

The History and Hydrogeology of Laywell, a Celebrated Ebb and Flow Spring at Brixham, Devon

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Following a letter in the Royal Society's Philosophical Transactions of 1693, the ebb and flow spring at Brixham was a famous landmark for the next 150 years. The spring, known as Laywell, rose at the junction of Middle Devonian limestones and mudstones about 36 m above mean sea level. The spring flowed continuously with cycles of ebb and flow superimposed on this background discharge. Numbers of cycles ranged from 9 to 20 per hour and were interrupted by periods of varying length and at irregular times when intermittent flow did not occur. The ebb and flow cycles can be explained by the action of a syphon operating within the cavernous limestones, but some aspects of the spring's behaviour remain a mystery. Intermittent flows ceased around 1840 either following attempts to improve the performance of the spring, local road works or through mining and quarrying of the limestone. Once used for public supply, water now runs through the town to the sea, the spring's former fame long forgotten.

INTRODUCTION

During the early part of July 1693, Dr William Oliver (1658–1716), a Cornishman who held the post of physician to the Red Squadron, the senior squadron of the Royal Navy, went ashore at Brixham in South Devon to stretch his legs and ‘breath a little Land Air’ (Oliver,

1693a, p. 909). He walked about a mile (1.6 km) into the countryside to see a locally celebrated well, called Lay-Well, which ebbed and flowed on a regular basis. Each flux and reflux cycle lasted about two minutes with a variation in water level slightly greater than five inches (0.127 m). The water was not mineralised and was used by the local people for general household purposes. He described his visit in a letter to his fellow Cornishman, the politician and writer, Walter Moyle (1672–1721), who communicated it to the Royal Society, where it was published in the *Philosophical Transactions* (Oliver, 1693a).

In response to some questions from Moyle, he visited the well again later that year, towards the end of August. This time he took with him a watch to measure accurately the length of the flux and reflux cycle. These observations showed that the cycle was completed in a little over a minute, but that the water then stood at its lowest ebb for two to three minutes, so that it completed about 16 cycles in an hour (Oliver, 1693b). He was told that sometimes this increased to 20 cycles an hour. As the water rose, bubbles ascended from the bottom of the well, but when the water level began to fall the bubbling ceased. The well measured five ft by five ft (about 1.5 x 1.5 m), was about six inches (about 0.152 m) in depth and situated well above sea level. As the water rose in the well it overflowed over a broad stone, joining other small streams, before discharging into the sea at Brixham. As Oliver noted the real rise and fall in water level was probably more than five inches (0.127 m), as the maximum height to which water could rise was controlled by the overflow point of the well.

That the depth of water in wells adjacent to the seashore varied with the ebb and flow of the tide had been noted by many early writers. For example, Sandford's Well at the village of Newton, near Porthcawl in South Wales, was recorded by William Camden in his *Britannia*, inspiring his correspondent to compose a verse celebrating the interaction of well and river (Camden, 1610, p. 644). Changes in water level in this well lagged behind those in the adjacent Severn estuary by about three hours (Madan, 1898). However, the situation at Brixham was very different, as the Laywell was in Higher (or Upper) Brixham, some 1.5 km from the coast and well above mean sea level. Fluctuations in water level were not related to the tidal cycle but had a periodicity of a few minutes.

Springs with fluctuations of this type are known elsewhere and are confined to karst limestone terrains. Various known as ebb and

flow, intermittent, periodic, rhythmic and reciprocating springs or potajnice, they are rare with an estimated 100 worldwide (Bonacci and Bojanić, 1991), although this is likely to be an underestimate. The Laywell is one of four such springs described from England by 17th and 18th century topographers; the others being at Tideswell and Barmoor Clough (near Chapel-en-la-Frith) in Derbyshire and Giggleswick in Yorkshire. This paper describes the history and hydrogeology of the Brixham spring, considers the theories put forward to explain the varying flow patterns recorded and considers why the spring ceased to ebb and flow in the middle of the 18th century.

HISTORY OF THE SPRING

Although Oliver referred to the spring as Lay-well, the hyphen was dropped in most subsequent accounts and the name Laywell will be used in the remainder of this paper. Although called a well, it was in fact a spring, which fed, via a basin, into a stream flowing through Brixham into Tor Bay. The designation as a well probably arises from the basin built to receive the spring water. It lies at National Grid Reference, SX 917549, in the bottom of a NW/SE trending valley, 36.06 m above mean sea level, overlooked to the south and east by land which rises to over 120 m (Fig. 1).

