'Evidence' for transition between Authigenic and Allogenic Aquifer functioning related to Regional Uplift and Sea Level Change in the Plymouth Coastal Karst Aquifer

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The Plymouth Coastal Karst Aquifer comprises Middle to Late Devonian limestones and underlies much of the early urban centres of Plymouth and Stonehouse. Whilst once important as a source of water the aquifer is now only used to supply limited water supply to industry, the aquifer becoming contaminated by saline intrusion in the 19th century. A tentative model for the development of the aquifer and the major limestone gorge complex which dissects it over the Middle and Late Pleistocene is presented. This model is based on regional and recessional uplift estimates and recent global eustatic sea level estimates. Periods when the aquifer may have functioned authigenically are linked to periods of high sea level and haloclinal cave development. Allogenic aquifer phases are linked to the development of vadose engulfment and the downcutting of the Limestone Gorge complex. Two such phases are identified in the western portion of the aquifer associated with the former Sour Pool. A tentative chronology of the phases and the development of the gorge is discussed in relation to the proposed uplift model. The maximum elevation of the aquifer suggests that the aquifer may have developed over the last 400 to 600 kyr. The development of the aquifer is considered in relation to other coastal aquifers in south Devon.

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Introduction

The Plymouth Coastal Karst Aquifer (Fig. 1) is a principal Environment Agency (EA) coastal telogenetic (Choquette and Pray, 1970) limestone aquifer with a long history of urban and industrial development (SWARF, 2008).

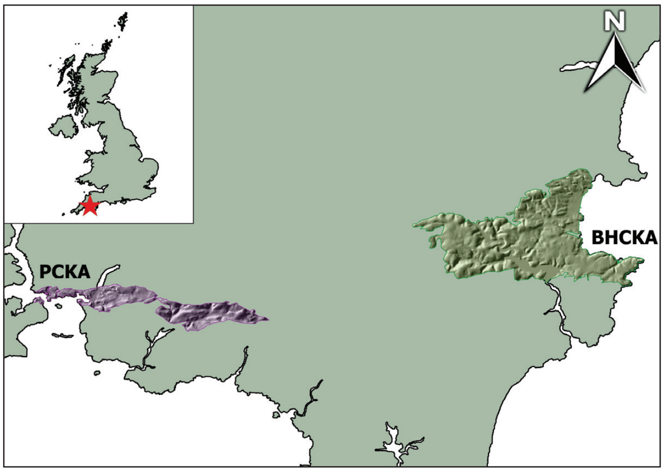

Figure 1. *Location Map, showing the relative locations of the PCK and BHCK aquifers on the south coast of Devon. This figure contains public sector information, licensed under the Open Government Licence v3.0 from the Environment Agency.*

The karst limestones have had a long association with human activity. Neolithic or earlier humans occupied or were deliberately interned in the limestone caves or shafts which connected directly with the surface (*c.f.*, Sutcliffe and Lewarne, 1977; SWARF, 2008) The medieval town of Plymouth grew up around the natural inlet known as Sutton Pool, obtaining much of its water supply from numerous wells and cisterns dug into the limestone and whose former locations are discernable from present-day road names. After the completion of Drake's Leat, which brought a reasonably reliable source of clean water to Plymouth from Dartmoor, the importance of the limestone aquifer to supply water reduced significantly. During the early nineteenth century boreholes were sunk to supply water to a number of local breweries or to provide local private water supplies in residential areas. A recent estimate of the current utilisation of the aquifer indicates that approximately 10% of the possible annual yield of 650 Mgal is used for industrial water supply with no licenced potable supplies (Roxburgh, 1983). This estimate is accounted for on the basis of the annual effective rainfall only and does not take account of any subterranean groundwater exchange to the limestone from the surrounding non-carbonate rocks. The current aquifer system developed in the limestone is limited to secondary permeability related to solution widened fissures and cavities. Storage is limited and the aquifer responds rapidly to recharge. There is also evidence that parts of the aquifer are directly connected to the sea. The degree of connection, however, does not appear always to be related to distance from the coast (Roxburgh, 1983).

The medieval towns of Plymouth and Stonehouse, together with the early modern town of Devonport expanded rapidly during the early part of the nineteenth century and by the 1860's formed a belt of dense, continuous urban development from the River Plym to the RiverTamar. Much of the building stone for this development was obtained from limestone quarries which were operated at (East) Stonehouse, West Hoe, Cattedown, Pomphlett and Plymstock, with significant quarrying occurring betweeen around 1820 to 1870. Subsequently, quarrying expanded to the east mainly serving the cement and aggregate industries. This easterly migration along the limestone outcrop continues to the present day. The earlier quarries of Stonehouse and West Hoe developed either for residential, recreational or industrial use. In addition, much of the remainder of the Shapter's Field area representing the remains of the original 'Catdown' was quarried in the early 2000's to provide additional level areas for industrial development and for providing fill for reclamation of land adjacent to Cattedown Wharves, now occupied by the TRAC2 theatre facility (Walkden, 2015). Quarrying has significantly modified the original topography of the limestone outcrop which requires to be considered in any reconstruction of its previous form.

