karst processes have been in action.

The collapse dolines constitute a conspicuous feature in the landscape because of their large dimensions. Their orientation seems to a greater extent than that of the other depressions to be dependent on the strike of the limestone and less on its joint orientation. The converse would perhaps have been expected.

Karren

About 80% of the karren in the area has been measured and the mean values given below were calculated. The values in brackets show the standard deviation. The material has been divided into classes and the variations in length, width, depth and dip are evident from Figs. 9 and 10.

n = 97

Length	0.58 m (0.32)
Width	0.16 m (0.07)
Depth	0.04 m (0.04)
Dip	46°E (21.7)

It has not been possible to obtain any correlation between, on one hand, the dip, and on the other, length, width or depth of the karren.

Discussion

Although, as mentioned earlier, only 5 months per year are frost free and, accordingly, the karst processes on the ground surface are active only during this period, the results presented indicate a relatively great karstification intensity. It is, however, hard to explain the great depression density and the well developed subterranean drainage system bearing in mind the short period of time which has passed since the area became ice-free. It is therefore tempting to assume that certain portions of the underground drainage system and the karst depressions developed sub-glacially in a late-glacial period when the meltwater supply was rich and water flowed along under the ice masses under high pressure. The adjacent engorged eskers and the thick glaciofluvial deposits in certain portions of the cave indicate that this may have been the case.

Today the intense vertical corrosion acts favourably for the enlargement of the karst depressions. It was pointed out above that up to 60 per cent of the underground waterflow of the area is made up of percolation water in the snow melting period May-July, when the principal part of the annual $CaCO_3$ transport takes place.

Conclusions

On the basis of the results presented in this paper the following conclusions can be drawn.

1. The landscape has high permeability with a well developed, vadose, underground drainage system. The karst springs, which can be grouped together at three different levels are under hydrostatic pressure and the small values of their rising coefficients indicate marked groundwater horizons.
2. The occurrence of glaciofluvial accumulations in parts of the Sotsbäcks Cave indicates a partial sub-glacial genesis of the underground drainage system.
3. The landscape, although an arctic one, displays a large number of morphological forms. The depression density is great even if the size of the depressions is relatively small, which results in low R_p values. Different types of karren occur but they are fairly rare.

Revised Manuscript received 9th October, 1973.

Ulf Helldén,
Inst. Physical Geography,
University of Lund,
Solvegatan 13,
22245 Lund,
Sweden.

References

Bögli, A. 1960. Kalklösung und Karrenbildung. Zeit.f. Geomorph. N.F. Supp.2, pp.4-21.

Corbel, J. 1957. Les Karst du nord-oest de l'Europe. Mem. Institute Etudes Rhodaniennes de l'Université de Lyon. Nr 12, 544 pages.

1959. Vitesse de l'erosion. Zeit.f. Geomorph. N.F. Band 3, pp.1-28.

1960. Nouvelles recherches sur les karsts arctiques Scandinaves. Zeit.f. Geomorph. N.F. Supp.2, pp.74-78.

Gavelin, A., Högbom, A.G. 1910. Norra Sveriges issjöar. S.G.U. Ser.Ca, No.7, pp.1-112.

Helldén, U. 1973. Limestone solution intensity in a karst area in Lapland, northern Sweden. (to be published in the proceedings of the 6th International Congress of Speleology 1973, Olomouc, Czechoslovakia).

Knutsson, G., Carlsson, L., & Nord, M. 1967. Hydrogeological investigation of a karst area at Björkliden, Lappland, Sweden. Transactions of Chalmers University of Technology, Gothenburg, Sweden. Nr 319, 32 pages.

Knutsson, G. 1970. Sparämnen som hjälpmedel vid grundvattenundersökningar. C.T.H. Inst. för vattenförsörjningsoch avloppsteknik. Publikation A 70:3, pp.1-40.

Kulling, O. 1955. Beskrivning till berggrundskarta över Västerbottens län. S.G.U. Ser. Ca No. 37, del 2, pp.105-287.

Köppen, W. 1936. Das geographische System der Klimate. 44 pages in: Köppen-Geiger, Handbuch der Klimatologie. Bd. 1, teil C, Berlin.

Mannerfelt, C.M.:son. 1945. Nagra glacialmorfologiska formelement. G.A. Arg. XVII, Häfte 1-2, page 225.

Williams, P.W. 1969. The geomorphic effects of ground water. In: Water, Earth and Man (Ed. R.J. Chorley). Chpt. 6. II:269-284.

1971. Illustrating morphometric analyses of karst with examples from New Guinea. Zeit.f. Geomorph. 15(1), pp.40-61.

Ångström, A. 1958. Sveriges klimat. G.L.A. Stockholm. 150 pp.

Trans. British Cave Research Association. Vol. 1. No. 1. pp.55-60. January 1974.

INDUCTIVE LOOPS AND CAVE SURVEYING

by R. Smith & R.A. Stevens

For a number of years the use of inductive loops has played an important part in cave surveying in many parts of the world. Cavers often refer to such systems as "cave radio" or the "radio surveying device". New cave entrances have been opened up (Jones 1960), and existing cave surveys corrected. Lord (1963) has developed the technique so that it can be used for location and voice communication between cave and surface, and reception through a thickness of 200m of limestone is claimed. Von Seggern and Adams (1967) have applied classical electromagnetic theory to the problem and developed formulae to take into account the effect of rock permeability. For practical purposes this effect is negligible. They also describe equipment for mapping lava tubes in Hawaii. For those more interested in the application of the device rather than in the theory of operation, only the basis of operation is explained below, together with circuits which have been found to operate satisfactorily. Other circuits and more detailed accounts of their operation are described in the literature. (Birchenough and Jones 1962, Lord 1963, Phillips & Standing 1969).

Use of Inductive Loops

If the loops are to be used for quantitative work (as is usual in cave surveying) they should be of rigid construction and impervious to water. The receiving coil should be fitted with a protractor scale and plumb bob so that the angle of the coil to the vertical can be readily measured. The transmitting coil is laid horizontally at the underground survey station to be located. Current is supplied to it from an oscillator oscillating at a frequency (in the equipment described below) of 2KHz and pulsed at about 3 to 5 times a second. The current in the coil sets up a magnetic field which can be detected some distance away by a similar coil connected to a simple amplifier system. Some concept of the problem can be grasped when it is realised that the intensity of the magnetic field diminishes according to the inverse of the cube of the distance.

