THE GEOLOGY OF THE HOT SPRINGS AT BATH SPA, SOMERSET

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Gallois, R.W. 2006. The geology of the hot springs at Bath Spa, Somerset.
Geoscience in south-west England, **11**, 168-173.

The three springs that emerge under artesian head at 45-46ºC beneath and adjacent to the Roman Bath in the centre of Bath Spa, Somerset are unique in the British Isles. There are only six known occurrences of thermal springs in the region, of which only that at Bath can be described as hot. The springs at Hotwells (Bristol), Taff's Well (Cardiff), Buxton and Matlock Spa (Peak District), and Mallow (Eire) all emerge at less than 30ºC. The thermal springs at all six localities are hosted in the Carboniferous Limestone in structural settings that allow meteoric water to descend to sufficient depth for it to be heated by the geothermal gradient, and then return to the surface without a significant fall in temperature. Those at Bath reach the surface on the floodplain of the River Avon via 'spring pipes', collapse structures that extend down through Jurassic and Triassic rocks to the concealed Carboniferous Limestone. The source of the Bath springs is known from geochemical studies to be rain that fell several thousand years ago and descended to depths of at least 2500 m on its path to the hot springs. Hypotheses proposed to explain their mechanism include volcanic heat, a simple hydraulic model and a Europe-wide fracture zone. However, none of these hypotheses explains why the hot springs are confined to such a small (20 x 80 m) area. Their formation appears to have been dependent on a geological history that is unique to this area, one that included the formation of limestone karst in Triassic deserts and the local melting of a permafrost aquiclude in the late Pleistocene.

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INTRODUCTION

According to legend and the historian Geoffrey of Monmouth (*Historia Regum Brittaniae*, 1136), the hot springs at Bath were discovered in the 9th century BC by Bladud, a Celtic prince who was so disfigured by leprosy that he became a wandering swineherd so that his people would not have to look upon his disfigurement. When he chanced upon the springs and noticed that the sores on his pigs were healed by their waters, he cured himself. He went on to become a great king who founded the city of Bath, learned to fly and sired King Lear. Later historians noted that Mesolithic remains and Iron Age coins, probably votive offerings, have been found adjacent to the springs (Cunliffe, 1983). However, the documented history of the springs did not begin until the Romans built the magnificent baths that now lie at the heart of the Bath Spa World Heritage Site. The extent of their walled city remained little changed until the end of medieval times (Figure 1).

Like most hot springs, those at Bath have been considered since time immemorial as magical by some and medicinally valuable by many more. King Bladud reputedly built a temple there dedicated to the Celtic goddess Sul (hence the Roman name Aquae Sulis) who was associated with medicine and fertility. Not all medicine is efficacious. The pool formed by the King's Spring is the richest source in Britain of Roman 'curse tablets', requests to the goddess by victims of theft to afflict unpleasant, sometimes fatal, ailments on the presumed thief. In the 18th century it was claimed that the hot springs could cure complaints as diverse as piles, sciatica, migraine and sterility, and that they were especially efficacious for rheumatic and skin problems. One result of this was that the first national hospital in Britain, the Royal Mineral Water Hospital, was founded in Bath in 1738 to treat those who could not afford private treatment (Rolls, 1991).

The discovery in 1903 of significant concentrations of radium salts in the spa waters led to the belief, at least temporarily, that this was the active beneficial ingredient and a 'radium inhalitorium' was constructed. It closed after the accident at Seascale (now Windscale) in 1959 (McNulty, 1991). Despite convincing evidence that immersion in the spa waters had beneficial effects for some conditions, treatment ceased to be available on the NHS in 1976. A new spa, the only place in the UK where one can bathe for healing, relaxation and leisure purposes in natural hot-spring water, opened in Bath in August 2006.

There are only six known occurrences of thermal springs in the British Isles, of which only that at Bath can genuinely be described as hot (>30°C). Those at Hotwells (Bristol), Taff's Well (Cardiff), Buxton and Matlock (Peak District), and Mallow (Eire) emerge at temperatures ranging from 20° to 28°C. The three hot springs at Bath, the King's Spring, Cross Bath Spring and the Hetling Spring (also known at various times as the Com[m]on Spring or Hot Bath Spring) are situated in a small (20 x 80 m) area on the floodplain of the River Avon (Figure 1). Their combined flow is currently *c.* 60 m^3/hr, similar to that of a small stream. Historical records suggest that the flows were higher in the past, but few of the measurements are sufficiently accurate to make meaningful comparisons with the accurate present-day monitoring. Records of the water temperatures at the springs have shown little variation over the past 100 or so years, being highest (46-47ºC) at the Hetling Spring and lowest at the Cross Bath Spring (44-45ºC).

