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THE HOT SPRINGS OF BRISTOL AND BATH

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The discovery of the presence of a pathogenic Amoeba (Naegleria fowleri) in the thermal water installations at Bath in 1978 triggered off a lengthy series of investigations, culminating in the sinking of an inclined borehole to tap the rising waters of the Kings Spring. Naegleria is an aerobic organism and cannot live in the unoxidised thermal water as this is deficient in oxygen. It was therefore necessary to devise a method of recovering unoxidised thermal water for use in the baths and Pump Room. It was during the course of this work that the age and origin of the thermal water came under critical review. The present paper is devoted largely to consideration of the problems relating to tectonic control of the thermal water movements at Bath. It is concluded that the thermal water springs originated during mid-Quaternary earth movements, when deep fissuring took place. Nevertheless the Variscan structures determine the position of the Palaeozoic rocks and thereby exercise a degree of passive control.

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DISTRIBUTION OF THE HOT SPRINGS

Some of the low temperature thermal springs which occur in England and Wales, as for example Taffs Well near Cardiff and Buxton in Derbyshire, have regular temperatures which are only slightly in excess of mean annual values. At Hotwells, Bristol, the principal spring issues in the intertidal zone in the Avon Gorge, near Clifton Suspension Bridge (Figure 1). The thermal water has a temperature of 24°C (75.2°F). Much higher temperatures are found in the Avon valley at Bath, where the temperature of the hottest spring is about 46° to 47°C (114.8° to 116.6°F). Both at Bristol and Bath the thermal springs are situated in the floor of the Avon valley and are confined to linear zones of post-Variscan and post-Mesozoic faulting and fissuring.

At Clifton and Hotwells the springs rise directly from Carboniferous Limestone, but at Bath, where the Carboniferous rocks are concealed by an unconformable cover of Mesozoic strata, the fissures and fault belt in which they rise to the surface are clearly of post-Middle Jurassic age, though the structures at Bath are proved to continue down into the Palaeozoic basement to depths of more than 80 m below the valley floor (Figure 3).

The Variscan folds and faults which affect the Palaeozoic rocks are more complex than those seen in Mesozoic terrain. Although the denuded Variscan structures control the distribution of the various Palaeozoic rocks (and therefore of major aquicludes and aquifers) they did not play an active part in promoting the thermal water movements responsible for the

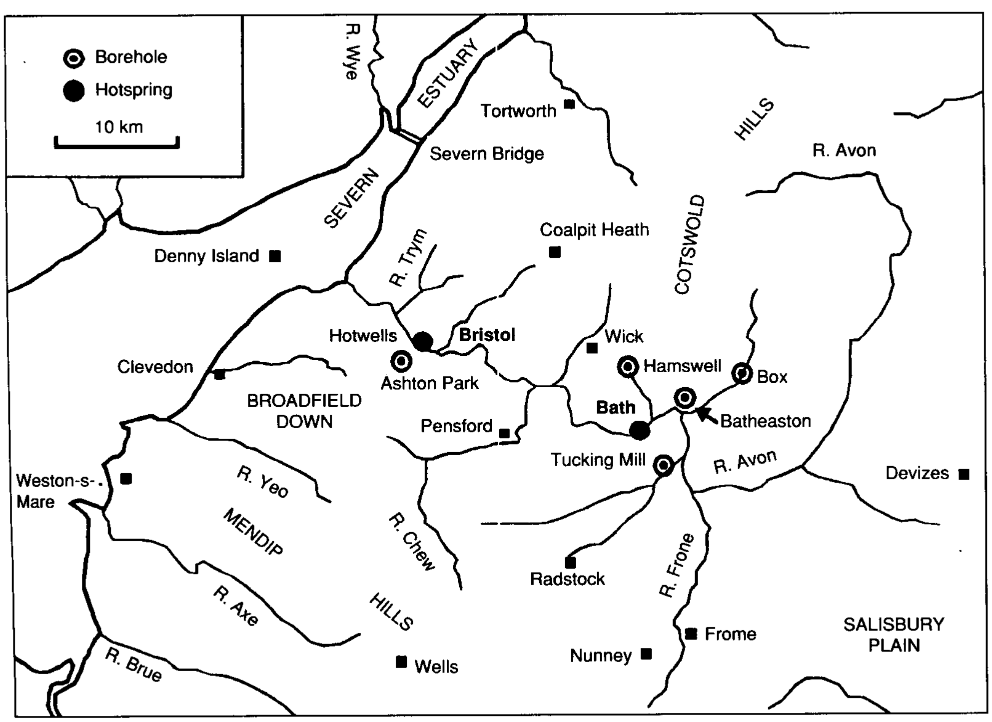

Figure 1: Key map. The Bristol Avon and its tributaries with sites of hot springs and boreholes which prove Palaeozoic rocks.