Fig. 1 shows the magnetic field developed by the 'transmitting' coil 'T'. Provided the receiving coil R has some of the magnetic lines of force passing through it, it will have a small signal developed inside which may be detected by a simple amplifier and fed to headphones. However, if the coil lies tangential to the lines of force no signal will be developed in it (a "null").

It is possible to locate the axis of the transmitting coil and to calculate its depth 'H' using the formula (see appendix)

$$H = d\ [\ \tfrac{3}{4} \cot \emptyset \mp \tfrac{1}{4}\sqrt{(9 \operatorname{cosec}^2 \emptyset - 1)}\ ]$$

where d is the distance from the axis of the receiving coil and $\emptyset$ is the angle to the vertical at which a null is obtained (see Fig. 1).

When working in the field such a formula would be cumbersome to use and so the term in square brackets has been regarded as a multiplying factor F and its value plotted for different values of $\emptyset$ (see Fig. 2) i.e. $H = d \times F$ (after Osborne 1969).

A Practical Circuit Diagram is shown in Fig. 3.

Transmitter Coil:	100 turns of 22 s.w.g. (0.711 m.m.) enamelled copper wire
	Coil Diameter: 40 c.m.
	Taps taken off coil after 3, 4 and 5 turns.
Receiver Coil:	500 turns of 30 s.w.g. (0.315 m.m.) enamelled copper wire
	Coil Diameter: 56 c.m.s.

Notes on the Circuit Diagram

1. The "transmitter" coil tunes to about 2KHz with a capacitor of 0.65μF. The receiver coil is tuned on test to the transmitter frequency by trial and error or using a decade capacitor box if one is available. A suitable capacitor can be made up from several preferred values connected in parallel. In the test circuit a value of 0.021μF was required.
2. The "transmitter" circuit works satisfactorily from up to three three-cell NIFE batteries. The average current drawn is about 150 mA. If there is difficulty in getting the circuit to squegg (produce short bursts of oscillation) through component tolerances, the tap on the coil may be altered in conjunction with slight modification to C2 and R3.
3. A high grade capacitor is required for tuning the transmitter coil C1 since large circulating currents flow in it and voltages between 200 and 300 volts are induced across it.
4. R1 and C3 (receiver circuit) form a filter to limit the upper frequency response of the amplifier to between 10 and 20 KHz. This is to prevent the base-emitter junction of the first transistor acting as a detector for radio frequencies which would mask the required frequency.
5. The coupling between the first and second transistors acts as a high-pass filter to reduce interference from overhead power lines. Even with this filter, power lines can pose a severe problem.
6. The receiver circuit operates from a 9 Volt battery.
7. Further technical details on the circuit design are to be found in the article by Stevens (1972).

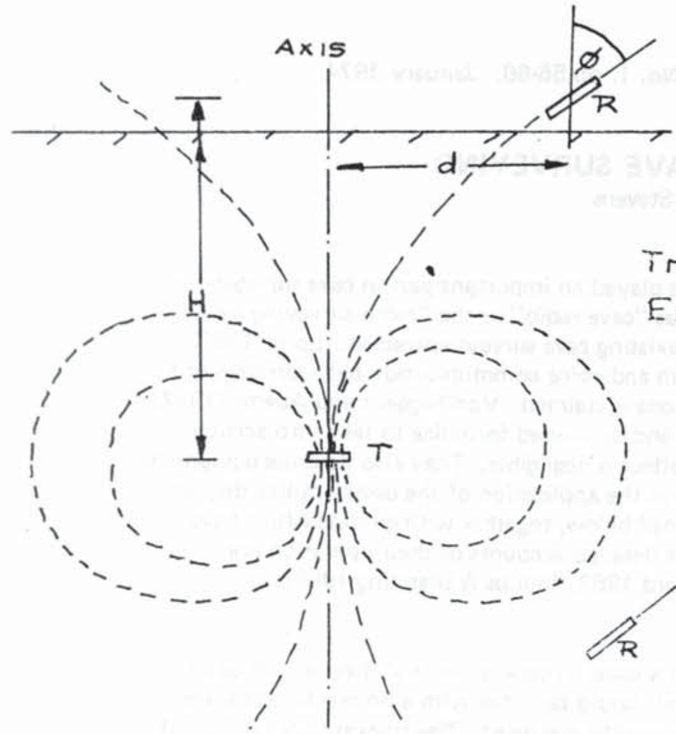


Fig.1. The magnetic field developed by the transmitting coil.

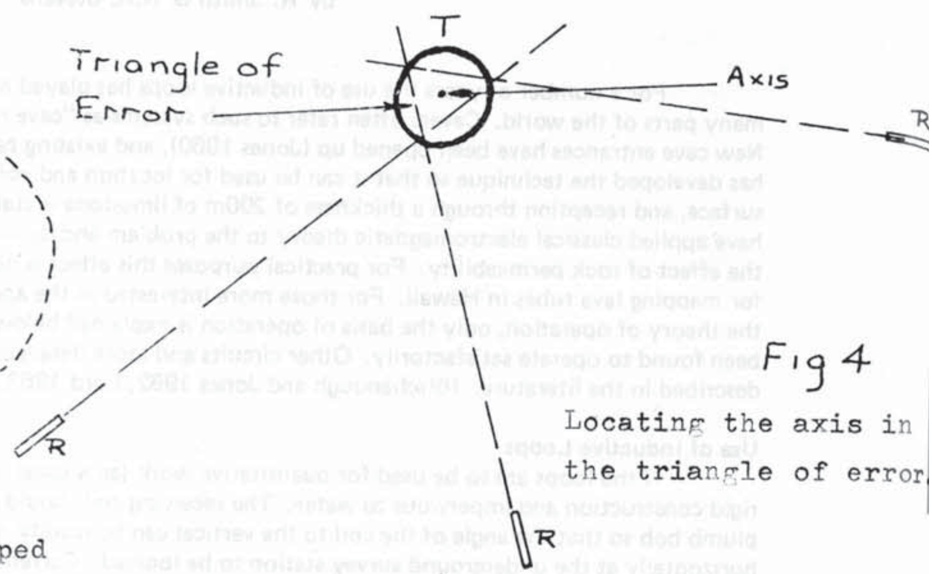
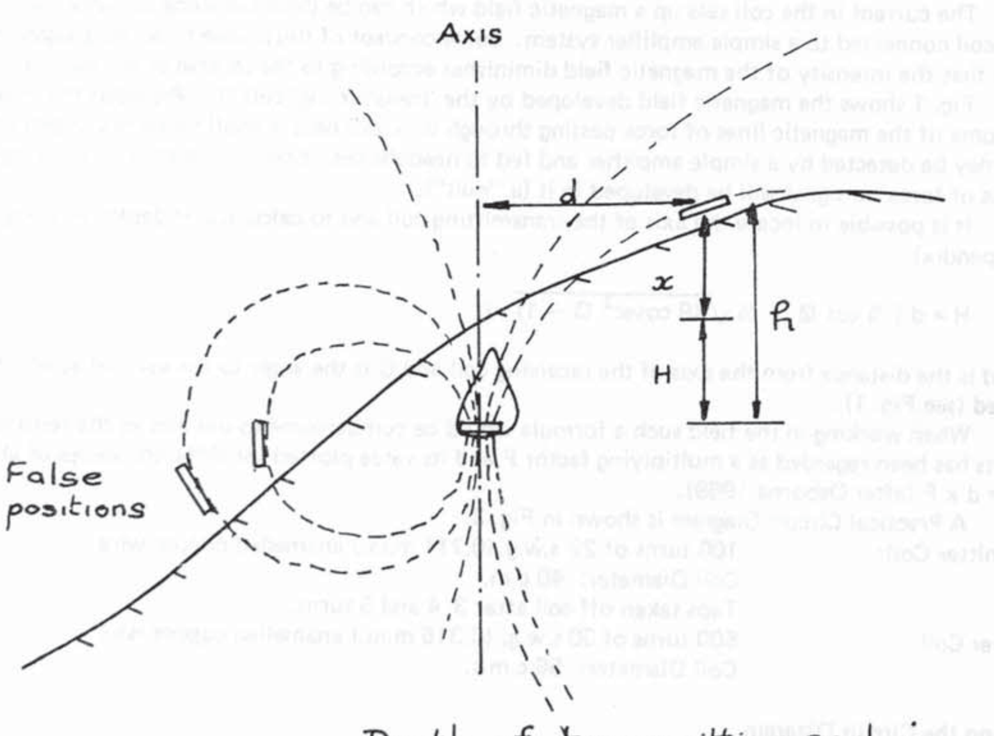