The springs have been under the care of the Civic Authority (currently Bath and North East Somerset Council) since 1590 and are now protected by an Act of Parliament (the County of Avon Act, 1982). They are currently estimated to attract over £300 million per annum of tourism benefits to the city. Successive councils have appreciated the need for independent geological advice on the nature of the springs and any possible adverse effects that building developments in central Bath might have on them. This advice was provided from about 1925 to 1977 by R. H. Rastall, from 1977 to 2002 by Dr G. A. Kellaway, and is currently supplied by the present author. Almost all the detailed knowledge of the geology of the hot springs and of the surrounding area stems from research

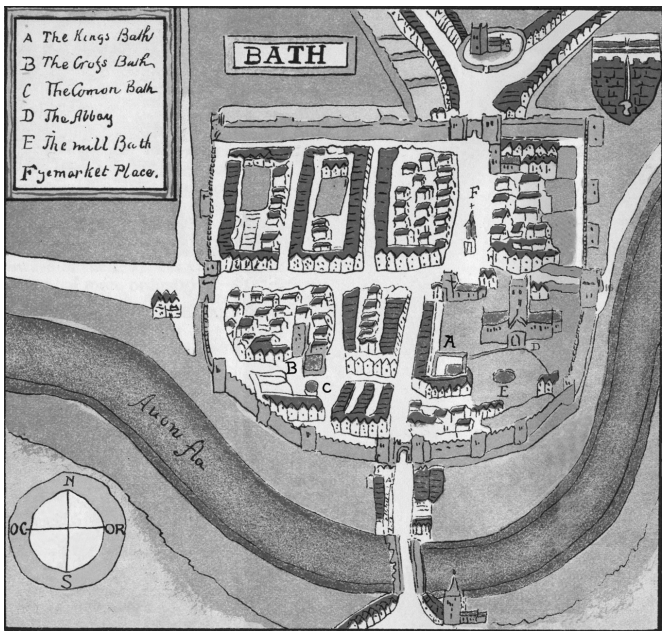

Figure 1. *The earliest known 'map' of Bath (William Smith, 1588) showing the city built around the three hot springs that fed the King's, Cross and Com[m]on baths. The Mill Bath was fed by the overflow from the King's Bath.*

carried out by Dr Kellaway. The history, geology, hydrogeology, geochemistry and medicinal uses of the hot springs are summarised in Kellaway (1991a). The present account supplements these results with data obtained from investigations carried out in the Bath area during the last 20 years.

GEOLOGY OF THE HOT SPRINGS

Geological setting

Bath lies on the eastern edge of a large basinal structure that contains a complete Carboniferous succession up to 4000 m thick (Kellaway and Welch, 1993). The area lies on the northern edge of the Variscan Front and was complexly folded and faulted during the later stages of the orogeny. Erosion and depositional infilling of an irregular topography during the Permo-Trias resulted in a low relief landscape in the latest Trias that was invaded by the early Jurassic sea. As a result, much of the Variscan structure is concealed beneath Mesozoic deposits (Figure 2). In the central part of the Bristol-Bath Basin, the Coalpit Heath, Pensford and Radstock sub-basins and their concealed extensions make up the Bristol-Somerset Coalfield. Coal seams ranging in age from Westphalian A to D (of the European classification) were extensively worked from at least the 13th century until the closure of the last mine in 1973. Taken together, the mines and associated exploration boreholes provided a wealth of geological data that revealed the most tectonically disturbed strata in any coalfield in Britain (Kellaway and Welch, 1993 and references therein).