Development of the aquifer

Eogenetic or syngenetic karst development occurred during the early history of the aquifer as the Devonian reefs may have been subject to sub-aerial erosion and dissolution at various periods since the late Devonian. Small scale surface karst features infilled with Fammenian age deposits are preserved in the waterfront exposures at Western King's Point (Orchard, 1974). In addition, a significant zone of dolomite occurs close to the centre of limestone outcrop close to the outcrop of a thrust zone which separated the aquifer into two structural units (Leveridge, 2002). This zone may be associated with earlier eogenetic dolomitization. Both these facts suggest that the current outcrop of the limestone represents a significant proportion of the original deposition.

Significantly more recent telogenetic halocline development is evident in a number of the near-shoreline quarry exposures particularly in the western and central portions of the aquifer (Smith *et al.*, 2008). A number of submarine springs are known to discharge offshore of the Plymouth Hoe and Millbay areas. The submarine spring off Millbay discharges at a depth of some 30 m below sea level (Leveridge, 2002). This is known as the Millbay Blue Holes although its origin has nothing in common with the Bahama Blue Holes after which it was named. Accounts of this spring date from the 1970s by the then Police Diving Team, which located a large discharge emerging from a number of fissures located close to the base of the near vertical submerged cliff which lies immediately to the south of the Millbay inlet (Fig. 2). The location of this spring within the main shipping channel together with its depth, have meant that this important hydrological feature of the Plymouth Coastal Karst Aquifer (PCKA) as been little investigated since its inital discovery.

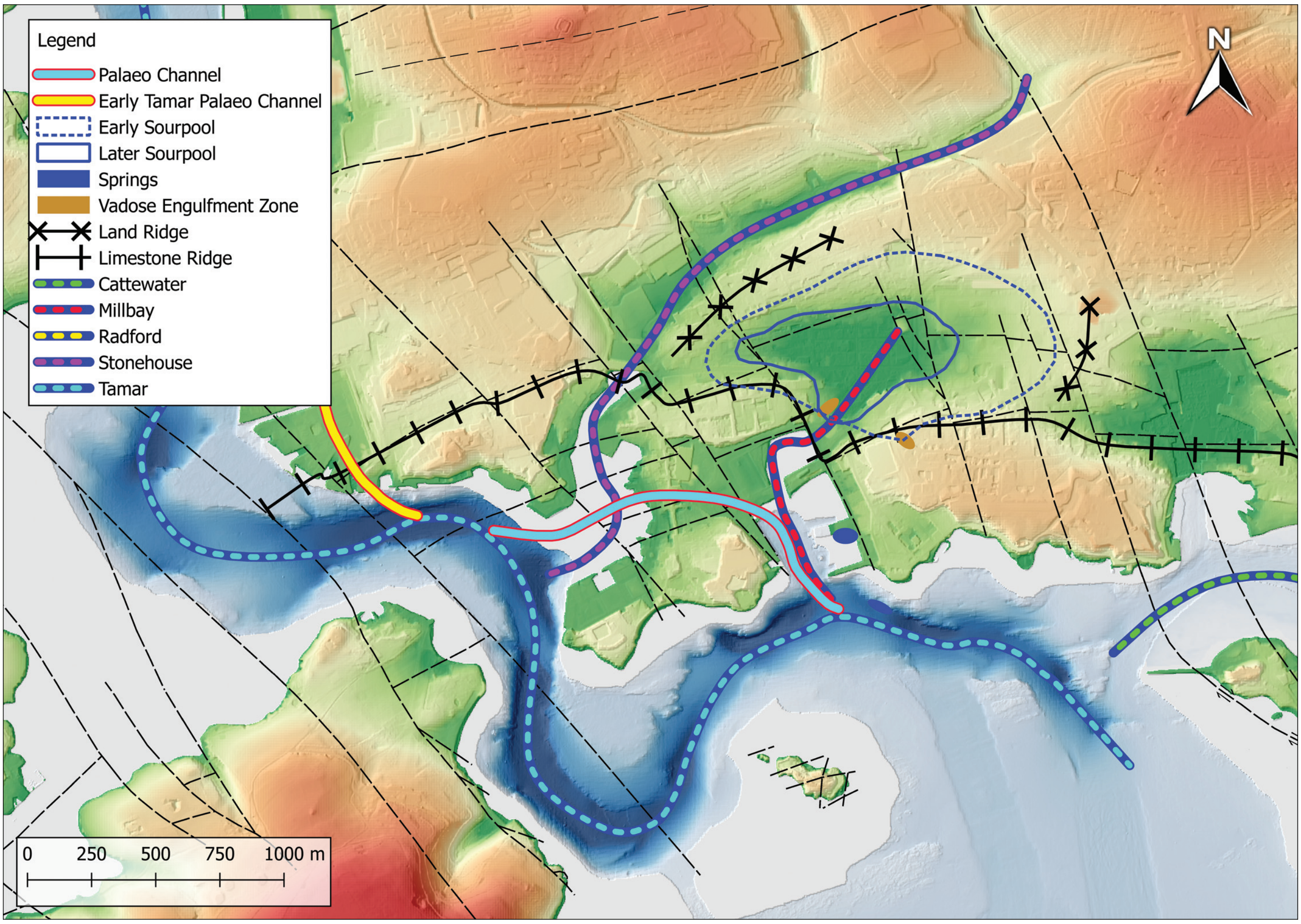

Figure 2. *Location Map of the PCKA showing the locations of the main palaeo-channels and other features referred to in the text. Contains public sector information, licensed under the Open Government Licence v3.0, from the Environment Agency and UK Hydrographic Office.*