Fig 4

Locating the axis in the triangle of error.



Depth of transmitting coil is given by $H = h - x$

Fig.5. Effect of uneven terrain on depth calculation.

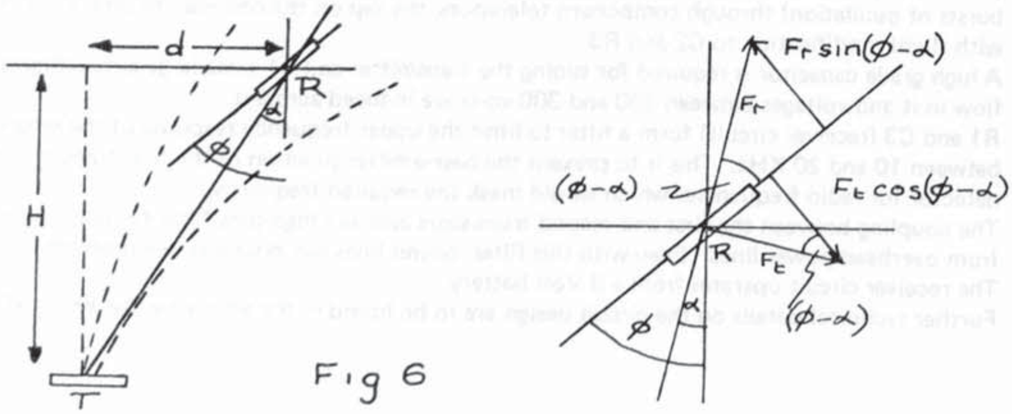
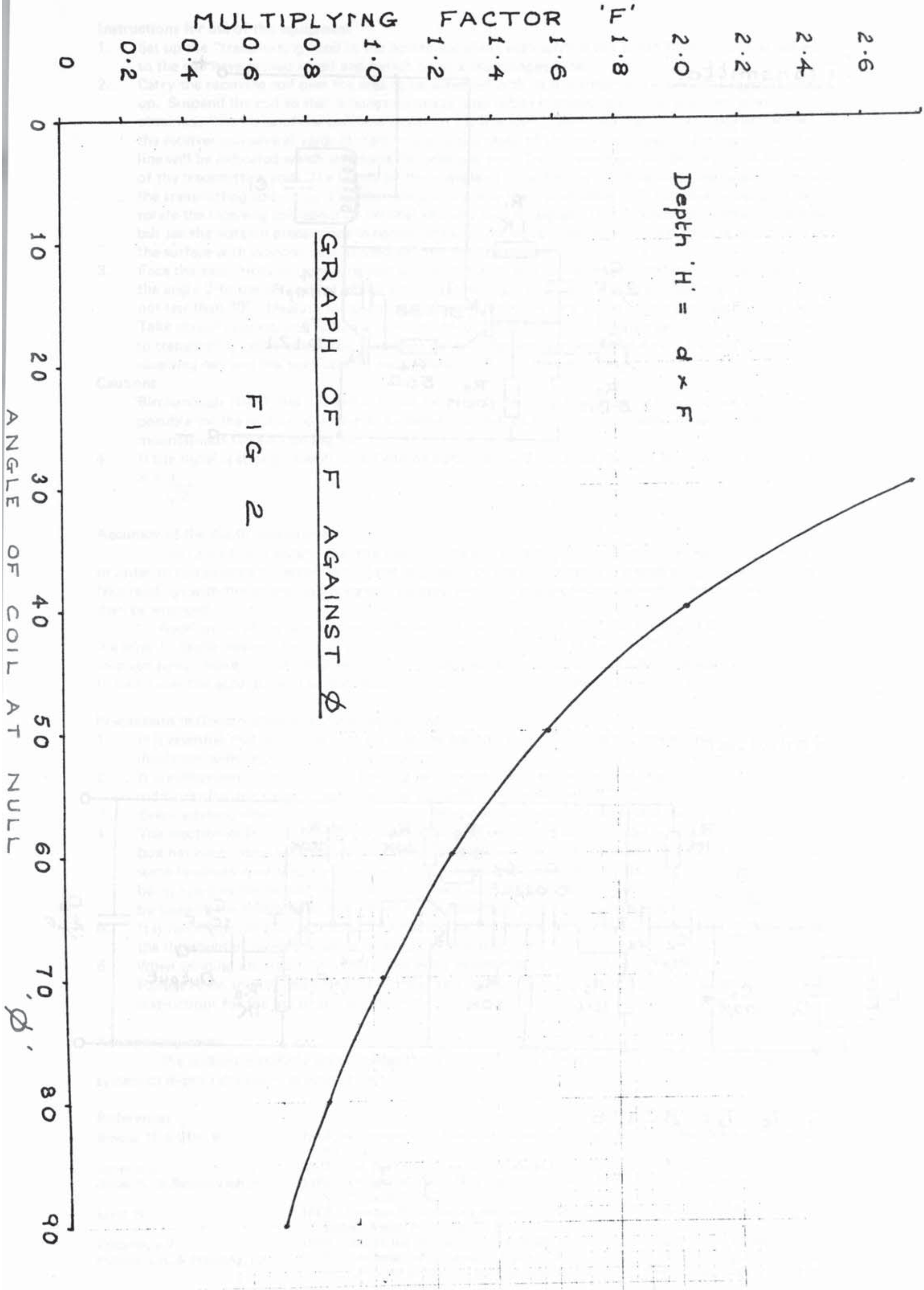