The spring is marked, as a non-Roman antiquity, on the modern 1:50 000 Ordnance Survey Sheet 202 (Torbay and South Dartmoor). On the 1st edition six inch to the mile Ordnance Survey map, surveyed in 1864 and published in 1869, the spring is marked as Lady Well (Fig. 1), a name from which Laywell is a possible corruption. However, on Benjamin Donn's 1765 map of Devon (Ravenhill, 1965), it is shown as Leywell (Fig. 2) and the name could equally refer to the well in 'the ley', a piece of land put down to grass for a limited period of time, in contrast to permanent pasture. According to Horsley (1988) the spring is thought to have been discovered in Roman times and then rediscovered in 1087, after which it was visited by pilgrims embarking from Brixham to visit the tomb of St James at Santiago de Compostela in Spain. However, evidence to support such legends is lacking.

Following Oliver's visit in 1693, the Laywell was visited and/or described by other travellers and topographers over the next 150 years. Cox (1700) reported that near the church in Brixham was 'a remarkable well, called Lay-Well, which ebbs and flows several times in an hour and bubbles up sometimes like a Boiling Pot' (Cox, 1700, p. 496).

have been a day trip from his father's home at Buckland Monochorum, on the River Tavy, some 16 km north of Plymouth (Atwell, 1732). During Oliver's visits some 35 years earlier the spring was ebbing and flowing on both occasions. In contrast, when Atwell arrived, the spring had ceased to ebb and flow about half an hour previously. For more than an hour he watched spring water flowing into a basin without noticing any variation in its flow. However, much to his relief, it was flowing rhythmically when he returned after lunching at a local inn and, in less than a minute, he saw the spring begin to flow with increased violence and likewise several other little springs outside the basin. The cycle of increase in flow, decrease and pause, was completed in about five minutes so that the spring ebbed and flowed about 12 times in an hour. Although not entirely clear, he thought that there was a slight reduction in the flow with each succeeding cycle.

A further series of observations was made by one of the gentlemen who made 'additions, improvements and corrections' to later editions of Daniel Defoe's tour through the British Isles, the first edition of which had appeared in 1724–1727. Defoe himself died in 1731, but one of his successors spent a period of 14 hours by the spring on the 10th July 1733 carefully observing its flow characteristics (Defoe and others, 1742). He found that, when it proceeded regularly, as it did over a period of eight hours, it ebbed and flowed 11 times an hour. However, sometimes the ebbing and flowing ceased, once for a period of 21 minutes and again for about an hour. His visit was in the middle of the summer, during a dry period, and he noted that what he called 'the perpendicular height of the flowing' varied. Sometimes the water level in the basin, which received the water stood at 1 $\frac{3}{4}$ inches (0.044 m), at other times not above $\frac{1}{2}$ inch (0.012 m) and generally at about 1 $\frac{1}{8}$ inches (0.029 m).

The prelate and traveller, Dr Richard Pococke (1704–1765), made a special trip across the River Dart from Dittisham to visit the well on September 25th 1750. He had heard that it ebbed and flowed nine times in an hour but on his visit '... the springs being low we could not discern it, but it does ebb and flow when the springs are high' (Chope, 1918, p. 186).

Another visitor was the lecturer and scientific instrument maker, Benjamin Martin (1705–1782), who spent about ten years travelling in England from 1746 visiting most of the prominent towns (Martin, 1759). Martin spent two days in Brixham in 1751, noting that there was no irregularity in the time of the ebbing and flowing of the spring, each cycle taking six minutes with ten cycles in an hour. The ebbing

and flowing was not confined to the well itself. Martin caused holes to be dug in the road by the side of the well and these holes were constantly filled and emptied by turns. The spring supplied a stream about 5 ft (1.524 m) wide and the whole stream ebbed and flowed with the well, with a difference in water level of about $\frac{1}{2}$ inch (0.012 m).

The well was also visited by the Reverend John Swete (1752–1821) during an excursion from his home at Oxton House, in the parish of Kenton, near Exeter, which he began on June 1st 1792 and which was described in volume two of his journals (Gray, 1997). Prior to his visit a Brixham gentleman had told him that the ebbing and flowing cycle was invariably performed 11 times an hour, whereas the local country people reported that it occurred only 9 times an hour and that this was uniformly so in both winter and summer. His own observations agreed with those of Benjamin Martin, in that the flux and reflux cycle was performed exactly ten times an hour. Swete drew a sketch of the form and situation of the spring (Fig. 3) which appeared ‘under a tufted hedge, amid which, some old trunks of trees walled around with stones rise upwards in a grotesque manner’ (Gray, 1997, p. 91).