formation of the hot springs. The thermal waters rise along much younger belts of small-scale faulting and rifting, which also controlled the development of the physical relief and surface drainage pattern. Much of the field evidence points to a geologically recent age for the formation of the hot springs and some of the changes associated with their development are clearly of Quaternary age. Recent investigations into the age of calcite deposits in the fissure systems point to the same conclusion, though at the time of writing the relevant results have yet to be published.

THERMAL REGIME

The thermal springs of Bath yield about 1.25 x 10^6 litres of water per day, at temperatures ranging from 41° to 47°C. Those in the Avon Gorge at Clifton yield about 0.41 x 10^6 litres at temperatures not exceeding 24°C. The total amount of thermal water in the Avon valley springs may be as much as 1.82 x 106 litres per day, but of this amount about 20 to 25% is cold ground water of shallow origin, which is mixing with the thermal water near its exit level. There are, in addition, a number of possible seepages and small springs which have not yet been thoroughly investigated. These include several sites at Bath where thermal water may be rising to the surface and other springs located in the Avon valley below Bath, where the temperature and chemical composition has not yet been determined.

TABLE 1: Summary of boreholes and shafts.

1. **Alice Park Bath. [ST 7650 6659]. Sunk by Drillsure Ltd. 1988.**
Ground level 32.03m O.D, Standing water level 27.28m; Temperature at bottom of hole c. 13.75°C. Yield on test more than 24,000 1/hr. Dip of Palaeozoic strata 25-30°.

	Thickness (m)	Depth (m)	O.D. level (m)
Lower Lias Clay and Blue Lias	(43.22)	43.22	-11.19
White Lias	2.80	46.00	-13.7
Rhaetic	6.31	52.33	-20.3
Carboniferous Limestone (Clifton Down Limestone)	(57.28)	109.61	-77.59

2. **Tuckingmill nr. Midford [ST 764616]. Sunk by Drillsure 1988.**
Ground Level 38m O.D. Standing water level 37.24m O.D. Temperature at bottom of hole (average) c. 14°C. Yield on test - very small flow. Dip of Palaeozoic strata 45-60°.

	Thickness (m)	Depth (m)	O.D. level (m)
Dyrham Silts and Lias Clay	(87.00)	87.00	-49.0
Blue Lias	26.2	113.20	-74.2
White Lias	6.15	118.35	-80.35
Rhaetic	4.02	122.37	-84.37
Tea Green Marl and Mercia Mudstone	101.31	223.68	-185.68
Carboniferous Limestone (Hotwells Group)	(34.21)	257.89	-219.89

3. **Batheaston Coal Shaft [ST 78186774]. Sunk 1805 - 11 by Batheaston Coal Company.**
Ground Level 58.7m A.O.D. Artesian flows from Blue Lias and Dolomitic Conglomerate. Temperature of water in 1808, 15°C; in 1888, c. 16°C. Dip of Palaeozoic strata not known.

	Thickness (m)	Depth (m)	O.D. level (m)
Lower Lias Clay	(52.3)	52.3	6.4
Blue Lias	24.1	76.4	-17.7
White Lias	3.04	79.44	-20.74
Rhaetic	6.80	86.24	-27.54
Tea Green Marl and Red Marl	9.50	95.74	-37.04
Dolomitic Conglomerate	45.04	130.74	-72.04
Carboniferous Limestone (Hotwells Group)	(77.51)	208.25	-149.55

Thicknesses given in brackets ( ) are incomplete.

indicate that the temperature gradient in fissured aquifers can differ from that in the surrounding rocks. Wethered's temperature measurements made underground in Coal Measures at Kingswood (Wethered, 1882) Several attempts have been made to calculate the geothermal gradient in the Bristol and Somerset Coalfield. The results are considered in more detail by Kellaway (1991b) and probably represent the most reliable local estimate for the geothermal gradient in a major aquiclude (1°F for 76 ft or 24°C/Km). The presence of a buried pluton would account for many of the features recorded at Bath, but no such mass of magmatic material is known to exist.