The Plymouth Coastal Karst Aquifer and its relationship to other coastal Karst Aquifers in Devon

Relative Sea Level (RSL) at any point on the Earth's surface is the result of past global eustatic sea level changes and regional or local isostatic changes in land elevation. The interactions of these changes are reflected in the concepts of apparent, real and relative sea levels. Burbank and Anderson (2001, p. 19, fig. 2.4) illustrate these concepts and the record of relative sea level change as an interaction between eustasy and various forms of isostasy. Estimates of eustatic sea level over the last 800 kyr are provided in Spratt and Liesecki (2016) and shown in Figure 3. They used a total of 12 individual records of different sea level proxies to determine an average eustatic sea level record for the past 800 kyr. They conclude that the averaged stack of sea level proxies should be a more accurate record of eustatic seal level than that provided by any single proxy record.

Westaway (2010) has reconstructed the uplift histories of several southern English rivers, based on several different indicators of past sea level, including uplift histories for different areas of the South West of England. Within his reconstructions for the South West of England, he incorporated 35 different data sets to estimate uplift from the western end of Cornwall to east of the Mendip Hills. In particular, he considered that data from marine terraces and sea level caves which adjoin the coastline in the Torbay area;

> ".. will match those of the sea surface and thus also provide a proxy for uplift. In general, use of (such features) to infer uplift requires subtraction of the palaeo-sea level (relative to modern sea level). To facilitate such calculations, global (eustatic) sea level is inferred to have been the same as at present during all interglacials back to the Mid Pliocene" (Westaway, 2010).

In addition, the use of sea level caves to infer surface sea level requires the consideration of the interaction of the surface sea level with the development of the halocline within the coastal aquifer, as it is at the halocline that such caves will form. (see below).

Westaway argues that it is reasonable to consider the same sea level for all interglacial stages as it assumes that the volumes of interglacial ice during previous ice ages were similar to the present day and the lack of any general consensus of opinion on global sea-level proxies which would support any more reliable estimate of past interglacial sea level. To a certain extent the use of a range of stacked proxies, as adopted by Spratt and Liesecki (2016) would tend to overcome, at least in part, this latter objection. It would therefore seem reasonable, based on the data provided by Spratt and Liesecki (2016) that a revised uplift history could be fitted to the data provided by Westaway recalibrated to the eustatic sea level maxima for interglacials back to 800 kyr. This provides the relative sea level curve applicable to the Plymouth Coastal aquifer shown in Figure 3.

The Plymouth Limestone in relation to Regional and Localised Uplift

The role of uplift in landscape evolution appears to remain a contentious subject. Brown *et al.* (2010), note the wide difference of opinion expressed between Watts *et al.* (2000) and Simms (2001) regarding the uplift of the Cotswold Hills and the role of the Northern Drift Group as evidence of uplift. The Bridgland model (Bridgland, 2000) presupposes that uplift is