Fig 6

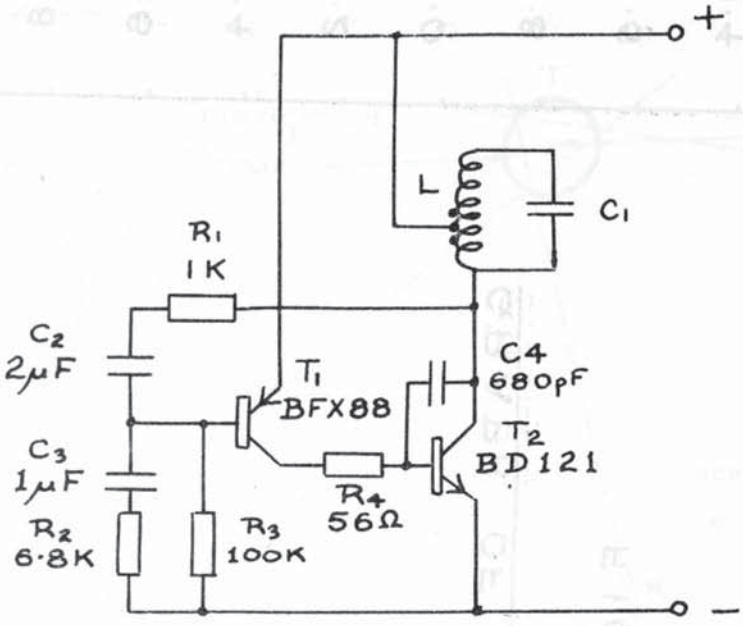
Proof of the formula used for depth calculation.



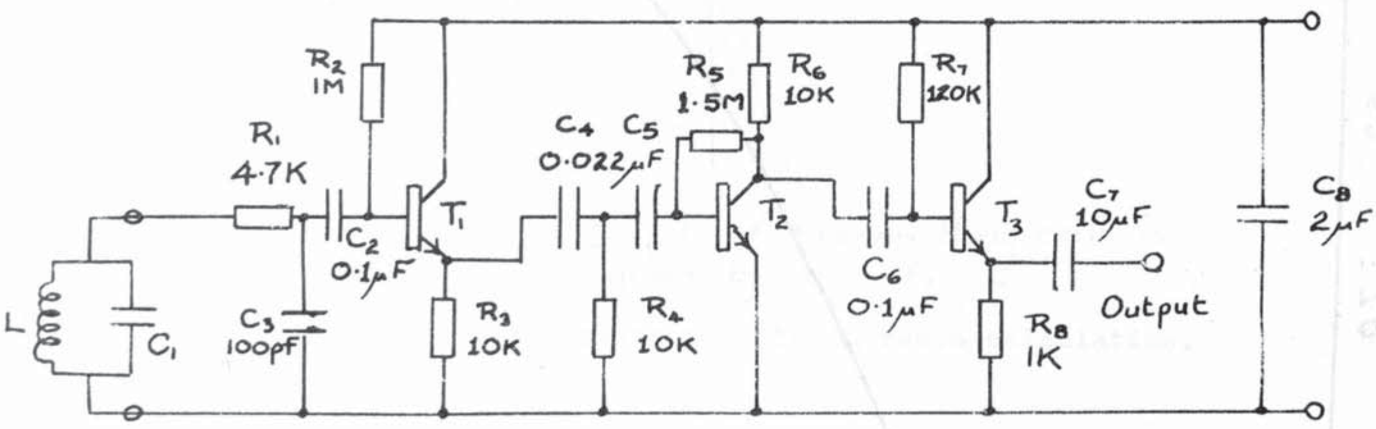
GRAPH OF F AGAINST ø

FIG 2

'Transmitter'



Receiver



T1, T2, T3: BC108

Fig 3

Instructions for use of the equipment

1. Set up the "transmitting" coil in the horizontal plane with spirit levels (small bubble levels attached to the coil have proved ideal) and switch on at a prearranged time.
2. Carry the receiving coil over the area to be surveyed with its plane horizontal until the signal is picked up. Suspend the coil so that it hangs vertically, and rotate it about its vertical axis until a null is obtained. The plane of the coil now indicates the line along which the transmitter must lie. Move the receiver coil several yards at right angles to the plane of the coil and repeat the manoeuvre. A new line will be indicated which intersects the previous one. This intersection will be very close to the axis of the transmitting coil. The centre of the triangle of error formed by three such lines gives the axis of the transmitting coil. (Fig. 4.) When vertically above the transmitting coil it should be possible to rotate the receiving coil about its vertical axis and hear no signal. This is rarely achievable in practice, but see the note on precautions in construction of the equipment below. Mark all lines and points on the surface with wooden pegs as soon as they are determined.
3. Face the axis. Hold the receiving coil with both hands and rotate it about its horizontal axis and note the angle Ø to the vertical for which a null occurs (Fig. 1). Choose a position such that this angle is not less than 30°. Measure the distance of the coil from the axis and calculate the depth using Fig. 2. Take several readings and obtain an average value. Note that the calculated depth is from receiving coil to transmitting coil and so allowance must be made for any surface variations in height between the receiving coil and the axis location point. See Fig. 5.

Cautions

Birchenough (1970) has pointed out that false locations can be obtained. These are likely if it is at all possible for the receiver operator to be *below* the level of the transmitter coil. This is a danger in mountainous terrain (see Fig. 5).

4. If the signal is strong enough, a null can be obtained for Ø = 90° i.e. the coil horizontal. In this case $H = \frac{d}{\sqrt{2}}$

Accuracy of the depth measurement

The calculations assume that the transmitting coil is small compared with the depth to be measured. In order to compensate for errors due to the alignment of the protractor and plumb bob, it is advisable to take readings with the plumb bob hanging over each sector of the protractor in turn. The two results can then be averaged.