Figure 3. View entitled ‘Reciprocating Spring Laywell’ by the Reverend John Swete, 1792 (Devon Record Office, 564M/F2/135, reproduced with the permission of Devon Heritage Service).

The reservoir which received the spring water was nearly 5 ft (1.5 m) square and the water rose about 2 inches (0.051 m). The beginning of the ebb and flow cycle began with a vibration on the surface of the water which soon changed into a violent current, accompanied by bubbles rising with considerable force from the bed of the well (reservoir) and a hollow murmuring sound.

Subsequent records of the spring generally repeat the earlier descriptions and there seem to be no further detailed recordings of the cycles of ebb and flow. Thus, the writer Richard Polwele (1760–1838), quotes the description given by Defoe and others (1742) and notes that the spring has no medicinal properties but ‘is only famous as a reciprocating fountain’ (Polwele, 1797, p. 17). Comparable brief references are given by, amongst others, Cooke (c. 1804), Lysons and Lysons (1822) and Carrington and others (1828). Some authors quote timings for the ebb and flow cycle which vary slightly from that given by previous observers. Thus Hyett (1800) states that the period of the spring’s cycle is irregular, varying from once to nine times an hour and Clarke (1820) quotes the number of cycles as twenty times an hour. Unfortunately it is not clear if such values were the result of personal observations and, if they were, at what time of year they were made. Edward Cockrem in his guide, *The Panorama of Torquay*, again relies on previous descriptions claiming the spring as a ‘great object of interest in the vicinity of Brixham’ (Cockrem, 1830, p. 62). However, in the 2nd edition of this guide, its author, Octavian Blewitt, notes that ‘The ebbings and flowings are extremely irregular, and often disappoint the visitor, who frequently exhausts his patience before the spring begins to play’ (Blewitt, 1832, p. 144).

Details of the well continued to appear in local guides into the 1830s and a manuscript description, which probably dates from 1840, and which is held by the Devon and Exeter Institution, suggests that it still exhibited reciprocating behaviour around that time (Stockdale, 1858). However, a few years later Henry Besley’s *Route Book of Devon* reported that ‘The celebrated spring at Laywell, at the upper end of the town, which used to ebb and flow, no longer possesses that singular property’ (Besley, 1846, p. 221). Thus somewhere in the early 1840s the spring lost its reciprocating character, maintaining a steady flow and undistinguishable from other springs in the Torbay area.

By the 1860s the existing water supply to Lower Brixham had become inadequate and on the 12th March 1867, the Local Board

considered a report prepared, by their Water Supply Committee, on the best means for procuring a good supply. One of the options considered, and reported by the *Western Times* on the following Friday, was that 'a reservoir should be erected in a field at Pole Hearn, Higher Brixham, for the purpose of collecting all the waste water from the many springs abounding in the locality'. The main spring was Laywell and this was to become the source of the new water supply. Following an inquiry conducted by a Home Office Inspector, on the 2nd April 1868 (*Western Times*, 31st March 1868), and detailed negotiations with relevant land-owners, tenders for the construction of a reservoir, and the laying of distribution pipes to supply water to Lower Brixham, were sought by the Local Board in April 1871 (*Western Times*, 28th April, 1871). The water became available the following year to businesses and domestic consumers who were prepared to pay for it and was supplied to public conduits in various parts of the town (*Western Times*, 17th June 1872).

With local government reorganisation in 1894, responsibility for the reservoirs (a second had been added), and the spring which supplied it, passed to Brixham Urban District Council. However, although water quality was good, reports of the water bailiff, contained in Brixham Urban District Council minutes, show that supplies were not always adequate. For example, his report for July 1911 states that the Laywell reservoirs continued to overflow by night. However, by October the reservoirs were going down and he sent the town crier round to ask consumers to be very careful over the use of water. By the end of November he reported that the springs had broken and the reservoirs were again full and overflowing. His reports contrast with comments in the 2nd edition of the Geological Survey Memoir, which state that the spring 'shews little diminution in flow during dry weather' (Lloyd, 1933, p. 152).