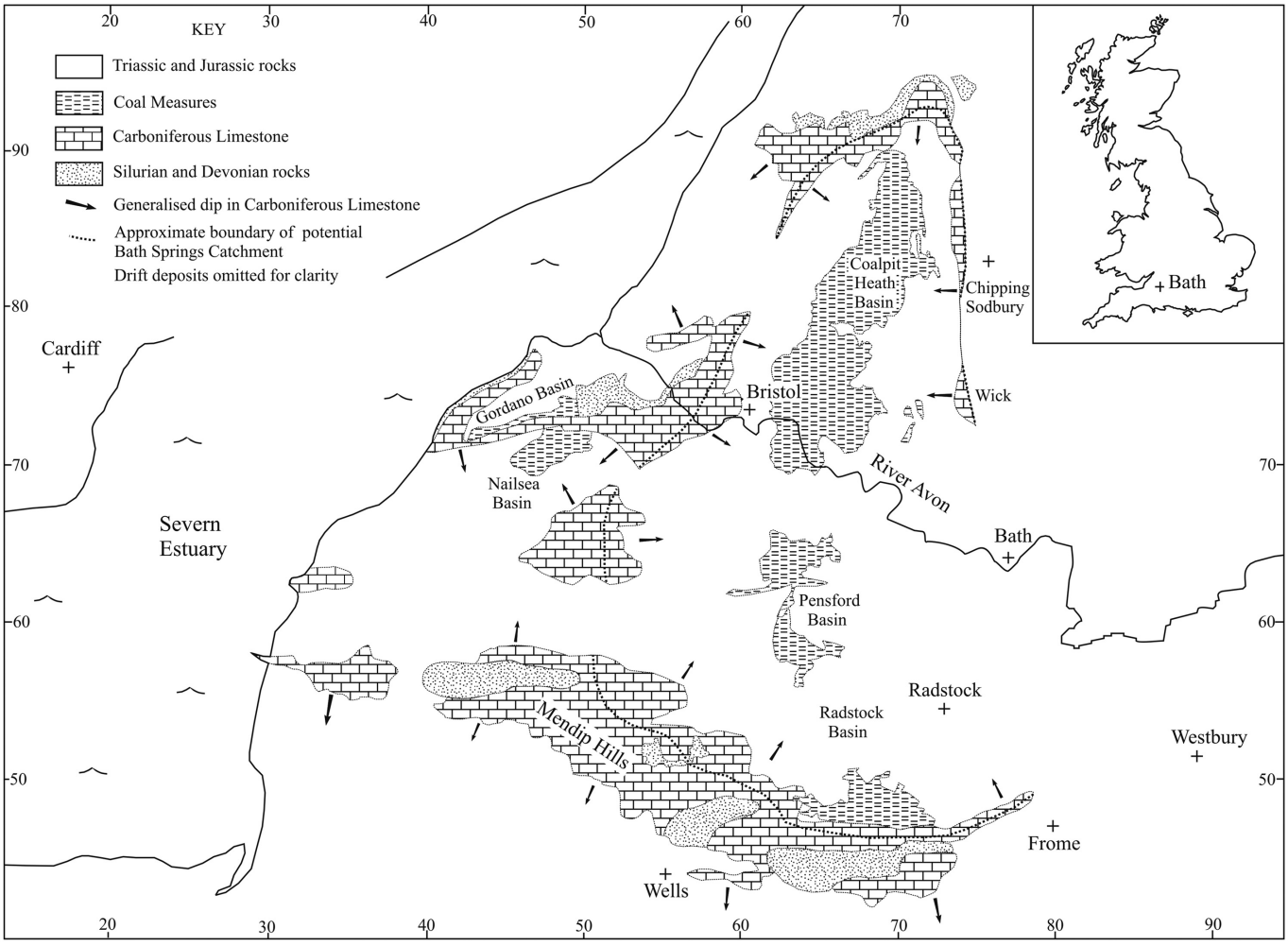

Figure 2. *Geological sketch map of the Bristol-Bath area showing the presumed potential catchment area of the Bath hot springs (based largely on Kellaway and Welch, 1993).*

Although highly complex in local detail, this Variscan structure can be envisaged as a series of large open folds separated by thrusts and numerous faults. The most important feature, as far as the mechanism of the hot springs is concerned, is the 1000-m thick Carboniferous Limestone succession that crops out intermittently around the edge of the basin. The topographically higher parts of the outcrop are in the Mendip Hills, and these have been assumed since the time of William Smith to be the recharge area for the hot springs. However, the basinward-dipping potential catchment area extends around the whole of the structure (see below).

The general geology of the area around and beneath the hot springs has been known since the early 19th century, from the time when William Smith and others obtained data from boreholes in the town and from coal-exploration boreholes in the adjacent areas. The springs originally emerged from gravel-filled pipes that William Smith (MS quoted by Phillips, 1844) referred to as 'spring pipes'. Beneath this an almost horizontal, unbroken late Triassic (Mercia Mudstone Group) to early Jurassic (Charmouth Mudstone Formation) succession rests with marked unconformity on steeply dipping Carboniferous Limestone at about 55 to 60 m below the original floodplain.

Information on the detailed geology beneath the hot springs remained relatively sparse until 1977-78 when two significant events occurred. First, subsidence at the Roman Baths prompted urgent remedial action. A pattern of site-investigation boreholes was drilled that enabled Kellaway (1991b) to determine the 3D shape of the top part of the 'spring pipe'. A subsequent investigation to stabilise the Roman buildings at the Cross Bath revealed a similar structure.