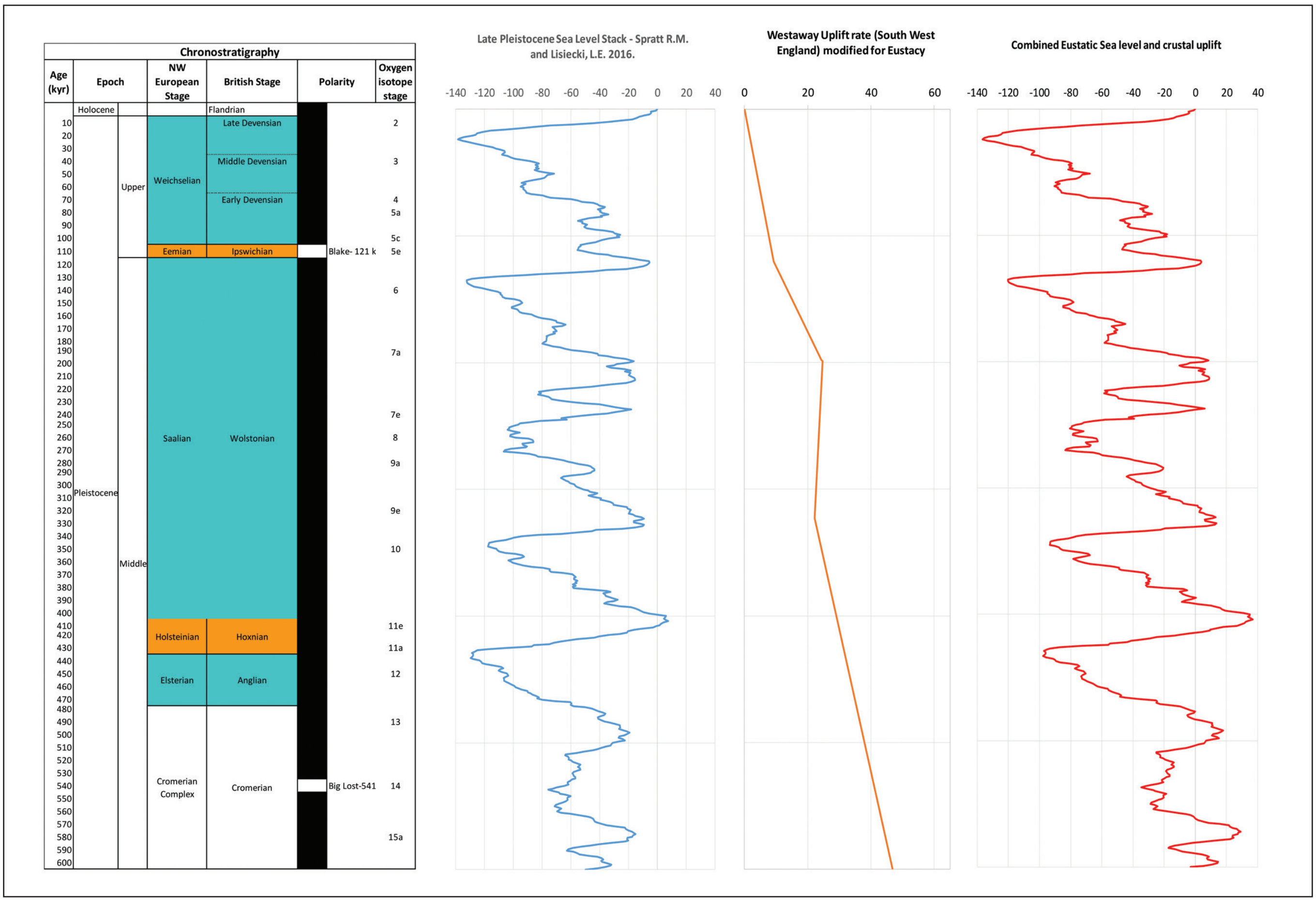

Figure 3. Relative Sea Level (RSL) curve for South Devon reconstructed from eustatic Sea level stack of Spratt and Liesecki (2016) and regional uplift reconstructions of Westaway (2010).

essential to the development of fluvial terrace staircases and forms the basis of Westaway's reconstructions for UK rivers. However, the ubiquity of regional uplift has been questioned by several of authors for example Simms and Farrant (2011). Based on the above, Spratt and Liesecki's (2016) estimate of eustatic sea level over the last 800 kyr. and the proposed age of halocline cave development in the BHCKA, without uplift, an alternative explanation would be necessary to explain differences of 20 m or more between the local sea level record and global eustatic sea level.

Lane *et al.* (2008) have suggested local isostasy related to erosion of the River Severn as a primary cause of uplift of the Cotswold Escarpment. Assuming similar properties for the lithosphere beneath the Severn and the Tamar and approximating R(Φ) with the areas of the respective river catchments, it could be expected that erosion by the River Tamar could result in approximately 1/10th of the localised uplift experienced by the Severn. They indicate that the Fourier Transform of the uplift R(Φ) is related to the Fourier Transform D(Φ) via a function which includes terms relating to the extent of the denudation and a number of lithospheric properties. We have simplistically assumed in our estimate of relative uplift for the Tamar that R/D approximates to R(Φ)/D(Φ). Lane *et al.* (2008) suggest that as much as 150 m of the present-day relief in the Cotswold Hills is related to denudation isostasy. Therefore, it would seem a reasonable estimate that with respect to the relative positions of the Plymouth and BHCKAs that the PCKA would have experienced at least 10 m of differential isostatic uplift due to the denudation of the Tamar River Basin, given their locations relative to the basin axis. If this had occurred after the development of the halocline caves at around 25 to 30 m above Ordnance datum (AOD) in both the P and BHCKAs, it would be expected that these would not now be at a similar elevation. This suggests that local isostasy at least over scales of 10 s of km has not been significant in South Devon at least since the Hoxnian (Marine Isotope Stage (MIS)11); a minimum age for these caves as suggested by Proctor and Smart (1991).

Green (1949) indicates an original eastern route for the River Dart which would have located the BHCKA close to a centre of denudation from an earlier Dart River system. The Dart would have been subsequently diverted to its present day southerly course below Buckfastleigh, earlier than the mid-Late Pleistocene (Anglian) boundary. It is difficult to conceive that had denudation isostasy been an important contribution to uplift since the Hoxnian, that halocline cave elevations from these two aquifers would match so closely. That uplift since the Hoxnian must have occurred to preserve these cave levels, then it is most probable that such uplift is regional in extent. Uplift and relative sea level curves for the PCKA are shown in Figure 3.

Relative Recessional Uplift in relation to the PCKA

With respect to any fixed point along the Tamar Gorge, development of the channel profile over time would continue to recede, resulting in the gradual lowering of the channel base unrelated to any change in sea level base level. Consequentially, this would lead to a relative apparent uplift of any earlier channel base with respect to the present-day channel related purely to the ongoing recession of the channel. Low eustatic sea levels during MIS2 and MIS6 are estimated to have undergone around 10 m of regional uplift. In addition to this, recessional uplift should also be accounted for, to determine the relative overall uplift of the Tamar Gorge base at any location along its length. Vertical changes due to horizontal recession rates along rivers vary widely and are also dependent on a wide range of factors. Recessional response to base level rise or sea level fall depends on the position of the particular point of interest with respect to the reach level of the point of interest relative to the relevant sea level base level. This paper assumes a constant relative recession rate over time which has been accounted for in the estimates of age of the earlier palaeo-Tamar channels shown in Figure 2 for the inferred sections of earlier channels shown in Figure 4 discussed below.