Application of the depth formula shows that for an error of 2° in the reading of Ø, where Ø = 90°, the error in depth measurement will be 5.7%. For a value of Ø = 30° this error will amount to 7.6%. The received signals however, are often very small for deep work and that the null often appears very ill defined. In such cases the accuracy will be very dependent upon how well the angle Ø has been determined.

Precautions in Construction and Use of equipment

1. It is essential that water does not get into the transmitting coil as this can cause reduction in winding insulation with impairment of performance.
2. It is convenient for a small neon bulb to be connected across the transmitting coil to serve as an indicator that the transmitter is working correctly when switched on.
3. Every attempt should be made to make all equipment carried underground stand rough usage.
4. The electronics for the receiving equipment should be housed in a screened enclosure (a die-cast box has been found satisfactory) and screened leads used between receiving coil and this box. In use some feedback may take place between headphones and receiving coil, resulting in a continuous signal being heard in the headphones. Experience will soon indicate to the user that this effect is eliminated by keeping the headphones away from the immediate vicinity of the receiving coil.
5. It is recommended that a good pair of headphones is used with ear muffs. It has been found that, on the threshold of reception, wind noise can be troublesome.
6. When winding the transmitter coil make every attempt to maintain windings as even as possible. Failure to do so may result in the electrical axis of the coil being non-unique (see paragraph 2 on the instructions for the use of the equipment).

Acknowledgments

The authors gratefully acknowledge the work of Mr. J.V. Osborne who developed the simple system of depth calculation produced here.

References

Brooks, N. & Ellis, B. 1956. An independent check on the survey of Ogof Ffynnon Ddu. S.Wales Caving Club N.L. 16.

Jones, J.C. 1962. The Tunnel Cave project. S.Wales Caving Club N.L. 42. pp.3.

Jones, N. & Birchenough, W. 1962. A magnetic positioning device. Technical Aids for Cave Exploration. C.R.G. No. 11. pp.87-102.

Lord, H. 1962. A device for surveying and speech communication underground. Proc. Brit. Speleo. Assoc. No. 1. pp.25-38.

Osborne, J.V. 1969. How to use the induction radio device. S.Wales Caving Club No.44. pp.6-10.

Phillips, J.A. & Standing, I.J. 1969. The detection of caves by equipotential surveying and electromagnetic induction location using a thyristor pulse generator. Proc. Brit. Speleo. Assoc. No. 7, pp.31-52.

Roeschlein, E.R. 1960. Mapping caves magnetically. Electronics Vol. 33, No. 39. pp.61

Seggern, D. von & Adams W.M. 1967. Electromagnetic mapping of Hawaiian lava tubes, Technical report No. 8 of Geophysical Exploration for Hawaiian groundwater, phase 1 O.W.R.R. project No. B-005-HI.

Stevens, R.A. 1972. An improved electromagnetic position finding device. Trans. Cave Res. Grp. G.B. Vol. 14. No. 1. pp.43-47.

APPENDIX

Proof of the Formula Used for Depth Calculation

The following proof is given as the authors are unaware of its existence elsewhere in the literature. It is developed in part by Osborne (1967) and in private correspondence between him and the authors.

For the case where the dimensions of the transmitting coil are small compared with the distance y, Gauss's law can be applied to show that the magnetic field at the receiver is made up of two components:

(1) a radial component F_f acting along TR where

$$F_f = \frac{2M \cos \alpha}{y^3}$$

and (2) a tangential component F_t acting at right angles to TR where

$$F_t = \frac{M \sin \alpha}{y^3}$$

y = TR and M is the magnetic moment of the transmitter coil.

For the field passing through the coil to be zero, i.e. for a null, the effects of the two components acting at right angles to the coil must be zero.

i.e. $$F_r \sin (\emptyset - \alpha) = F_t \cos (\emptyset - \alpha)$$

Substituting for F_r and F_t gives

$$2 \cos \alpha \sin (\emptyset - \alpha) = \sin \alpha \cos (\emptyset - \alpha)$$

$$\therefore 2 \cot \alpha \tan (\emptyset - \alpha) = 1$$

Replacing $\cot \alpha$ by $\frac{H}{d}$ and expanding gives

$$2\frac{H}{d} \cdot \frac{\tan \emptyset - \frac{d}{H}}{1 + \frac{d}{H} \tan \emptyset} = 1$$

or $$2\frac{H^2}{d^2} \tan \emptyset - 3\frac{H}{d} - \tan \emptyset = 0$$

or $$\frac{H^2}{d^2} - \frac{3}{2}\frac{H}{d} \cot \emptyset - \frac{1}{2} = 0$$

which is a quadratic in $\frac{H}{d}$

Hence $$H = \frac{d}{2} \left[\tfrac{3}{2} \cot \emptyset \pm \sqrt{\left(\tfrac{9}{4} \cot^2 \emptyset + 2\right)} \right]$$

$$= d \left[\tfrac{3}{4} \cot \emptyset \pm \tfrac{1}{4} \sqrt{\left(9 \operatorname{cosec}^2 \emptyset - 1\right)} \right]$$

$$= d \times F$$

where F is the multiplying factor referred to in Fig. 2.

Trans. British Cave Research Association. Vol. 1. No. 1. pp.61-64. January 1974.

DEVELOPMENTS IN LIMESTONE GEOLOGY IN THE INGLETON-SETTLE AREA

A. A. Wilson

(paper given at the C.R.G. symposium at Lancaster in March 1973)

Summary

Initially the Great Scar Limestone was subdivided using fossils, but the most modern work relies heavily on lithological characters. Beds of D_1 age in which most caverns occur have been divided into nine cycles using major bedding planes and joint intensity measurements. Underground studies show that clay bands occur at a number of levels. Future underground and surface studies using horizons at which breaks occur in the normal pattern of carbonate sedimentation are suggested.

1. Division of Great Scar Limestone using Fossils.

The Great Scar Limestone with its spectacular scenery attracted early attention from Sedgwick (1835) and Phillips (1836), but the first systematic division of the formation by Garwood and Goodyear (1924) was on faunal grounds. Using a scheme developed in north-west England by Garwood it was possible to divide the succession into coral-brachiopod zones. In addition certain bands with a distinctive fauna and lithology were used as marker horizons, which were mapped over a wide area between Ingleton and Settle. A concise account of this research was given by Dunham *et al.* (1953).