In considering the age of the hot springs, ie. the length of time over which the exit has been in use, we have to remember that the isotopic age of the water may differ substantially from this. It has commonly been assumed that the isotopic age of the thermal water indicates the date of the formation of the springs from which it issues. Not all the estimates of isotopic age agree, however and most estimates are lower than the age of the springs as indicated by the archaeological and geological evidence. Thus the springs at Bath were certainly in being some 7000 yrs. BP, when Mesolithic man occupied the site. The position of the springs and their drainage channels leading to the buried channel of the Avon, indicate that they already existed in Devensian times although their temperature may have differed from that at the present day. Nevertheless it is possible that their position in the low-lying ground of central Bath is due to their development on Ipswichian or late Wolstonian fissure belts along which the Avon valley developed.

STRATIGRAPHICAL AND STRUCTURAL CONTROL OF THERMAL WATER MOVEMENTS

At Clifton and Hotwells, Bristol, the springs issue from Carboniferous rocks, whereas the hot springs of Bath emerge from Drift-covered Jurassic strata in the valley floor. However it has now been established by boring that the thermal water at Bath is also rising from fissured Carboniferous Limestone. The major structures which control the distribution of the Palaeozoic rocks in the Bristol and Somerset Coalfield and the Mendips are of Variscan or older date. Their influence on the thermal water movement is essentially passive, in that they determine the distribution and form of the masses of folded and faulted Silurian, Devonian and Carboniferous rocks, some being aquicludes, others aquitards or aquifers. The direction of the movement of the thermal water is controlled by the presence of unmineralised open fissures, along which the water is transmitted. These fissure systems commonly intersect the Variscan structures. They coincide locally with Mesozoic faults and fissures where the alignment is favourable, but elsewhere they appear to have an independent existence (Hawkins and Kellaway, 1991).

The most difficult aspect of defining the course of the thermal water in its passage through the rocks, arises from the fact that the fissure zones can seldom be located other than by excavation, or by the inspection of sections in river and sea cliffs such as those in the Avon Gorge at Clifton. Zones of fissuring can be seen in limestone quarries, as for example in the Great Oolite on Bathampton Down. Locally they produce a linear effect on the surface relief which is recorded on aerial photographs.

If we look at the geological map of the region drained by the Bristol Avon and its tributaries, we observe that there are a number of areas, mostly uplands, where the Carboniferous Limestone is exposed at the surface. Of these the Mendip Hills form the largest tract, roughly 30 miles (48 km) in length (Figure 1) and extending from Frome in the east to Weston-super-Mare on the Bristol Channel coast. Noted for their gorges, caverns, underground rivers and big cave systems, the Mendip Hills are obvious candidates for selection as the possible source of the thermal water rising at Bath. The springs in the Avon Gorge at Clifton and Hotwells are less easily explained, but the truth is that neither here, nor at Bath, has it been possible to prove the supposed relationship.

Comparison of ground water levels in the Mendips (Stanton 1991) and Broadfield Down suggests that water levels in the Carboniferous Limestone uplands are sufficiently high to force the water under hydrostatic pressure through the limestone at depth beneath the Coal Measures, causing it to

TABLE 2a: Generalised thickness of Palaeozoic strata.

	Feet	Metres
Carboniferous		
Coal Measures (9,500 ft; 2895.6m)	Feet	Metres
Supra - Pennant Measures (mainly mudstone)	4000	1219.2
Pennant measures (mainly sandstone)	3000	914.4
Infra - Pennant Measures (mainly mudstone)	2500	762
Millstone Grit (c. 300 ft; 91.44m)		
Quartzitic Sandstone Group (very thin in south)		
Carboniferous Limestone (3150 ft; 960.1m)		
Hotwells Group (including U. Cromhall Sst.) }		
Clifton Down Group (mainly limestone*) }	2800	853.4
Black Rock Group }		
Lower Limestone Shale Group		
(Shale and thin limestones)	c350	106.7
DEVONIAN		
Upper Old Red Sandstone (Portishead Beds)	c1500	457.2
Lower Old Red Sandstone (Thornbury Beds)	0-1500	0-457.2

* The arenaceous facies known as Cromhall Sandstone is developed at Wick, where the Middle and Upper Cromhall Sandstone are present (Kellaway, 1967). The Middle Cromhall Sandstone is absent at Bath and in the Mendips when the Upper Cromhall Sandstone is thin or absent.