Reorganisation of the water industry in 1974, and further changes leading to privatisation in 1989, saw the Laywell site pass to South West Water Ltd. At this time the licenced abstraction rate was 909 m³/d and the total permitted annual volume was 136,300 m³, equivalent to 373 m³/d. This latter figure can be taken as a guide to the typical daily abstraction rate, but it could be that the spring yielded less than this during drought periods. The relatively low yield, and the risk of contamination presented by a spring source in a built-up area, meant that the resource did not fit in with their forward plans. By 1992, water from the spring was no longer contributing to the supply network



Figure 4. Signs in Higher Brixham recording the former importance of the Laywell Spring.

and the abstraction licence was revoked in 1998. The spring can still be found, on private land, to the rear of Nutwell Court on the northern side of Milton Street (B3205 road), between a Western Power Distribution Depot and a private house, *Monkswell*. A number of house names, road signs and the Laywell Storage Reservoir, currently (2013) owned by Torbay Council, survive to mark its former importance (Fig. 4).

BRIXHAM GEOLOGY

The Torbay area is underlain by a sequence of sedimentary and volcanic rocks of Middle and Late Devonian age (Leveridge *et al.*, 2003; Leveridge and Hartley, 2006; Leveridge, 2011). The Devonian rocks were deposited in fault-bounded basins and on intervening submarine highs. One of these highs occurs around Brixham (Fig. 5) where it separates the Looe Basin to the south from the South Devon Basin to the north. The boundary faults provided pathways for basaltic magma and on the Brixham High, lava flows up to several tens of metres thick occur, together with subordinate volcanoclastic rocks. This volcanic sequence is assigned to the Ashprington Volcanic Formation.

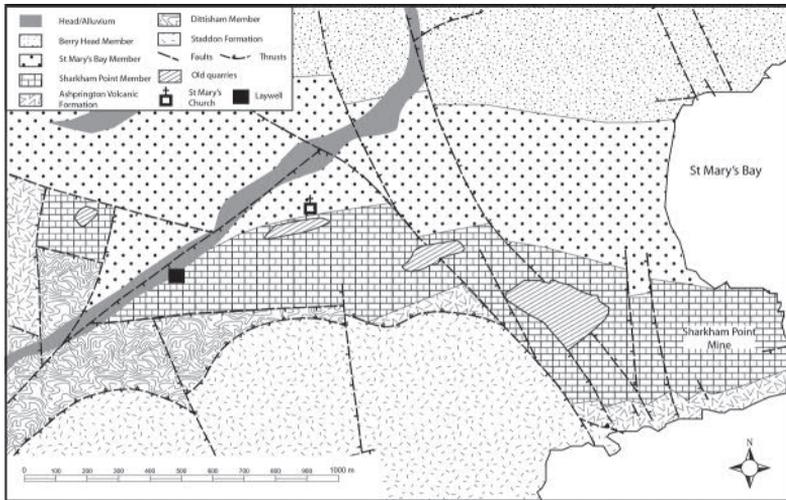


Figure 5. Geological map of Higher Brixham showing the position of Laywell and the historic quarries to the east and west along the outcrop of the Sharkham Point Member of the Brixham Limestone Formation (Geological Map Data © NERC 2004).

The highs were maintained at relatively shallow water depths allowing the development of carbonate platforms, which included limestone reefs. Around Brixham a variety of limestone facies accumulated, forming the Brixham Limestone Formation which is divided into three members: the Sharkham Point Member at the base, overlain by the Berry Head and Churston members. Following the deposition of the Sharkham Point Member the carbonate platform was drowned, as water depth increased, leading to the deposition of grey silty mudstones belonging to the St Mary's Bay Member of the Nordon Formation. This formation represents the background sedimentation in the marine basins to the north and south of the Brixham High and was succeeded by limestones of the Berry Head Member as water depths became shallower once again. On the southern margin of the Brixham High, limestones of the Sharkham Point Member are faulted against Looe Basin sediments, notably mudstones belonging to the Dittisham Member of the Nordon Formation and overthrust sandstones, siltstones and mudstones of the Staddon Formation (Fig. 5).

In the northern part of Torbay the Devonian rocks are unconformably overlain by Permian deposits. Although these are largely absent

around Brixham, their former presence is demonstrated by hematite replacement of the Devonian Limestones. Poorly stratified periglacial deposits, commonly described as head, infill smaller valley bottoms and form a mantling deposit, generally less than 1 m in thickness, over much of the area.

Structurally the area is complex and it was not until late in the 20th century that it was possible to place the marine Devonian rocks within a coherent evolutionary framework (for a review see Leveridge and Shail, 2011). Major Variscan deformation began with compression in the early Carboniferous, resulting in folding, thrusting, cleavage development and strike-slip faulting. Two subsequent phases, prior to intrusion of the early Permian granites of the region, have formed a structurally complex sequence of rocks, cleaved and folded, sometimes with inverted beds, and broken up into blocks by faulting.