The lowest strata contain the distinctive fossil *Michelinia grandis* (C_2 age). These are conglomerates formed of debris from the sub-Carboniferous landscape in a calcareous matrix, together with limestones. The beds range in thickness from 0-15 m and are thickest near the North Craven Fault, though they also occur in pockets in the undulating basement rocks further north.

Next come well-bedded limestones of S_1-S_2 age, with calcareous mudstone partings in the lower layers and *Linoprotonia corrugato hemispherica* in the upper. They are altogether some 90 m thick, but thin out entirely against a hump in the pre-Carboniferous land surface in Crummackdale. The top of S_2 is marked by the Porcellanous Bed, a layer of very fine grained limestone less than 1 m thick.

The S_2 beds are overlain by 100 m of D_1 strata in which the main cavern systems occur. Bedding planes are often further apart than in underlying beds and there are a number of massive units alternating with more thinly bedded limestones. The top was drawn by Garwood and Goodyear at the *Girvanella* Band, a persistent band of algal nodules in a limestone matrix averaging 1 metre in thickness. Within D_1 Garwood and Goodyear mapped a brachiopod bed with *Davidsonina septosa* which occurs distributed through some 9 m of strata. They thought it was easily distinguishable from a second band with *D. septosa,* locally present 6 m. higher in the sequence.

2. Division by Major Bedding Planes

The emphasis in research centres largely on details of rock structure and lithology following the work of Schwarzacher (1958) who noted that certain well-defined bedding planes in limestones of D_1 age were remarkably persistent. They were picked out in selected measured sections ranging from Kingsdale across Ribblesdale to Malham and with less certainty as far away as the Brough area. The intervening measures between the master bedding planes comprised nine cycles averaging 10 m thick and numbered 1 to 9 from the base upwards. The bedding planes themselves were considered to be free of shale partings except for a rare reddish clay film.

The detailed analysis of individual horizons showed that the Porcellanous Bed at the top of S_2 was not a wholly persistent horizon. In the Ravenscar section near Ingleton the Porcellanous Bed was thought to be represented only by a bedding plane, whilst there was a lower porcellanous horizon some 19 m lower in the succession. At Malham the Porcellanous Bed was represented by a bedding plane and no lower porcellanous horizon was recognised.

The second horizon used as a mapping line by Garwood and Goodyear (1924) has also proved likely to be unreliable. In cycle 5 a shell bed with *D. septosa* occurred at all localities in the area between Kingsdale and Malham. The shells were sometimes present through the whole cycle, but often made one or two bands with greater concentrations. Besides cycle 5, *D. septosa* was also present in cycle 7 at most localities and more rarely in cycles 6 and 8.

The third mappable band of Garwood and Goodyear, the *Girvanella* band, was found to be persistent in the localities where measurements were carried up to this high horizon. It lies some 2-4 m above the top of cycle 9.

3. Division by Joint Density Measurements

Doughty (1968) studied an area broadly similar to that of Schwarzacher, namely from Kingsdale eastward to Malham. In addition observations were made in Wharfedale. Density of jointing was measured at successive closely spaced levels in S_2 and D_1 limestones. Successive measurements in S_2 limestones showed that joint density varied little in each successive bed (Fig. 1). In D_1 limestones a different pattern emerged. Joint density was found to be almost invariably greatest in the lower part of Schwarzacher's cycles, all nine of which were recognised, and least dense in the upper part of each cycle (Fig. 1). In some places cycles showed a double maximum and minimum indicating two minor cycles. This cyclicism is broadly related to lithology. The lower beds with the densest pattern of joints are generally coarsest in grain