TABLE 2b: Rocks proved beneath Sub-Triassic surface.

	level of Sub Triassic surface	Palaeozoic Formation
1. Kingsmead Car Park Borehole*	-30.7mOD	Hotwells Limestone on Clifton Down Limestone
2. Sports Centre (Pultney No.1 Borehole)*	faulted	Hotwells Limestone
3. Stall Street (inclined borehole)*	-40mOD	Upper Cromall Sandstone
4. Cross Bath (inclined borehole)*	-40mOD	Upper part of Hotwells Limestone
5. Alice Park (see Table I)	-20.3mOD	Clifton Down Limestone
6. Tuckingmill, Midford (see Table 1)	-185,68mOD	Top of Hotwells Group
7. Batheaston Coal Shaft and Borehole (see summary Table 1)	-72.0mOD	Upper part of Hotwells Group

* *Details given in 'Hot springs of Bath' (Kellaway 1991).*

emerge as resurgences at Hotwells and Bath. However, reconstructions showing the Radstock basin as having a relatively simple form, with the limestone overlain by synclinally disposed Coal measures, ignore the complexity for which the coalfield is noted. It must be borne in mind that in terms of predictability only the uppermost 2000 to 3000 ft (610 to 901 m) is known in sufficient detail. Below these levels the structure of the Carboniferous Limestone is virtually unknown in the central part of the coal basins.

So far as the eastern Mendips is concerned, quarrying of the Carboniferous Limestone has adversely affected ground water levels. However there is no evidence of any corresponding reduction in the flow of the thermal water at Bath, despite the fact that ground water levels in the eastern Mendips have been falling for several years, during which time monitoring of the thermal water has been continuous.

On the other hand, the east Mendip ground water levels indicate west to east migration of ground water at depth and it is generally agreed that this movement continues beneath the unconformable Mesozoic cover at least as far east as Oldford [ST 790 901], north-east of Frome. While there is a possibility that some of this ground water may find its way into a natural `reservoir' feeding the Bath hot springs, there is, at present, no means of proving that any such connection exists.

THE CARBONIFEROUS ROCKS (FIGURE 2, TABLE 2A)

Up to 9000 ft (2704 m) of Millstone Grit (Namurian) and Westphalian Coal Measures overlie about 2250 ft (686 m) of Carboniferous Limestone in the central part of the Bristol and Somerset Coalfield. Here the middle part of the Namurian, (H and R zones) is missing. The remainder of the Namurian is represented however and the overlying Westphalian Coal Measures succession is well-developed. Much of the Namurian consists of barren mudstone with thick beds of intensely hard quartzitic sandstone, from which the local lithological term Quartzitic Sandstone Group is derived. In the central region of the coal basin between Bristol and Bath the Quartzitic Sandstone Group is about 400 m thick, but it is thinner in the eastern Mendips, due mainly to the attenuation or absence of the lower and middle strata.

The Coal Measures are divisible into Lower, Middle and Upper Coal Measures, the Lower and Middle divisions being dominantly mudstone with coal seams and thin sandstones. The Upper Coal Measures have at their base the sandy barren mudstones and lenticular beds of coarse sandstone or subgreywacke known as the Pennant. Forming the highest part of the Upper Coal Measures is the so-called 'Upper Coal Series' or Supra-Pennant Measures. This includes the productive Coal Measures with the Farrington and Radstock seams. Taken as a whole the Coal Measures constitute a major aquiclude, and the evidence from the Radstock Basin indicates that very little descending ground water penetrates the Supra-Pennant Measures. The two highest groups of worked seams in the Upper Coal Measures, the Farrington and Radstock seams, are separated by unproductive rocks consisting of sandstone, fireclay and red mudstone. The Barren Red Measures, as they are called, yield saline water at Radstock (McMurtrie, 1886). This does not penetrate the underlying Farrington seams and forms a body of perched saline water which is confined to the centre of the Radstock Basin. The chemistry of this water shows that it cannot contribute to the thermal water rising at Bath. Transmissivities in the Namurian mudstones and quartzitic sandstone and the Middle and Lower Coal Measures are very low, so water carried in fissures in the Carboniferous Limestone is unlikely to penetrate the Coal Measures from below, unless there are newly-formed open fissures of deep-seated origin, through which the ground water can migrate under pressure. The position of the thermal springs at the margin of the concealed Coal Measures (Kellaway 1991b, Fig. 7.2) points to the Namurian and Lower and Middle Coal Measures as constituting a major aquiclude. This restrains the upward migration of water trapped in the upper part of the Carboniferous Limestone in the basinal areas.