GEOLOGY OF THE LAYWELL SITE

Fig. 5 shows that the Laywell spring is situated at, or very close to, the junction of limestones belonging to the Sharkham Point Member of the Brixham Limestone Formation and mudstones of the St Mary's Bay Member of the Nordon Formation. Stratigraphically the mudstones overlie the limestones; however, the strata are inverted and overturned to the north (British Geological Survey (BGS), 2004, cross section 3). The evidence suggests that the contact between the limestones and mudstones at the Laywell site will be conformable but dipping steeply to the south.

A few tens of metres to the east of Laywell, a SE/NW trending fault probably controls the course of the Laywell stream. Mudstones crop out to the east of this fault and a well at Laywell House (SX 916551) proved 60 ft (18.3 m) of 'slates' (Ussher, 1903). A fault-bounded block of limestone, just to the east of Laywell House, seems to be isolated from the main outcrop of the Sharkham Point limestone to the west (Fig. 5). To the south of Laywell the limestone is again faulted against mudstones, this time belonging to the Dittisham Member of the Nordon Formation.

The valley of the Laywell stream is underlain by a ribbon of superficial deposits (Fig. 5). Mapped as alluvium by Ussher (1903), described as river gravel by Lloyd (1933), this valley bottom deposit is now considered to be head and a relict of periglacial conditions.

The Sharkham Point Member is well exposed in the coastal section, some two km to the west of Laywell. The lower part of the member comprises reddened, grey, slaty mudstone and thin, graded beds of limestone, interbedded with volcanic rocks (Leveridge *et al.*, 2003; Leveridge, 2011). These pass upwards into limestones with the thickness of beds increasing towards the top. The St Mary's Bay Member consists largely of grey to dark grey slaty mudstone in which limestone occurs as laminae. The proportion of limestone increases in the lower part suggesting a transition from the Sharkham Point Member.

The Sharkham Point limestones to the west of Laywell are characterised by localised replacement of the limestone by hematite grading into unaltered rock. Limestone breccias show overgrowths of botryoidal goethite, limonite and hematite and some joint surfaces show aggregates and coatings of barite. The limestone was quarried for agricultural use (to 'sweeten' acid soil) and building stone in both the faulted block east of Laywell and along the strike to the west. Upton Quarry some 750 m west of Laywell is marked on the 1869 OS map and an even closer quarry, to the south of St Mary's Church in Upper Brixham and 350 m from the spring, is shown on the 1907 map (Fig. 5). Additionally iron ore was discovered and a mine was opened in Upton in 1841 (Born, 1989). According to White (1850) the lode was about 35 ft (10.7 m) in width and cropped out within a metre or so of the surface. Depths of 40 ft (12 m) had been reached by 1850 and 130 ft (40 m) by 1856 (White, 1850; Born, 1989).

HYDROGEOLOGY

It is suggested that Laywell is fed by groundwater from the limestones of the Sharkham Point Member which extend westwards from the spring (Fig. 5). Bounded by steeply dipping mudstones to the north and faulted mudstones to the south, groundwater will be channelled eastwards from the watershed down hydraulic gradient to the fault-controlled valley of the Laywell stream. Here springs are thrown out at the limestone/mudstone contact, either along the fault or where overturned folding has created an equivalent barrier to lateral flow (Fig. 5). A number of small springs occur along this contact but most of the discharge is concentrated at Laywell. Previous writers have suggested that the spring emerges 'near the northern boundary of the river gravel' (Lloyd, 1933) or from 'gravel of the river terrace deposits' (Leveridge

et al., 2003). The supposed river gravels are now interpreted as head and it seems inconceivable that such poorly sorted deposits could support such a spring. However, water could have been forced through thin head deposits at the springhead, giving the appearance that it was 'gravels' yielding the water.

The observations of Laywell made by 17th and 18th century visitors, taken with the records of other ebbing and flowing springs worldwide, support a theory that the intermittent flows are due to one or more natural syphons operating in the limestone. This interpretation of the operation of the spring seems to have been put forward first by the Reverend Joseph Atwell, an early visitor (Atwell, 1732). The idea that a syphon operating 'in the bowels of the earth' could account for anomalous fluctuations in pond water levels had been put forward by the Reverend John Theophilus Desaguliers in the *Philosophical Transactions* some years earlier (Desaguliers, 1724). This principle was applied to fountains (springs) by the French Jesuit Pêre Regnault in his *Philosophical Conversations*, an English translation of which had appeared the year before Atwell's visit (Dale, 1731). If the syphon theory is to be accepted, it must account for observations recorded by visitors to Laywell and evidence is needed that a suitable network of caverns and passages is likely to exist.