Second, in 1978 a 12-year-old girl died from the brain disease meningoencephalitis after swimming in a public pool that was fed by hot water from the springs. The cause was shown to be a thermophilic amoeba (*Naegleria fowleri* Carter) that was subsequently found to be present in large numbers in the oxygenated waters of the King's Bath. All use of the spa water ceased and an alternative, medically safe source was sought for use at the popular drinking fountain at the Roman Baths. Funds were provided by the council and, under the direction of Dr Kellaway, an inclined borehole was drilled from the road (Stall Street) outside the Roman Baths to intersect the source of the King's Spring in the Carboniferous Limestone where it would be anaerobic and free from amoeba (Figure 3). Additional boreholes were subsequently drilled into the Carboniferous Limestone for water-supply purposes close to the Cross Bath and Hetling springs. The boreholes drilled at all three springs confirmed that the hot water emerges from 'spring pipes', conical structures infilled with mixtures of river gravel and clasts of Triassic and Jurassic rocks. Most significantly, the Stall Street Inclined Borehole showed that this loosely compacted debris extended down to the Carboniferous Limestone in partially filled cavities (Figure 3). A recent CCTV survey showed that the clasts on the floor of the deepest cavity proved in the borehole (70 m below ground level) include river gravel and what appear to be fragments of Roman tile.

The importance of the springs to the local tourist trade and the World Heritage designation, combined with the probable sensitivity of the springs mechanism, led to the passing of the Avon Act in 1982. This is designed to ensure that all excavations (including boreholes) made to a depth of greater than 5 m in central Bath (10 m and 15 m in the adjacent areas) are carefully monitored. Most of the site-investigation boreholes since that time have been continuously cored, and this has resulted in much additional data. Taken together, they have shown that a laterally variable mid to late Triassic succession of terrestrial deposits (Dolomitic Conglomerate and Mercia Mudstone Group) infills an irregular topography cut in Carboniferous rocks. This is overlain by latest Triassic brackish-water to early Jurassic marine sediments (Westbury Formation to Charmouth Mudstone Formation) that show little lateral variation either in thickness or lithology. The hot springs overlie a high point on the late Triassic land surface that appears to be a small knoll of karstified limestone (Figure 4).

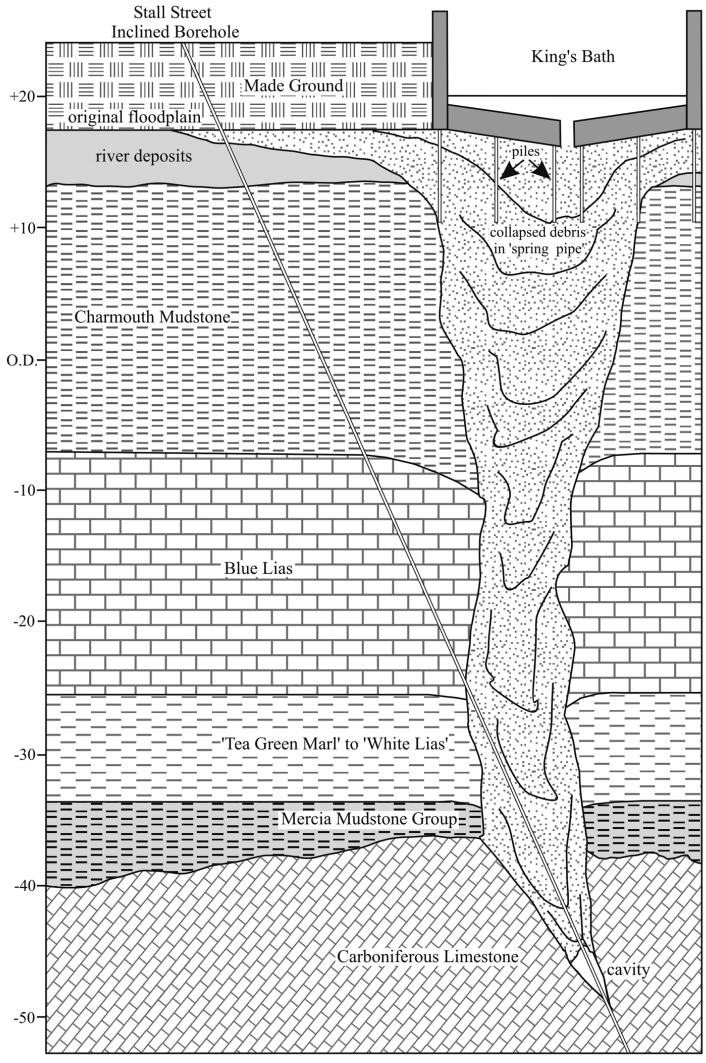

Figure 3. *Geological succession and structure proved in the Stall Street Inclined Borehole (after Kellaway, 1991b).*