THE NORTH-EASTERN AND EASTERN MARGIN OF THE CONCEALED RADSTOCK BASIN

Between Oldford near Frome and the Avon valley at Batheaston, the margin of the Somerset Coalfield is concealed by Mesozoic formations. Since 1978, however, boreholes made in connection with the thermal water investigations at Bath have established the nature of the sub-Mesozoic surface at a number of different locations in the Avon valley. The results of the borings made in the centre of Bath are given in the account of the geological investigations between 1977 and 1987 (Kellaway 1991a).

Two further boreholes, one at Alice Park east of the centre of Bath, the other at Tuckingmill near Midford (Figure 1) have since been sunk.

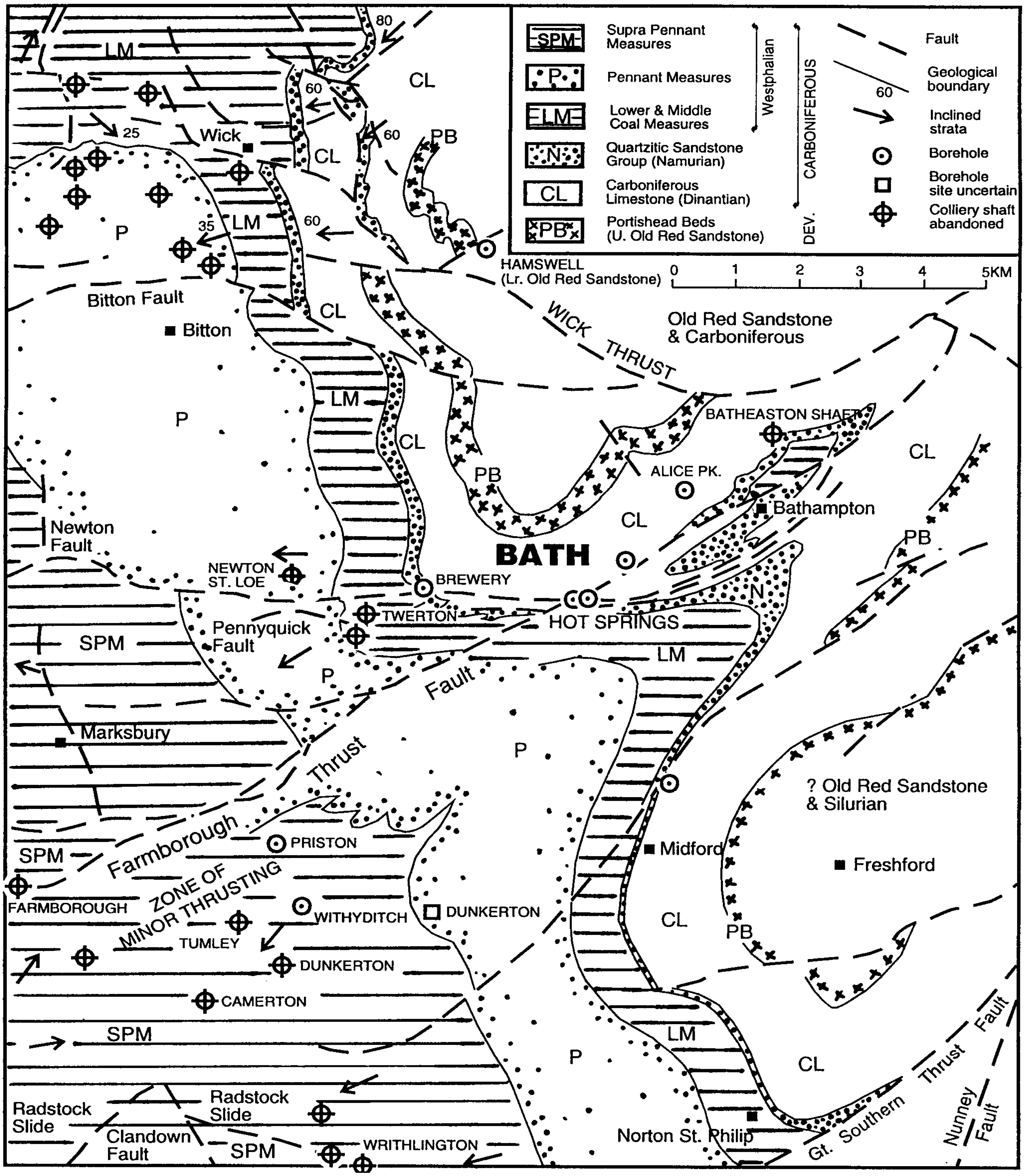

Figure 2: The geology of the sub-mesonzoic surface of the Bath district.

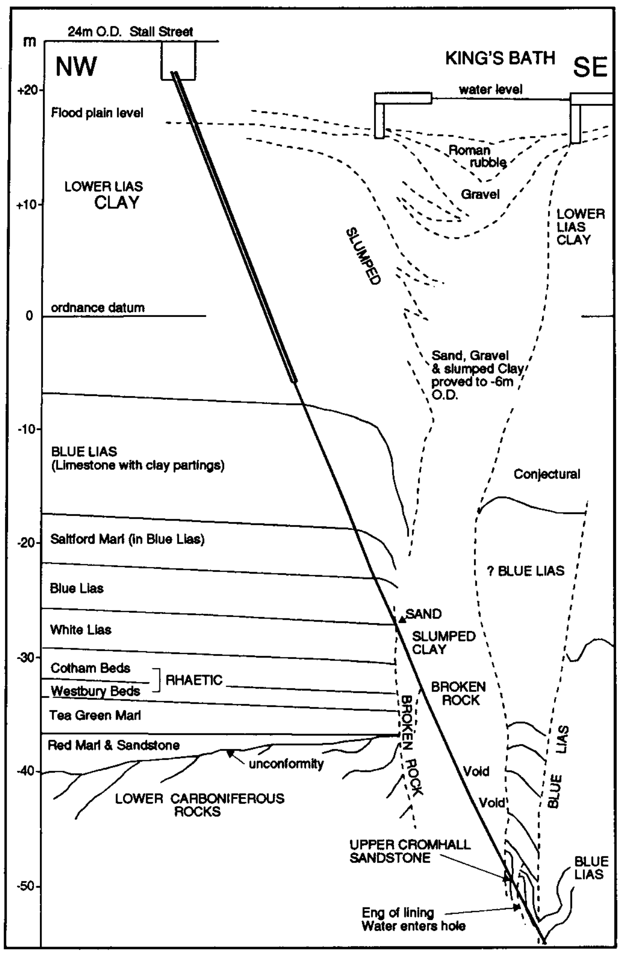

Figure 3: Section through the Stall Street inclined borehole at Bath.

Detailed results have not yet been published: brief summaries are given in Table 1, and the section in Batheaston Shaft and boring (Kellaway, 1991a) is included for comparison. The level of the sub-Triassic surface and the classification of the Palaeozoic rocks proved at various sites in and around Bath are set out in Table 2b.

A reconstruction of the geology of the sub-Triassic surface is given in Figure 2. Some parts of this are necessarily speculative, but the main outlines are supported by a substantial body of evidence. Thus the structure of the coalfield is known in considerable detail, particularly in the areas north of the Bitton Fault and south of Priston. At Wick the Carboniferous Limestone (Visean) and the Quartzitic Sandstone Group are exposed in extensive quarries, the base of the Coal Measures being defined by the Ashton Vale Marine Band. West of Bath the structure of the disturbed Coal Measures at Twerton and the workings of Globe Pit at Newton St Loe provide valuable data used in the reconstruction.