The Devonian limestones have insignificant primary porosity and the storage and transmission of groundwater depends on a well-developed series of fractures and bedding planes which have been enlarged by solution. Several substantial cave systems have been discovered and explored. In the Berry Head Member of the Brixham Limestone Formation, where extensive quarrying has taken place, caves fall into two types: firstly vertical and steeply sloping passages, and secondly, horizontal passages and chambers which often form networks (Baker and Proctor, 1996). There are three major zones of horizontal cave development at -2 to 2 m OD, 5 to 9 m OD and 22 to 26 m OD. These are not bedrock related and cut across dipping bedding planes and other geological features. Higher level caves exist in the Berry Head limestone, the most famous of which is the Bone Cave on Windmill Hill at an elevation of about 30 m (Boylan, 2008). In neighbouring Torquay, the extensive cave system of Kent's Cavern lies between 49.9 m and 68.7 m OD (Proctor and Smart, 1989). There seems no reason to suppose that comparable networks will not exist within the Sharkham Point Member of the Brixham Limestone, with some of the groundwater discharging

at Laywell spring. Such a network of chambers at different elevations within the limestone, connected by passages, represents an ideal environment for the development of natural syphons.

The spring flowed continuously and the cycles of ebb and flow were superimposed upon this background discharge. Records suggest that the number of cycles ranged from 9 to 20 per hour. Most observers visited in the summer months and, although it is difficult to judge if there are seasonal variations, these are not obvious. As flow began there was a vibration on the water surface, followed by bubbles rising with considerable force, accompanied by a hollow murmuring sound. Bubbling ceased as the water ebbed. The cycles of ebb and flow were not always continuous and quiescent intervals of up to one hour were observed by some visitors, with a gap of 'two hours or more' noted by Atwell (1732). On the basis of Pococke's observations in 1750, it is possible that ebb and flow cycles ceased altogether at times of low spring flows. However, the evidence is inconclusive as his day visit meant that his time at the well would have been limited to a few hours at the most, which could have coincided with an extended quiescent interval. The observation by Blewitt (1832) that the ebbings and flowings were extremely irregular suggests that the quiescent intervals were becoming more frequent by the 1830s.

The volume of water discharged during a period of ebb and flow cycles was not the same for each cycle and there may have been a slight reduction in the flow with each succeeding cycle. A picture emerges of periods of ebb and flow in which the volume of water discharged per cycle decreased gradually, followed by a quiescent interval of variable length before a further period of ebb and flow began. The final observation which needs to be explained by any theory is that rhythmic fluctuations were not confined to the spring, but occurred also in adjacent small springs and in holes dug in the road, by the side of the spring.

A possible conceptual model for the operation of a syphon at Laywell is shown in Fig. 6. Groundwater collects in a karst chamber, which acts as a reservoir, and from which a conduit first rises in the direction of the spring and then falls. When water in the reservoir rises above the level H1 in the conduit, the water flows over into the descending branch. If this is narrow, or contains a constriction, a column of water builds up and primes a syphon which sucks water out of the reservoir until the level has fallen to H2, when the flow stops

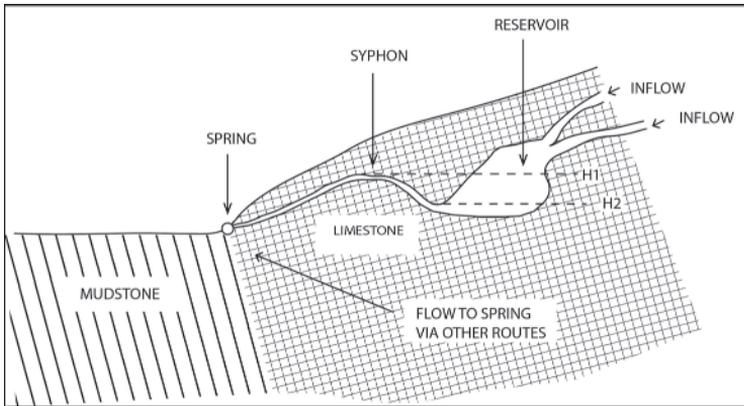


Figure 6. Simple conceptual model of the operation of a syphon system, resulting in flows showing many of the characteristics of the Laywell spring.

abruptly. If the syphon is close to the spring, discharge conditions will change sharply from a strong rush of water, carrying with it air expelled from the syphon, to no flow. If it is some distance away variations are likely to be muted, as drainage of the downward branch of the syphon may not be complete before the syphon is once again recharged.