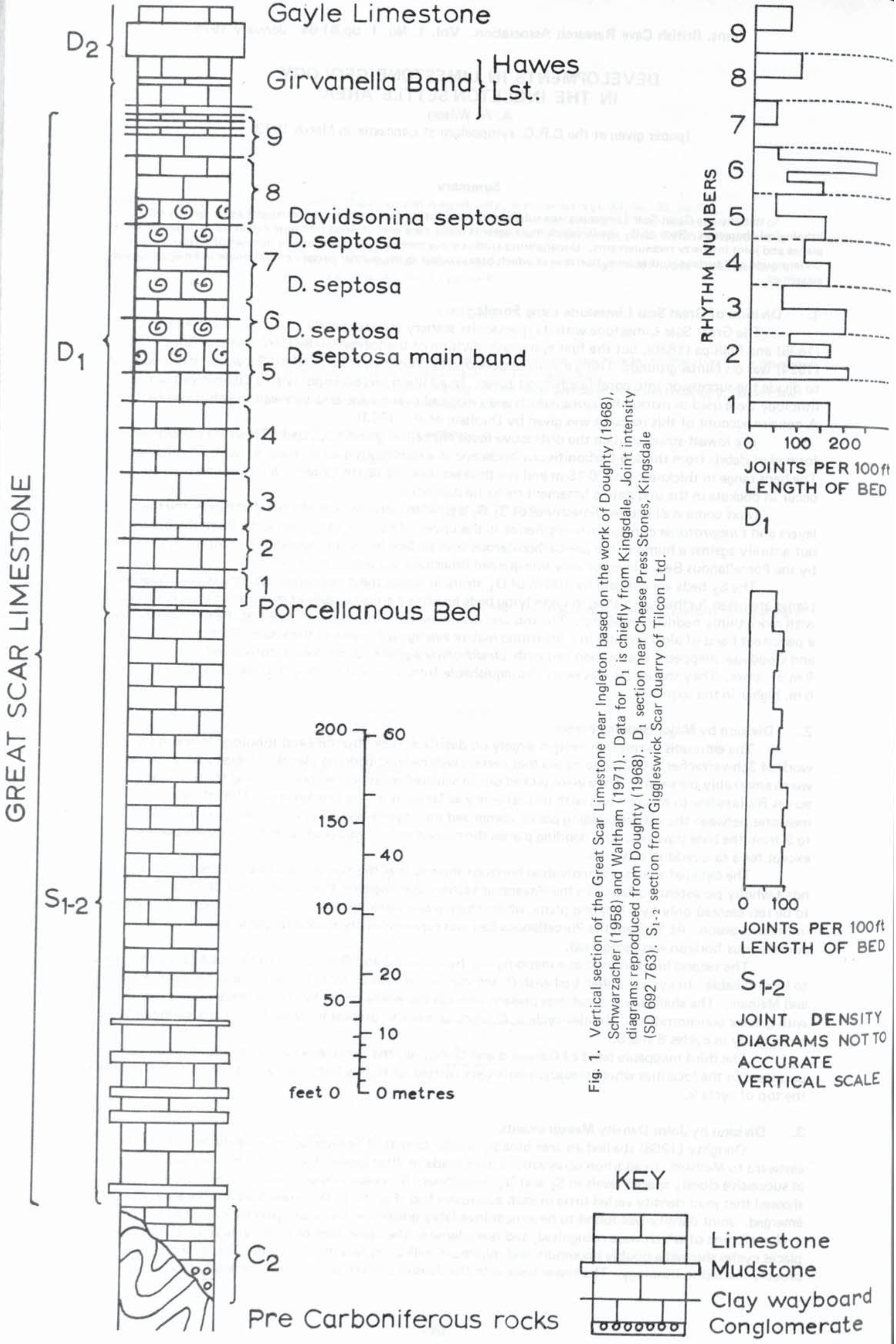


Fig. 1. Vertical section of the Great Scar Limestone near Ingleton based on the work of Doughty (1968), Schwarzacher (1958) and Waltham (1971). Data for D_1 is chiefly from Kingsdale. Joint intensity diagrams reproduced from Doughty (1968). D_1 section near Cheese Press Stones, Kingsdale (SD 692 763). S_{1-2} section from Giggleswick Scar Quarry of Tilcon Ltd.

size whilst the finer beds in the upper part of each cycle are less densely jointed. In S_2 beds the grain size varies little, in common with the almost invariable intensity of jointing.

Doughty noted that, in some cycles, high density jointing gave way upwards fairly abruptly to low density jointing. In other cycles there was a more gradual passage. The lower parts of cycles as well as being coarsest in grain tended to show more current bedding and more organic debris.

Currently, a new paper by Doughty (in press, 1973) takes the recognition of the nine cycles by joint density variations a step further. For the first time the cycles have been mapped, the area covered being near Settle. The likelihood that the *D. septosa* band would prove unreliable due to its occurrence at multiple horizons is confirmed. A number of faults inserted on earlier maps of the area, notably by Garwood and Goodyear (1924) are discounted since they were originally postulated to account for apparent repetitions, presumed to be due to faulting of one *D. septosa* 'band'.

The mapping of the cycles, backed by joint density measurements, holds considerable promise for future surveys of the Great Scar Limestone, since it appears to be a practicable basis for refining the subdivision of a very thick lithological unit.

4. Mudstone Bands in D_1 Limestones

The recent work of Waltham (1971) has added a new dimension to studies of the Great Scar Limestone. He made a detailed examination of continuously exposed sections in cave systems on Gregareth and Ingleborough and found numerous mudstone partings, not noted at surface by Schwarzacher (1958). Though as many as fifteen partings were seen in an individual section of D_1 beds, the majority proved to be discontinuous when correlated from cave to cave. To assist with correlation the Porcellanous Bed and to a lesser extent the *Girvanella* band were used as datum planes. Of the mudstone bands the most persistent 30 m above the Porcellanous Bed is rarely absent on Gregareth and Ingleborough and is 2 m thick in Lost John's Hole on Gregareth. This bed may well persist into Wharfedale, according to Waltham.

The mudstone partings described by Waltham are usually 1 to 40 cm thick consisting of unfossiliferous pyritic mudstones, showing rusty weathering. In places the mudstones lie on channelled and "potholed" surfaces of the underlying limestones.

In the Derbyshire Dome mudstone partings are quite common in the D_1 limestone sequence and the most detailed descriptions are by Walkden (1972a). The clay wayboards, as the mudstone bands have been called for many years, show several points of resemblance to those described by Waltham in the Ingleton area. The Derbyshire clay wayboards are usually a few millimetres to over a metre thick and as many as thirty are recorded from a single 100 m section of D_1 limestones. Typically these clay bands are unlaminated, pyritic, rusty weathering and unfossiliferous. The mudstone bands are best seen in quarries and artificial cuttings and Walkden noted that in natural exposures the clay has often been lost by extrusion under pressure and subsequent weathering. This would tend to explain why Schwarzacher (1958) recorded no mudstone partings in his measured surface sections near Settle, yet they were common underground (Waltham, 1971). Walkden (1972b, fig. 2) illustrated a karstic surface with "potholes" beneath a K-bentonite clay wayboard. "Potholing" has also been noted beneath mudstone bands near Ingleton by Waltham (1971).

X-ray and differential thermal analysis of clay wayboards by Walkden (1972a) shows that they are potassium-rich bentonites likely to be argillation products of falls of volcanic ash. On the whole the ash bands were not found to be laterally persistent and were of limited use for correlation.

Recently a boring in the valley of Ashfoldside Beck, 5 km WNW of Pateley Bridge, gave the following details relating to mudstone bands in the Great Scar Limestone. Within the probable Stump Cross Limestone (D_1) four bands of pale grey pyritic mudstone occur ranging from 0.20 to 0.60 m thick. The highest and lowest bands have been examined by Mr. K.S. Siddiqui who was unable to confirm the presence of K-bentonite which would be expected to occur in the form of a mixed layer clay. He reports as follows:–

"An X-ray powder photograph (NEX 2094) of the untreated material showed a multiphase pattern of predominant illite, with subordinate kaolinite and minor pyrite. No lines of any mixed layer clay were identified. Another sample treated with glycerol (NEX 2095) failed to show any expansion in the lattice of the clays, confirming the stabilised structure of illite and the absence of any interlayered clay or expanding lattice sheet structure'."

5. Beds Above the Great Scar Limestone

Overlying the Great Scar Limestone and forming the upper slopes of many notable fells in the Yorkshire Dales are rocks of Yoredale facies. These are limestones, mudstones and sandstones repeated in some eleven major cycles and several minor ones, through about 350 m of strata. The clastic components of the cycles, the sandstones and mudstones, are thickest in the north-west, but thin south-eastwards towards Grassington. Individual limestones are seldom over 30 m thick and only rarely contain sizeable cavern systems. The exception is the Middle Limestone which is up to 60 m thick in lower Coverdale and in Upper Nidderdale (Wilson, 1960). Caves occur in this limestone in both dales (Ford, 1964). The Main Limestone is the most consistently thick limestone and locally carried underground streams.

The cappings of the highest fells such as Ingleborough and Whernside are in beds of Millstone Grit facies, chiefly sandstones and mudstones.

6. Correlation of Results and Prospects for Further Work

An attempt has been made in Fig. 1 to synthesise in the vertical section the work of Schwarzacher and Waltham. The data from D_1 has been purposely taken from exposures as close together as possible.

Surface measurements by Schwarzacher on Shoutscar, Kingsdale, have been combined as far as possible with Waltham's underground measurements of clay wayboard horizons in Rowten Pot. The sections are 1 km apart on the ground. A more accurate synthesis, preferably using the joint density system of Doughty seems desirable.