North of Bath the position of the Wick Thrust Fault is speculative, but the fault is well exposed at Wick, where it has a stratigraphical throw of about 1500 to 1750 ft (457 to 533 m). To the north and north-west of Wick it appears to split up into a number of faults and folds, some of which intersect the southeastern part of the Coalpit Heath basin. South of Wick the position of the Wick Thrust is uncertain. The reconstruction given in Figure 2 suggests that the thrust may lie within the Lower Old Red Sandstone at Hamswell and this in turn implies that the rocks above the thrust in the area immediately north of Bath are likely to include both the Upper and Lower Old Red Sandstone.

All the boreholes in the centre of Bath and at Alice Park and Batheaston have proved the upper part of the Carboniferous Limestone (Visean), the lowest horizon yet identified, (the middle of the Clifton Down Limestone) being found at Alice Park.The highest strata (Upper Cromhall Sandstone) were proved in the Stall Street inclined borehole and at Batheaston. It is clear from the evidence of the Kingsmead, Stall St, and Cross Bath boreholes that the Carboniferous Limestone must be strongly folded and faulted, but at the present time it is not possible to relate the various structures to one another. In the Stall Street inclined borehole the presence of the Rownham Hill Coral Bed (Kellaway 1991, p. 115) suggests that Namurian strata may be present in the vicinity and much the same consideration applies to Batheaston. This has been allowed for in the reconstruction.

The Sub-Triassic crop of the Farmborough Thrust Fault in the Radstock basin is defined by a belt of continuous disturbance in which coal working was virtually impossible. Farmborough Pit was sunk to a depth of 440 yds (402 m) on the north side of the main thrust, in a trough filled with barren measures (Publow Group) which lie above the Radstock seams (Anstie, 1873, p.92). These are among the youngest Coal Measures in the Radstock and Pensford basins.

Farther east at Twerton, strongly faulted and folded mudstones with thick coals (Middle Coal Measures) were proved at Twerton Colliery which was situated in Pennyquick Bottom between the Pennyquick and Newton faults (Figure 2). The northern or Newton Fault forms part of a system of east-west faults, and can be traced across the Somerset Coalfield to Burnett [ST 665 656], where it forms the northern boundary fault of the Pensford and Bromley coal workings, and thence towards Winford and the northern part of Broadfield Down. Younger than the Farmborough Fault, it shows partial Mesozoic reactivation and is thought to be the locus of the mid-Quaternary movements which have given rise to rifting and fissuring at Bath. The Pennyquick Fault together with the Newton Fault (or a parallel and closely related structure), gives rise to the belt of very strong fissuring which crosses the northern face of Bathampton Down. The linear collapse structures of tectonic origin affecting the Jurassic rocks at Bathampton differ from those produced by gravitational slides and rotational landslips. They are shown on the published Geological Survey 1:50 000 Bath map (Sheet 265), as Foundered Strata, and their linear trend and deep penetration distinguish them from much younger rotational slips, such as the huge Devensian landslide on the north-eastern face of Bathampton Down (Kellaway 1991, Plate D, pp. 280-281). Difficult cartographic problems arise where the valley sides at Bath have been affected by both these processes; in built up areas it may be impossible to distinguish between them.

Between Newton St. Loe and the Bitton Fault there have apparently been no coal pits sunk along the presumed incrop of the Lower and Middle Coal Measures and Pennant Measures. Yet workable coals almost certainly extend between Newton St Loe and Bitton. The apparent absence of old workings is due partly to the thickness of the Mesozoic cover rocks in the Lansdown promontory and partly to the presence of ground water in the concealed Pennant Measures. Another factor which must have dissuaded the old miners from attempting to mine this area is the presence of huge landslips on the flanks of Lansdown Hill. It would have been both difficult and unsafe to sink shafts on these steep landslipped slopes. The absence of coal workings in this tract is therefore explicable in terms of mining practice, and does not imply that the position of the incrop of the productive Coal Measures as shown in Figure 2 is incorrect. In fact this may be one of the few areas in the coalfield where substantial reserves of coal are still intact.