Mechanism and formation of the hot springs

The chemistry of the hot-springs waters is well documented (Andrews, 1991; Edmunds and Miles, 1991; Darling and Edmunds, 2001; Edmunds 2004) and there is, therefore, general agreement on the conditions required to produce them. The stable-isotope compositions indicate that the source was meteoric, and the noble-gas compositions that it was precipitated in a temperate, post-glacial climate thousands rather than hundreds of years ago. Silica geothermometry indicates that the water has been heated to a maximum temperature in the range 64° to 96°C. The regional geothermal gradient is about 20°C/km depth (Downing and Gray, 1986; Baker *et al.*, 2000), which suggests that on its path from the catchment area to their outfall the hot-springs water has been buried to a depth of at least 2500 m (Edmunds *et al.*, 2002).

Several hypotheses have been published to explain all or part of the mechanism that gives rise to the hot springs. Rastall (1926) suggested that deeply buried hot volcanic rocks or a concealed granite batholith might be the heat source. However, the local geothermal gradient is low (heat flow 40-50 mW/m^2), markedly less than that over much of Britain (Downing and Gray, 1986), and there is no geophysical evidence for a batholith (McCann *et al.*, 2002).

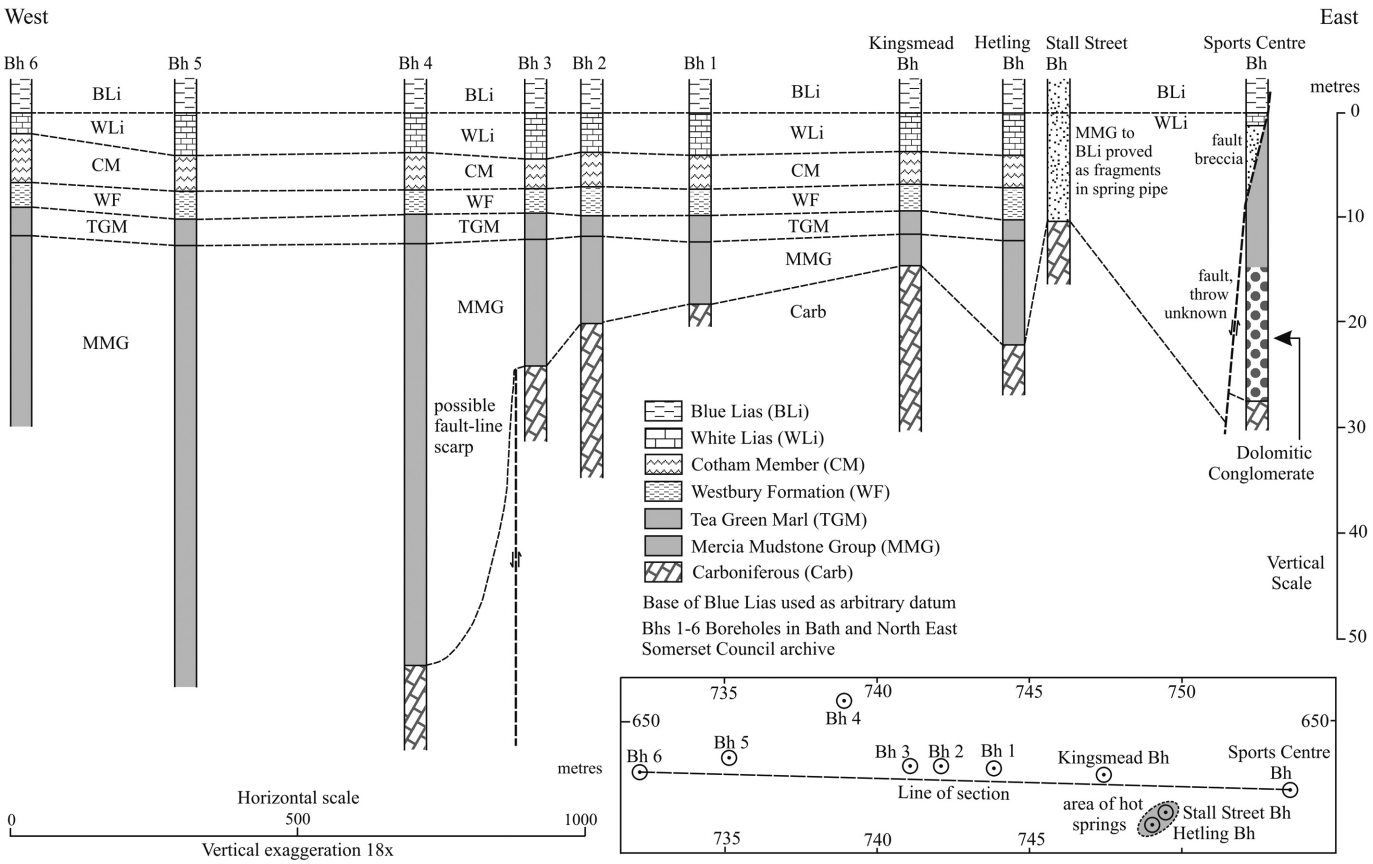

Figure 4. *Geological sketch section through central Bath and the hot springs area based on selected boreholes.*

The most widely accepted explanation to date has been the Mendips Model (Andrews *et al.*, 1982). This envisages rain falling on the Carboniferous Limestone outcrop of the Mendip Hills, descending on its north-easterly path to a depth of more than 2000 m beneath the predominantly impermeable Coal Measures of the Radstock Basin, and emerging rapidly at Bath via a belt of highly fractured rock along a Variscan thrust (Figure 5). The model also explains the artesian head of up to 9 m above natural ground level at the hot springs.

The model is in accord with the chemical results, but not with the known geology. First, the assumption that the Carboniferous Limestone sheet is unbroken and in hydraulic continuity between the Mendips and Bath is unproven. It is unlikely to be correct given the tectonic complexity proved at the southern end of the section where there are large gravity-collapse structures (e.g. Kellaway and Welch, 1993, figure 25). Second, there is to date no evidence for the major thrust that is presumed to be the conduit that allows the heated water to escape quickly to the surface beneath Bath.