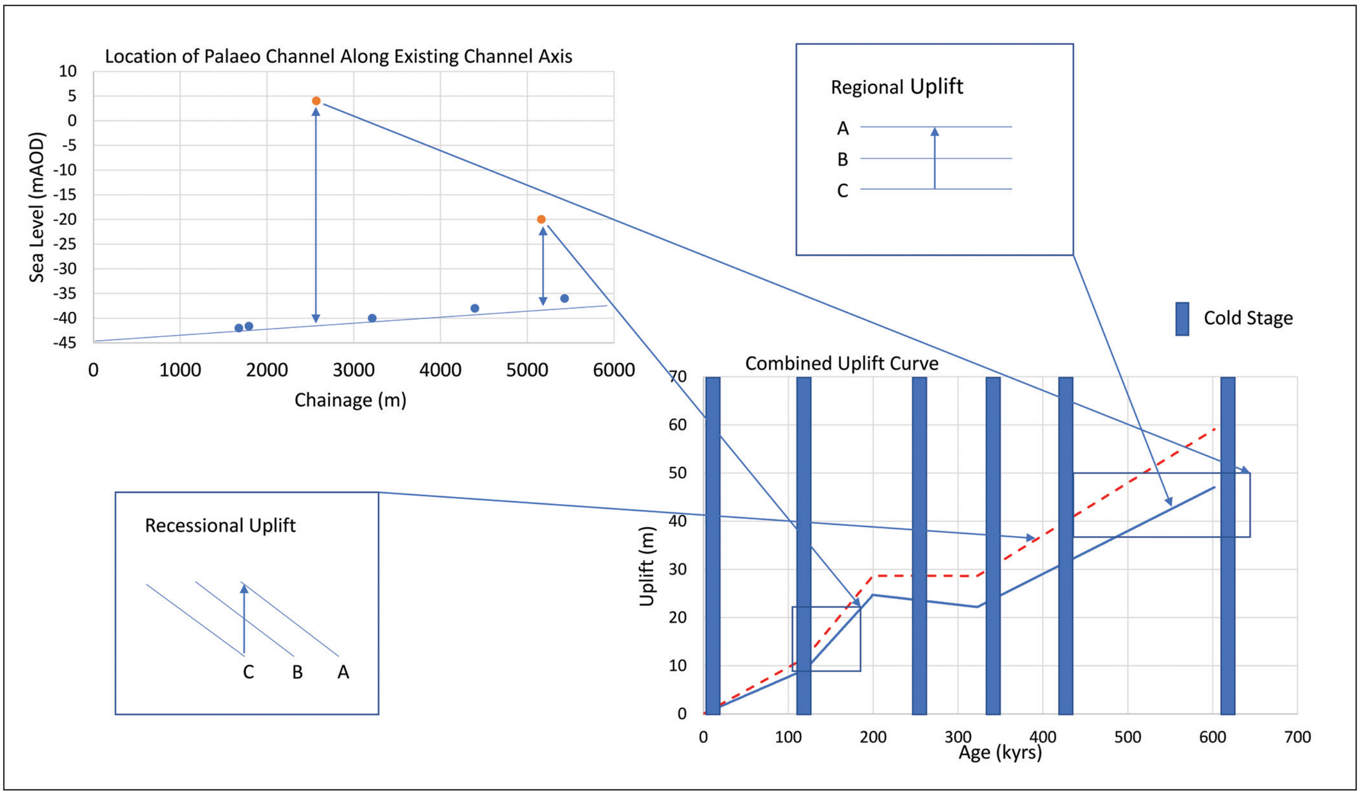

Figure 4. *Palaeo-channel uplift reconstructions for the Tamar incorporating: A - no recessional uplift component; and B - a constant rate of recessional uplift component.*

Early Hoxnian Haloclinal Development of the PCKA

The PKCA currently rises little more than 35 m above the level of the present-day sea level. Halocline related caves within the aquifer occur at current elevations of 23 to 25 m AOD (Smith *et al.*, 2008). The same elevations are recorded for similar origin caves within the Berry Head Limestone (Proctor, 1988, Proctor and Smart, 1991). Both sets of caves within the PCKA and BHCKA have formed within telogenetic limestone aquifers in which water flows are dominated by secondary fractures permeability with very little primary permeability. These limestones do not display significant primary permeability characteristics typical of younger limestones such as the chalk where their groundwater characteristics can be modelled most appropriately using a dual porosity model (Price, 1987), and from which their development and hydrological behaviour differ considerably. Bedding and jointing development in the two aquifers are similar, as both aquifers are developed in rocks of the same age and will therefore have undergone a similar tectonic history. Critically these two aquifers differ in the elevation of their upper surfaces. The BHCKA rises to approximately 60 m AOD, whilst the PCKA only reaches approximately 35 m at its highest. Therefore, if these two sets of caves were formed at the same time, and if both have undergone similar minimal denudation in the intervening period, then the PCKA would have risen during the Quaternary no more than 5m above the sea level whereas the BHCKA would have been elevated by around 30m. This would have potentially allowed a thicker freshwater lens to develop and a depressed halocline within the BHCKA. On this basis, it would be expected that the original depth of the halocline-related caves during their formation within the PCKA would be less than in the BHCKA. That they are now at the same elevation implies that the BHCKA has been uplifted to a greater degree since its formation than is the case for the PCKA. This is consistent with the findings of Westaway (2010) who indicates that the Torquay area had risen by about 2 m more than the western extremity of Cornwall since the end Ipswichian, MIS5e. The PCKA approximately midway between the two would therefore be expected to have uplifted by approximately 1 m less than the BHCKA since this time. A difference in uplift rate between the two aquifers does seem to be a plausible explanation for the expected differences in halocline depth in the two aquifers not resulting in different present-day elevations of the two halocline related cave systems.