North of the Bitton Fault the intensively worked Coal Measures, and the exposed contact of the Pennant Measures and productive Lower and Middle, Coal Measures provide ample evidence for the incrop as shown, as do the exposed areas of Carboniferous Limestone and Quartzitic Sandstone Group seen in Wick Quarry. Here the Carboniferous Limestone and Quartzitic Sandstone are cut by the Wick Thrust, the base of the Gully Oolite being in contact with the Quartzitic Sandstone Group which forms the footwall of the Wick Thrust. The course of the thrust from Hamswell to its contact with the Farmborough Thrust is speculative however, as there is no underground evidence immediately north of Batheaston and Alice Park. The incrop of the Carboniferous Limestone as shown in Figure 2 fits the evidence from the various boreholes made between Batheaston and Bath, as well as that of some older borings in the Avon Valley, where the classification of the Palaeozoic formations is less certain.

South of Bath hot springs the position of the Tuckingmill Borehole is critical, since this borehole proved steeply-dipping rocks which correlate with the Tanhouse Limestone and cherts of the Yate area. These beds lie at the top of the Carboniferous Limestone and their presence implies that the Tuckingmill boreholes entered the Carboniferous Limestone a very short distance east of the incrop of the Dinantian/Namurian contact.

In the south-eastern corner of the map area the position of the 'Great Southern Thrust Fault' is extrapolated from its known position and trend in the Radstock Basin. The Nunney Fault is part of a suspected major disturbance affecting the Carboniferous Limestone of the eastern Mendips. The extent of this displacement is unknown; like the Farmborough Fault it may be an oblique slip fault with a substantial horizontal component.

The geological structure of the Palaeozoic rocks at Bath is therefore extremely complex and can only be predicted in general terms. Yet sufficient is known of the structure between Bath and the eastern Mendips to suggest that a very cautious attitude is required in respect of theories which derive the thermal water from the Carboniferous Limestone of the eastern Mendips. Whatever the hade of the 'Great Southern Overthrust Fault' it is certainly a major dislocation, and its magnitude is such that it may have affected all the rocks down to and including the Old Red Sandstone. The same consideration affects the Farmborough Thrust Fault. Thus it will be observed that all the sites where the hot springs occur or where thermal water has been recovered in boreholes, tunnels and shafts are either in the reactivated part of the fault zone or in the faulted rocks of the valley floor to the north of it. With the exception of one doubtful record at Dunkerton all quarries shafts and borings south of the fault have yielded water which is of shallow origin, at temperatures which approximate to M.A.T. or appropriate to the depth at which it occurs. In the case of the Tuckingmill Borehole the yield is so low that the Carboniferous Limestone can be described as 'dry'. If ground water is reaching Bath from the eastern Mendips, it is probably moving along some indirect route by way of reactivated Mesozoic or Tertiary faults. As yet, however, the monitoring of the thermal water yield at Bath has given no indication that quarrying of the Carboniferous Limestone in the eastern Mendip area has affected the hot springs at Bath.

THE DEVELOPMENT OF THE HOT SPRINGS IN RELATION TO PHYSIOGRAPHIC EVOLUTION

Considerable attention has been given to this problem (Kellaway, 1991c) and the indications are that the springs may have been formed in pre-Ipswichian post-Cromerian times. The initiation of the present drainage system may be older, but the formation of the hot springs demands hydrostatic pressures which could only have been generated by the creation of a substantial relief during the dissection of the Mesozoic and Tertiary cover. In effect this places the development of the hot springs in the range of 200,000 to 500,000 years B.P. The evidence for an older system of north-west — south-east drainage crossing the site of the lower Severn valley has been discussed elsewhere (Kellaway, 1991c). All the stages in the development of the westerly-flowing Bristol Avon have not yet been worked out, but the magnitude of the change is clear enough. It resulted in much of the water which formerly fell on Wales and the borders and then found its way to the Thames or the Solent, being diverted to the Bristol Channel. This change is commensurate, and may be roughly contemporaneous, with, the diversion of water which formerly found its way from the Cotswolds through the Proto-Soar valley to the Trent. This was diverted to the Severn estuary by the development of the Warwickshire Avon, and the opening of a channel between the Cotswolds and the Forest of Dean at Purton Passage. These particular changes in the drainage of England took place in the period following the Cromerian and preceeding the Ipswichian interglacial. Tectonic movement may have played a significant part in the generation of the changes, as did the erosional effects produced by glacial meltwater.

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