Many of the features which were observed at Laywell, such as the regular cycles of ebb and flow and the noise and bubbles as flow begins can be explained by this simple model. The abrupt changes in flow and the murmuring sound suggest that the syphon was close to the spring. The range in the number of cycles per hour is likely to be related to rainfall. Water levels in karstic limestones respond rapidly to rainfall and after heavy rain the reservoir feeding the syphon may have filled more rapidly than at times of low or average rainfall, thus decreasing the time taken to recharge the syphon. The occurrence of fluctuations in surrounding small springs and holes dug in the road suggests that water from the main spring conduit was discharging laterally within superficial deposits which, in consequence, reflected conditions at the spring. However, although the conceptual model can be used to explain many of the features of Laywell, others, such as the irregular periods of quiescence, remain unexplained.

There are a number of reasons why an ebb and flow spring might temporarily cease to function. At times of high water levels the syphon may become flooded and not function because of a lack of air; at

times of very low water levels it may not be possible to prime the syphon (Meinzer in Cady, 1936; Bögli, 1980). However, conditions of high and low water levels are likely to go on for some days or even weeks and do not explain the short breaks of the order of minutes or hours observed in the ebb and flow of Laywell. Meinzer also suggested (Cady, 1936) that irregularities in the periodic action might result from variations in the air-tightness of the syphon. For example in wet weather, when soil and rock pores are full of water, the syphon is more likely to discharge completely than when pores are dry or only partly saturated, when syphon action could be interrupted by air leaks. This could result in a variety of discharge irregularities. It is also possible that air, carried by turbulent flow into the reservoir, could form an air pocket at the bend in the syphon causing a temporary loss of suction and incomplete discharge of the syphon. However, this does not explain the breaks of an hour or more during which no ebb and flow occurred. Alternatively the system may be more complex than shown by the simple model presented in Fig. 6.

Atwell (1732, p. 308)) explained his observations 'to be occasioned by two Streams or Springs, one of which passing through two Caverns or natural Reservoirs with Syphons, meets with the other Stream in a third Reservoir without a Syphon; where being joined they come out of the earth together'. The diagram which he produced to support this hypothesis of two syphons operating in series is reproduced as Fig. 7.

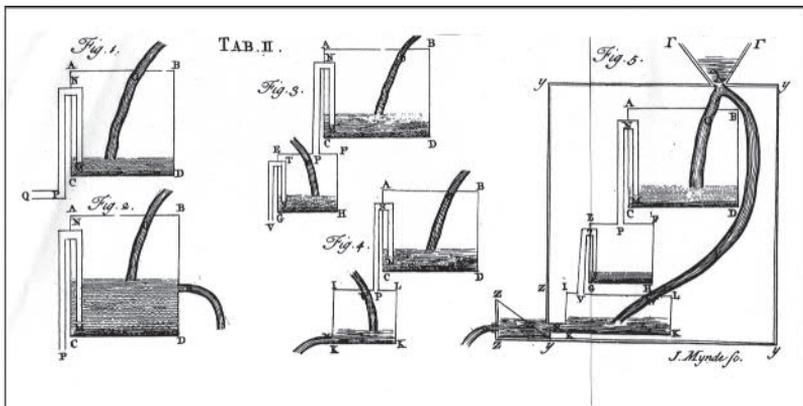


Figure 7. Scheme of interacting reservoirs and syphons, proposed by Atwell (1732) to explain the workings of the Laywell spring.

His *Fig. 1* is the equivalent of *Fig. 6* above and in *Figs. 2–4* he introduced other variables, such as another discharge outlet (*Fig. 2*), two reservoirs of differing sizes, both discharging by syphons, with or without a second feeder stream coming in to the second reservoir (*Fig. 3*) and a second reservoir, not discharging by a syphon, but receiving variable discharge from another stream (*Fig. 4*). Putting these various elements together (*Fig. 5*) he considered that he could explain the behaviour of an ebb and flow spring, such as Laywell, with its quiescent interludes. However, syphons are rare in karst terrains and the chance of two syphons occurring in series appears remote. Also his scheme does not adequately address the irregularity of the intervals between periods of ebb and flow.