Based on the reconstructed relative sea level for the past 800 kyr., the latest period that relative sea levels could have achieved a height sufficient to develop these cave systems would have been at the end of the Hoxnian, MIS (11e) approximately 400 kyr. This estimate is consistent with Proctor and Smart (1991) who considered the 23-25m caves to be related to a mid to late Pleistocene sea level stand at 28 mAOD equivalent to the degraded surface of the Oxley Head Shore Platform on the BHCKA. This equates to the first previous time when eustatic sea level have been estimated by Spratt and Liesecki (2016) to have exceeded present day sea levels.

The age of Devon caves, and more particularly Plymouth caves, is discussed by Leveridge *et al.* (2002). However, their main criterion for age determination appears to be that all Devon caves developed at a base level related to a former sea level. This criterion should only be applied to caves for which a haloclinal origin can be demonstrated. In addition, the contribution of regional uplift throughout the Pleistocene in elevating caves above the reach of eustatic sea level rise, further negates their argument that present cave elevation suggests caves originated in the Paleogene or Neogene. There is no evidence for such ancient origins for any of the major cave systems of Devon.

Proctor and Smart (1991), citing Donovan and Stride (1975), suggest that the top planar surface of the BHCKA, elevated at an altitude of 58m AOD, is late Pliocene in age. This would suggest that there has been little denudation of the general surface elevation of this aquifer over the subsequent Pleistocene. The present altitude of the top of the PCKA would indicate that, were this also the case for this aquifer, then it would not have been exposed to significant sub-aerial erosion prior to MIS13. The importance of the Cretaceous unconformity on landscape evolution in the South West of England has been highlighted by several authors. Lane *et al.* (2008) indicate the importance of the Cretaceous unconformity in the development of the escarpment of the Cotswolds Hills. Thomas (2001) suggests that the presence of the Cretaceous unconformity has a similar importance in the overall landscape development in South Devon. In the Plymouth area, this unconformity surface can still be discerned to dip generally to the south and may well form a surface at around an altitude of 110 m AOD.

Neither the upper surface expressions of either the BHCKA, or PCKA, form part of this unconformity and lie significantly below its elevation by between 50 to 80 m. As it has been argued above that there has been little erosion of the BHCKA since the Pliocene, it is likely that much of this erosion occurred during the earlier Neogene or Paleogene. This is consistent with the earlier assertion that there has been a lack of differential localised denudation uplift since at least the mid Pleistocene, suggesting most of the removal of material from the Tamar Basin must have been completed sometime before the Hoxnian. Subsequent erosion, as indicated by the decrease in post Hoxnian elevation of the land surface to the north of the limestone outcrop (see below) may have been very local. In addition, as argued by Brown *et al.* (2010) for the River Exe Basin, erosion and deposition of sediment may have been recycled throughout much of the Middle to Late Pleistocene, thus maintaining the overall sediment within the river basin at a similar level. This would be a mechanism for limiting denudational isostasy.

Haloclinal Development of the Plymouth Coastal Karst Aquifer since the Hoxnian

Smith *et al.* (2008) used a simple weighting method to indicate the presence of related cave levels below present-day sea level equivalent to sea level stands of -1 m and -8.5 m AOD. Within the model presented by Proctor (1988) and Proctor and Smart (1991) their presence would be related to relatively warm periods when sea level remained constant over a relatively long time period. Given the continued uplift, these caves are likely to post-date the Hoxnian and would therefore be related to periods of elevated sea level.

An alternative is that the submerged caves pre-date the Hoxnian and are related to even earlier elevated sea level stands although with continued regional uplift increasingly isolating the present day elevation from the former eustatic level, this becomes increasingly unlikely.

The development of the Tamar palaeo-channel

Figure 5 shows the long profiles of the Tamar, Plym, Stonehouse and Millbay/Sour Pool palaeo-channels. The depths of these palaeo-channels have been estimated from several sources. The maximum depth of the Millbay Channel has been determined from points along the palaeo-channel and is based on borings carried out during the construction of the outer docks. (Codrington, 1898), those of the Cattewater and Plym from site investigation data from the 1970's, and borings for the construction of the Laira and Plym road bridges. The depth of the Stonehouse Creek palaeo-channel was obtained from publicly available borehole scans held within the British Geological Survey Borehole database.