In addition, there is no reason to assume that the Mendips outcrop is the only catchment area that would allow water to descend to the required depth. The top of the Carboniferous Limestone is at a depth >2500 m in a NW-SE trending area of *c.* 5 x 22 km beneath the Pensford and Radstock basins. Given the extent of the known faulting and associated fracturing in the Bristol-Bath Basin, there is no reason why rain falling on the Carboniferous Limestone outcrops of the Bristol area could not contribute to the groundwater in the deepest part of the basin. The Coalpit Heath Basin down to a depth of at least 500 m is probably also in hydraulic continuity with the Pensford Basin. If this is the case, then the Carboniferous Limestone around the edges of the Bristol-Bath Basin has a potential catchment area of about 200 km^2 and the formation within the basin has a potential reservoir volume of *c.* 480 km^3 below the present-day water table. This reservoir would probably be sufficient to supply the relatively small flow at the hot springs for several hundred years even if there was no additional meteoric intake during that time.

Wilcock and Lowe (1999) have suggested an even larger possible catchment area, one that includes the Carboniferous Limestone outcrops west of the Severn Estuary in the Chepstow and Forest of Dean areas. Their sub-Severn hypothesis envisages 'deep flow' in the Old Red Sandstone driven eastward by high hydrostatic heads. The proven structural complexity beneath the estuary combined with the presence of outcrops of Old Red Sandstone along the eastern shore and springs beneath and adjacent to the estuary, suggest that any such flows do not reach the Bristol-Bath Basin.

The artesian heads at the hot springs remain problematical, but are unlikely to be due to the difference in topographical height between the Mendips and the springs. Artesian heads are absent *c.* 2 km west of the hot springs where the Westbury Formation, the aquiclude that confines the head at the springs, comes to crop. Artesian heads are also absent from the Carboniferous Limestone where it is confined beneath the Westbury Formation in the Alice Park [ST 7650 6659] and Tuckingmill [ST 7640 6160] boreholes, 2.5 and 3.5 km from the hot springs respectively. In our present state of knowledge, the most likely explanation of the artesian heads is that they are a local phenomenon related to the high-relief topography of the Avon Valley at Bath.

In an alternative to the Mendips Model, Kellaway (1996) suggested that the hot springs are located either on an Avon-Solent Fracture Zone, a deep-seated, NW-SE-trending geological structure that extends from Wales to central France (Kellaway, 1996), or on a southerly continuation of the N-S trending Malvern Fault Zone (Kellaway, 1994). Both fracture zones are presumed to cross the Avon Valley at Bath. The Avon-Solent Fracture Zone theory is indirectly supported by data from borehole breakouts that shows the current regional stress field in southern Britain to be relatively constant with a minimum horizontal stress direction of NE-SW (Brereton and Müller, 1991).