Schwarzacher attempted northward correlation of his nine cycles as far as Brough, but more detailed work seems desirable. Schwarzacher believed that cycle 8 was probably equivalent to the Robinson Limestone of the Alston Block and 9 to the Peghorn Limestone (Fig. 1). Beds containing the *Girvanella* band equate with the Hawes Limestone and are labelled thus on Fig. 1. Beneath the Hawes Limestone in Wensleydale there is a sandstone, the Thorny Force Sandstone. The equivalent horizon near Ingleton appears to be a clay band which appears to be rather higher in the succession than the parting mapped by Turner (1968), which was incorporated in the IGS One-inch map (Hawes sheet No. 50) and seems to be at the top of cycle 7 or thereabouts.

Work on D_1 limestones is currently being carried out on the eastern fringes of Morecambe Bay by R. Grayson (personal communication). Emergent limestone surfaces and bioturbated horizons indicating breaks in carbonate deposition are likely to be laterally extensive and to be good features for identifying on water washed surfaces within caves.

Acknowledgements

The Author thanks Dr. E.H. Francis, Dr. W.H.C. Ramsbottom and Mr. I.C. Burgess for critical reading of the manuscript.

References

Doughty, P.S. 1968. Joint densities and their relation to lithology in the Great Scar Limestone. Proc. Yorks. Geol. Soc., Vol. 36, pp.479-512.

1973. *Davidsonina (Cyrtina) septosa* and the structure of the Great Scar Limestone north of Settle, Yorkshire. Proc. Yorks. Geol. Soc. In press.

Dunham, K.C., J.E. Hemingway, H.C. Versey & W.H. Wilcockson 1953. A guide to the geology of the district round Ingleborough. Proc. Yorks. Geol. Soc., Vol. 29, pp.77-115.

Ford, T.D. 1964. The Goyden Pot drainage system, Nidderdale, Yorkshire. Trans. Cave Res. Grp. G.B. Vol. 6(2), pp.79-90.

Garwood, E.J. & E. Goodyear 1924. The Lower Carboniferous succession in the Settle district and along the line of the Craven Faults. Q. Jl. Geol. Soc. Lond., Vol. 80, pp.184-273.

Phillips, J. 1836. Illustrations of the geology of Yorkshire. Part 2. The Mountain Limestone district. xx+ 253 pp. London.

Schwarzacher, W. 1958. The stratification of the Great Scar Limestone in the Settle district of Yorkshire. Liverpool & Manchester Geol. Jl., Vol. 2, pp.124-42.

Sedgwick, A. 1835. Description of a series of longitudinal and transverse sections through a portion of the Carboniferous chain between Penighent and Kirkby Stephen. Trans. geol. Soc. Lond., Sec. 2, Vol. 4, pp.289-308.

Turner, J.S. 1968. A note on the Meal Bank coal horizon around Ingleborough. Trans. Leeds Geol. Assoc. Vol. 7, pp.265-8.

Walkden, G.M. 1972a. The mineralogy and origin of interbedded clay wayboards in the Lower Carboniferous of The Derbyshire Dome. Geol. Jl., Vol. 8, pp.143-160.

1972b. Karstic features in the geological record. Trans. Cave Res. Grp. G.B., Vol. 14, pp.180-183.

Waltham, A.C. 1971. Shale units in the Great Scar Limestone of the southern Askrigg Block. Proc. Yorks. Geol. Soc., Vol. 38, pp.285-292.

Wilson, A.A. 1960. The Carboniferous rocks of Coverdale and adjacent valleys in the Yorkshire Pennines. Proc. Yorks. Geol. Soc., Vol. 32, pp.285-316.

Received 6th August, 1973.

Albert A. Wilson,
Institute of Geological Sciences,
Ring Road Halton,
Leeds LS15 8TQ

The TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION covers all aspects of speleological science, including geology, geomorphology, hydrology, chemistry, physics, archaeology, and biology in their application to caves, as well as technological matters such as exploration, equipment, surveying, photography and documentation. Papers may be read at General Meetings held in various parts of Britain, but they may be submitted for publication without being read. Manuscripts should be sent to the Editor, Dr. T. D. Ford, Geology Dept., University of Leicester, Leicester LE1 7RH, who will be pleased to advise in cases of doubt about the preparation of manuscripts. The Transactions is normally issued four times a year to paid-up members of the British Cave Research Association. Subscriptions are due on January 1st annually.

Full Members £3 per annum or U.S. $8.50

Corporate Members Clubs £3 per annum or U.S. $8.50

Institutional Members £4 per annum or U.S. $11.00

OFFICERS FOR 1974

Chairman: Eric Hensler, 12 Knighton Close, Woodford Green, Essex.

Deputy Chairman: P. B. Smith, 49 Alderson Place, Sheffield, 2.

Secretary: D. M. Judson, Bethel Green, Calderbrook Road, Littleborough, Lancs.

Assistant Secretary: J. R. Wooldridge, 9 Chelsea Court, Abdon Avenue, Birmingham, 29.

Treasurer: R. V. Davis, Westmorland Teachers Centre, Kendal, Westmorland.

Editor: Dr. T. D. Ford, Geology Dept., University of Leicester, Leicester LE1 7RH

Bulletin Editor: Dr. A. C. Waltham, Geology Dept., Trent Polytechnic, Nottingham NG1 4BU

Foreign Secretary: G. Matthews, 15 Netherfield Road, Sandiacre, Nottingham.

Librarian: Peter Haigh, 7 Parkinson Lane, Halifax, Yorkshire.

Sales Officer: Bryan Ellis, 7 School Lane, Combwich, Bridgwater, Somerset TA5 2QS

Biological Recorder: Mary Hazelton, Seaton House, Shrublands Road, Berkhamstead, Herts.

Archaeological Recorder: J. D. Wilcock, 22 Kingsley Close, Rising Brook, Stafford.

Conservation Secretary: Dr. G. T. Warwick, Geography Dept., University, P.O. Box 363, Birmingham, 15.

Mining Recorder: D. Williams, 7 Larch Way, Brockwell, Chesterfield.

Back numbers of the Transactions and other publications can be obtained from Bryan Ellis, 7 School Lane, Combwich, Bridgwater, Somerset TA5 2QS

Opinions expressed in this publication are the sole responsibility of the individual authors and in no way may be taken as representing the official views of the British Cave Research Association, unless otherwise stated.

Printed by Hawthornes of Nottingham Ltd.