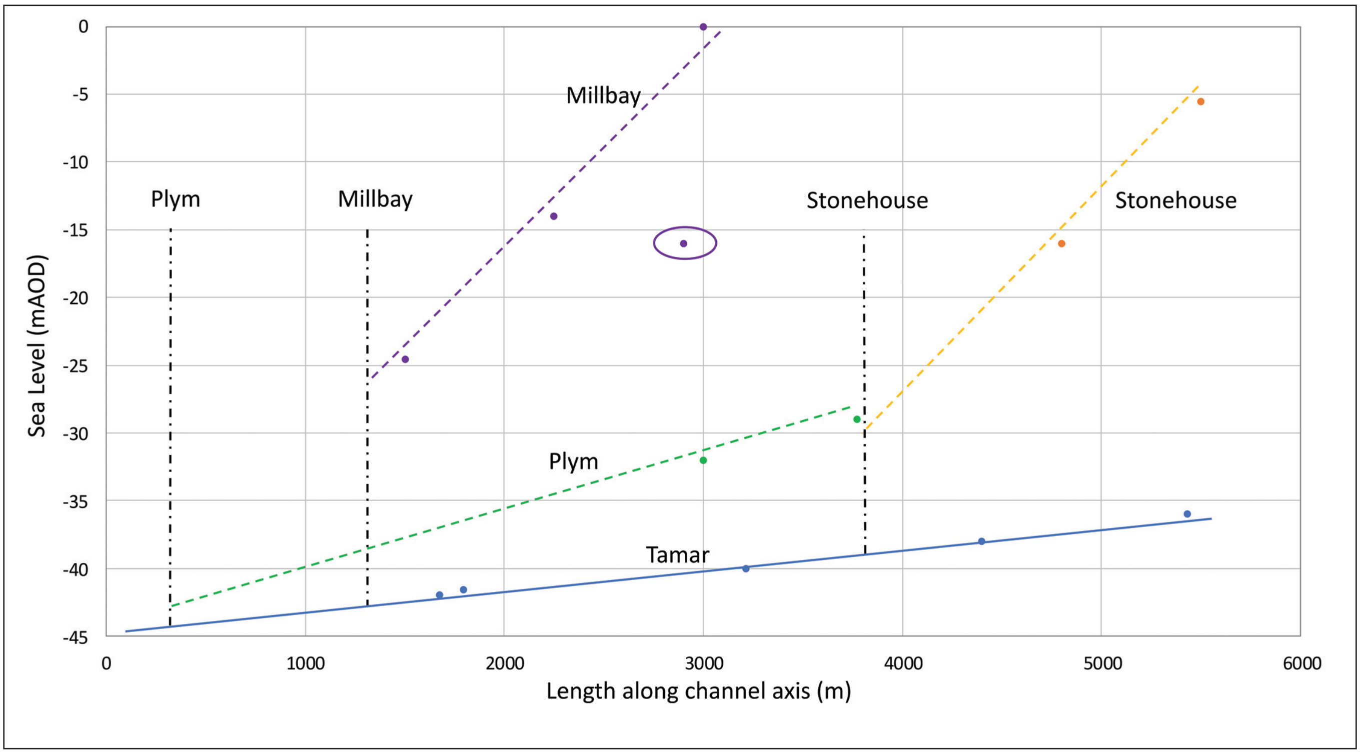

Figure 5. *Long profiles of the Tamar and Plym rivers, and Stonehouse and Millbay creeks based on recorded lowest bathymetry and published borehole records. Profiles are plotted from an origin at the downstream end of the limestone gorge of the Tamar. The anomalous depth recorded along he Millbay Tributary (highlighted) indicates probable past subsurface drainage.*

Eddies and Reynolds (1988) suggest that the hollows found along the bed of the present submerged Tamar channel to the south of the Hoe are evidence of significant collapse into limestone caves beneath the bed of the Tamar. Whilst this hypothesis supports the long held hypothesis of axial valley cave development similar to that originally proposed by Bretz (1942) it tends to ignore the topographic restraint whereby the current southern boundary of the bedrock limestone gorge must represent the lowest base level for any Cenozoic phase of vadose cave development in the exposed PCKA. Any cave development below this level would therefore have to be entirely phreatic in origin.

We consider that these 'hollows' represent areas of preferential erosion of sediments infilling the gorge base. It is well known for example that large quantities of sediment in the form of a granite boulder slush deposit were rapidly deposited along parts of the River Erme during the late Pleistocene (Gilbertson and Sims, 1974; Bertran, 2008). These deposits are known as the Ivybridge Boulder Beds. These deposits could relate to rapid climate changes known as Dansgaard-Oescher and Heinrich events, which have recently been linked to the collapse of the last British-Irish Ice Sheet (Clark *et al.* 2010). It is likely that similar quantities of sediments would have been produced in the Tamar River Basin as a response to the same climate events. In addition, when comparing the profile of the Palaeo-Tamar constructed by using maximum depth records results in a smooth long profile. This is consistent with these depths recording the base of a fluvial channel. Were these records of karst hollows, there would be no reason that their depths would fit into any consistent pattern.

Eddles and Hart (1989) described the gradual infilling of the palaeo-Tamar channel since the late Devensian, MIS2 glacial stage from a coast line at depth of around 120 m below sea level and located approximately 120 km to the south of the present day coastline.

Maximum estimated depths have been plotted against the distance along the Gorge Complex from an origin taken from where the gorge floor crosses the southern limit of the limestone outcrop. This origin is located to the west of the Mount Batten Pier. In addition, Figure 5 plots the relative levels of the base of sections of inferred former side gorges palaeo-channels, sections of which may still be present above the elevation of the main palaeo-channel.