This suggests that fractures with a NW-SE orientation are more likely to be open than those with other trends.

As with the Mendips Model, the assumption that the hot springs are underlain by rocks that are more heavily fractured than those of the adjacent areas is difficult to test. It would require the construction of borehole (for cross-hole geophysics) and/or shafts and tunnels beneath a World Heritage Site in ground that is saturated with hot water under artesian head. Seismic-reflection surveys carried out in 1999 to determine the structure of the Carboniferous Limestone in the area beneath and adjacent to the hot springs were unable to detect any faulting or fracturing that could be directly related to them (McCann *et al.*, 2001; 2002).

Neither the Mendips Model nor the fracture hypotheses explains why the hot springs are unique in Britain nor why they are confined to such a small area. There are other locations where suitable aquifers and structures are present in areas with significantly higher geothermal gradients than that at Bath. An alternative hypothesis (Gallois, in press) focuses on the geology of the springs where they emerge rather than on where they are sourced and how the water gets to Bath. It suggests that the key to their formation is the recognition that the 'spring pipes' are collapse structures that formed over a local high point on a Triassic palaeokarst surface. This may have been the site of thermal springs when the knoll of Carboniferous Limestone was exposed in the late Triassic. These would have been sealed beneath a thick cover of predominantly argillaceous Jurassic rocks, and would have remained sealed until the excavation of the Avon Valley in the Pleistocene. Rapid down-cutting at that time, when the groundwater in the region was additionally confined by permafrost, could have brought warm water in the limestone knoll close enough to the surface to melt the permafrost and produce springs in the valley floor (Figure 6). Once formed, their flows would have increased and removed fine-grained material in the cavities in the limestone. This, in turn, would have caused collapse of the overlying sediments to form the 'spring pipes'. With time, higher flow rates would allow deeper-hosted water to reach the surface more quickly and the temperature at the springs to increase. This process would have continued until an equilibrium was reached in which the rate of flow was balanced against the transmissivity of the infilling materials in the 'spring pipes'.

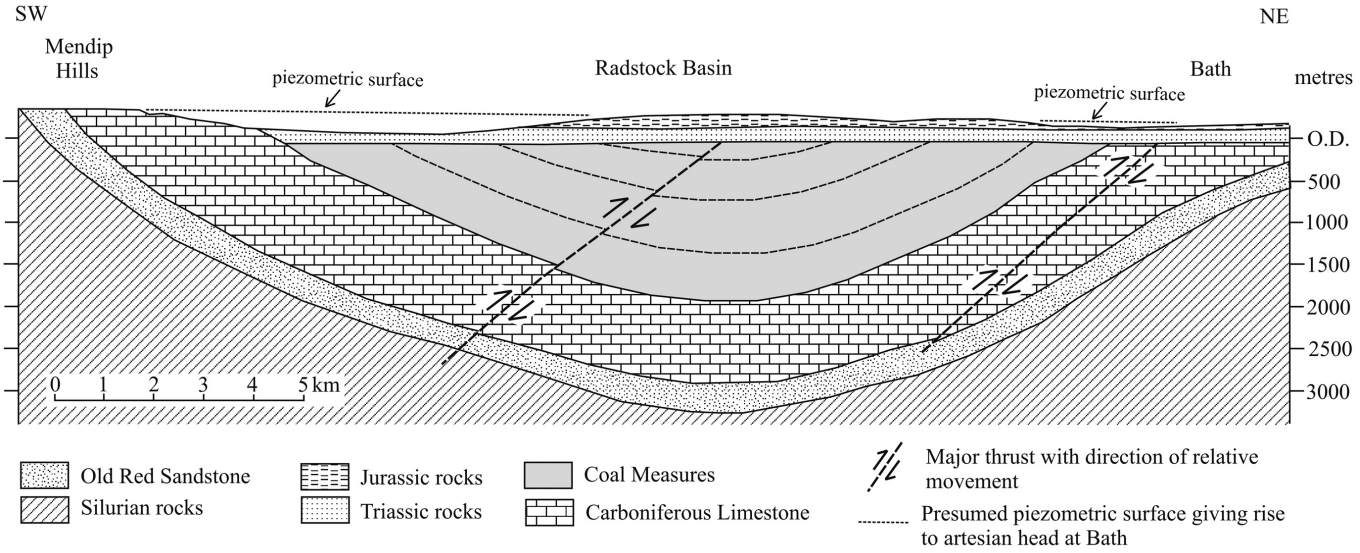

Figure 5. *Conceptual hydrogeological section to illustrate the Mendips Model (after Andrews* et al.*, 1982). Rain falling on the Mendip Hills descends down dip in the Carboniferous Limestone, is geothermally heated to at least 65°C, and rises to the surface at Bath via a Variscan thrust zone to form the hot springs.*