DISCUSSION

The main difficulty in sorting out the hydraulics of the karst network, which supported Laywell in the past, lies in the lack of detailed observations. Most observers spent limited time at the site; there are no accurate measurements of water level or discharge fluctuations, rainfall or, in some cases, even the month of the year when observations were made. However, there are other sites in the world where detailed hydrographs have been maintained for extended periods. At some of these springs it has been possible to erect mathematical models to simulate their behaviour (Bonacci & Bojanić, 1991) but at many this has proved impossible. Călugări ebb and flow spring in the Apuseni Mountains of Romania, first noted in 1822, was monitored closely between 1986 and 2001 (Orășeanu, 2010). Despite all the data collected it has not been possible to explain how the spring works and the reason why high oscillations in water level are interspersed with periods of small or no oscillations and longer amplitude bell-shaped oscillations. In the USA, the so-called Tide Spring in Virginia, was monitored for 5 years between 1927 and 1932 (Cady, 1936) and again between 1982 and 1987 (Lehman, 1990). The work reported by Cady was carried out by the renowned American hydrogeologist Oscar Meinzer. It was never published in detail, perhaps because he was unable to explain the puzzling irregularities in flow, joking ‘that it seems as if its behaviour were manipulated by mischievous elves residing in the caverns of the locality who take delight in bewildering and mocking those who endeavour to discover its laws of flow’ (Cady, 1936, p. 53). Over 50 years later, Lehman (1990, p. 111) was still only

able to conclude that 'The challenge of deciphering the underground profile remains'.

Experience at these Romanian and North American sites indicates that there are still features of these syphon systems which are not understood. Such springs have been described as temperamental (Lehman, 1990) and the reasons for their unpredictable mood swings remain obscure. The unidentified factors, coupled with an absence of monitoring data for Laywell, mean that the puzzling irregularities observed by 17th, 18th and 19th century observers remain and are likely to remain a mystery.

The Laywell spring appears to have ceased to ebb and flow around 1840, after which it behaved like other springs in the area. Two main reasons for the loss of intermittent flows seem possible, either the syphon was damaged or recharge to the reservoir was altered or terminated altogether. Henry Besley seems to have had no doubt on the cause of the spring's demise, writing that 'Some years ago an old wiseacre of the place being surveyor of the highways, had some part of it filled up, with a view of improving it, and by that means destroyed this interesting and natural curiosity' (Besley, 1846, pp. 221–222). This was confirmed by Besley, some years later, in an exchange in the *Western Antiquary* (Parfitt, 1882, 1883). Alternatively others suggested that road construction had been its downfall, with *White's Directory* recording that the ebbing and flowing spring 'was destroyed some years ago, when the high road was altered' (White, 1850, p. 424). File notes in the Brixham Museum (Gardner, 1989) suggest that the spring was destroyed in the 1860s, when the owner of Laywell House chose to improve the track leading from the house past the well to St Mary's Church. However, the spring had ceased its reciprocating behaviour well before that date.

Highway repairs and improvements adjacent to the springhead could have damaged the syphon, but there was another activity initiated in the early 1840s which might also have influenced spring flows. Limestone quarrying had probably been going on for some time when the iron mine was opened at Upton on the hill to the west of Laywell in 1841 (Fig. 5). Both quarrying and mining can have an impact on groundwater levels, particularly in karst terrains where flow will be through a network of passages and chambers. Interference with a conduit system could, for example, divert groundwater into another system at a lower level in the limestone, cutting off completely recharge to the reservoir driving the Laywell syphon. The temporal

association between the beginning of mining and cessation of ebb and flow cycles strongly suggests a relationship.

CONCLUDING REMARKS

The ebb and flow spring at Brixham was one of only four in England noted by 17th and 18th century topographers. Following its description by Oliver (1693a, b) and Atwell (1732) in the Royal Society's *Philosophical Transactions* its fame spread. Unfortunately, its relative isolation meant that no observer remained at the site for long and observations are descriptive and fragmentary. The straightforward ebb and flow cycles can be explained by the action of a syphon, but other aspects of the spring's behaviour remain a mystery. It is likely that its demise resulted from man's activities, either through attempts to improve it, local road works, or because of mining and quarrying in the vicinity.

Research in progress shows that the other ebb and flows springs recorded from northern England have suffered the same fate, although those at Barmoor Clough and Giggleswick survived into the 20th century, before nearby quarrying interfered with their plumbing systems. Today the Laywell ebb and flow spring would have been an interesting addition to the natural attractions of the Torbay Geopark. It still flows from Higher Brixham to the sea, although the elves and fairies that once played in its depths have been gone for 160 years.

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