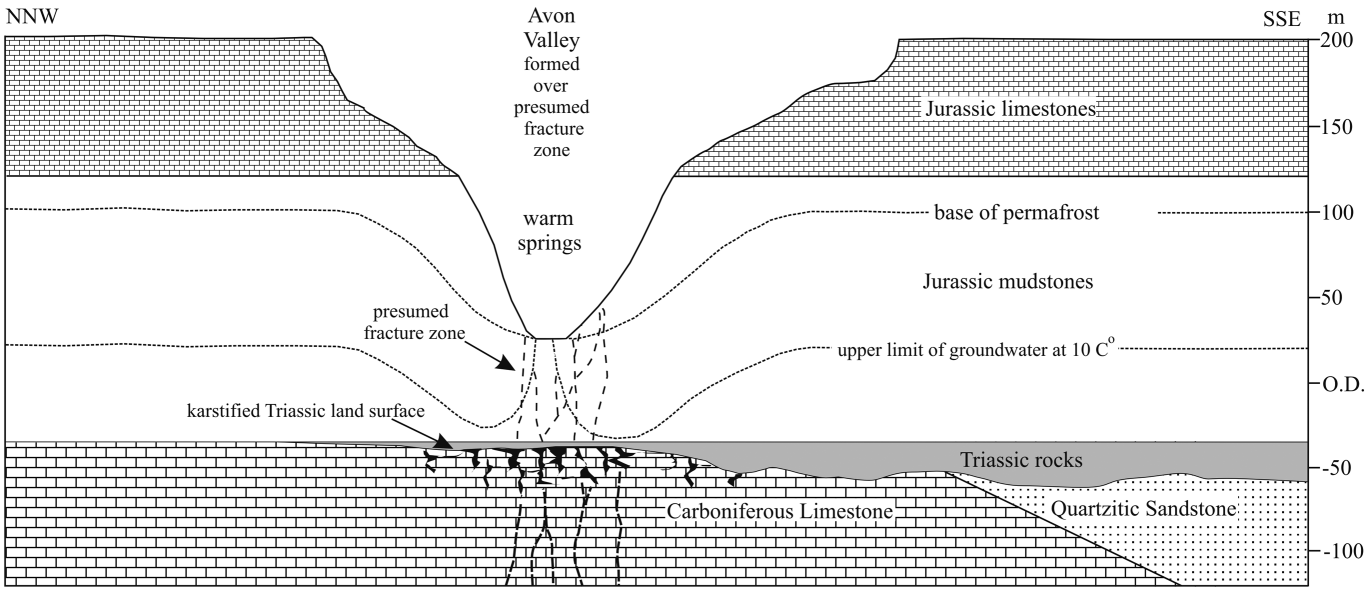

Figure 6. *Sketch section through the Avon Valley to illustrate the suggested origin of the hot springs in the latest Pleistocene (after Gallois, in press).*

Conclusions

The thermal waters that emerge at 45-46ºC in the centre of Bath Spa, Somerset are unique in Britain. The four other thermal springs in Britain are also hosted in the Carboniferous Limestone aquifer, but they emerge at significantly lower temperatures. They differ from those at Bath in that none have been linked to karst features other than joint widening and, most importantly, none is overlain by an impermeable caprock that would prevent mixing with cool near-surface waters.

The source of the Bath hot springs is known from geochemical studies to be rain that fell on the Carboniferous Limestone outcrop several thousand years ago, and was geothermally heated at depths of at least 2500 m on its path to the springs. Bath lies on the eastern edge of a complexly folded and faulted Variscan structure, on the edges of which the Carboniferous Limestone has extensive outcrops and beneath which groundwater is sufficiently deeply buried to reach temperatures in excess of 64°C. However, these factors alone do not explain why the hot springs are confined to such a small (20 x 80 m) area. Their formation appears to have been dependent on a combination of geological events, including the formation of karst in the Triassic and the melting of permafrost in the Pleistocene, that is unique to this one small area at Bath.

Acknowledgements

Almost all the pioneer work relating to the geology of the hot springs at Bath was carried out by Dr G. A. Kellaway, whose advice and encouragement is gratefully acknowledged. North East Somerset Council (B&NES) are thanked for access to their borehole databases, and Mark Williams of B&NES for his assistance throughout this study.

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