When plotted in this way, several features are evident. The gradient of the main Tamar channel where it flows over the limestone outcrop is of the order of 1/1000. This is approximately half of the gradient determined by Durrance (1971) for the buried channels of the Dart and Teign palaeo-channels. This may be as a result either of the rock type over which the channel has developed, or continued use of the same channel over more than one period of low sea level.

The gradients of both the Millbay and Stonehouse channels are significantly steeper than that of the aforementioned channels, and as a consequence of their length have a much higher relief ratio than the Tamar or Plym. This is simply a consequence of their lower order. However based on the relative elevations of their channel profiles to the main Tamar palaeo-channel indicate, that at least for the Millbay palaeo-channel, hang at a significant elevation above the Tamar.

Figure 4 plots the relative level of the base of two possible remnants of former palaeo-channels associated with the Tamar preserved on the western side of the PCKA. The locations of these are shown on Figure 2. The reconstructed uplift curves for the base of the remnants of two former Tamar palaeo-channels suggest ages dating to between MIS6 and MIS11 for these remnants.

Non-halocline related cave systems in the PCKA in relation to the downcutting of the Tamar

Jakucs (1977) classified the evolution of karst limestones into two fundamental variants, which he termed Authigenic or "A type" and Allogenic or "B type". This karst morphogenetic classification is based on the orographic relationship between the limestone and adjacent non-limestone landmass. Consequently, this reflects on the relative position of the elevations of the current limestone hydrological base level and that of the surrounding non-limestone bedrock. Where the limestone base level of erosion is elevated above the surrounding non-limestone, a specific limestone hydrology tends to develop whereby rain falling directly on to the limestone is the (authigenic) source for groundwater in the limestone. However, where the base level of erosion of the limestone at some point is lower than the adjacent non-limestone, rain falling on the non-limestone area can form streams which then flow into the limestone, resulting in an allogenic source for the groundwater in the limestone aquifer. These two situations lead to two distinctive forms of hydrological organisation within the limestone aquifer. In Authigenic karst, hydrological flow-paths tend to be diffuse between numerous input sources, ponors etc., and numerous outputs, springs. In an allogenic type karst, underground flow is characterised by multiple inputs which tend to concentrate to a limited number of springs. Currently, this would classify the PCKA as a 'B- type' aquifer as the current base level of erosion of the aquifer is lower than the level of potential allogenic input from non- limestone rocks bounding the aquifer.

It is possible that during its development, the PCKA has undergone a series of transitions between 'A-type' and 'B-type' limestone aquifer variants linked to the development and downcutting of the Tamar buried Channel during periods of previous low sea levels stages.

The climate of the South West of England during cold stages is discussed by Lundberg and McFarlane (2012) in relation to the development of cryogenically fractured stalagmite. During cold stages, periglacial ground conditions would have applied to much of the South West of England and several climate models (e.g., Barron and Pollard, 2002) would place the South West of England within the zone of either permanent or discontinuous permafrost. They indicate a range of summer and winter temperatures based on warm and cold models for MIS3 between +5ºC to -2ºC, and -2ºC and -9ºC. Given that this modelling was carried out for MIS3 it would be expected that during the more severe MIS2 Last Glacial Maximum, temperatures would have been even more severe. Current estimates of the extent of permafrost cover in northern Europe are ambiguous as to whether the South West of England would have been covered with a continuous or discontinuous permafrost layer. However, the presence of soliflucted Head deposits in the Plymouth area which directly overlie the limestone, together with a range of permafrost generated features, unequivocally indicate the former presence of permafrost.

With respect to the development of allogenic 'B-type' karst within a periglacial environment, Ford (1987) discusses a model for the Nihanni Karst region of Canada where he vertically separates the karst into three zones. These are an upper zone of complete permafrost, a middle zone of the periodic drainage impedence and a lower zone of unimpeded drainage. Periodic allogenic streams flowing onto the limestone can continue to sink as their channel bases cut down below the level of complete permafrost. Present-day mean annual temperatures for the Nahanni Karst are between -6ºC and -8ºC and the area was last glaciated around 300 kyr. Brook and Ford (1980) also describe the impact of large scale summer floods on the present-day development of the Nahanni Karst as well as concluding that the scale of development within the Karst under periglacial conditions may be as large as under tropical or temperate climates.

It is suggested that a similar zonation as suggested by Ford (1987) may have been present within the Plymouth area during previous cold stages, but that the thickness of these zones could have been much reduced from those described for the Nihanni Karst. Smith (*in prep.*) discusses independent evidence for a thin permafrost profile as evidenced by ice segregation rock fracturing beneath the permafrost thaw limit elsewhere in South West England. Figure 6 illustrates the suggested allogenic development during cold periods for the PCKA.

In contrast to the BHCKA where nearly all the known caves are related to halocline development, caves types within the PCKA are more varied. This variation is likely related to the comparative topographic isolation of the BHCKA which is likely to have formed an upstanding ridge of limestone exposed to the sea on three sides with only a very thin land connection to the west. Under these conditions the BHCKA has acted as an 'A- type' aquifer throughout the Pleistocene.

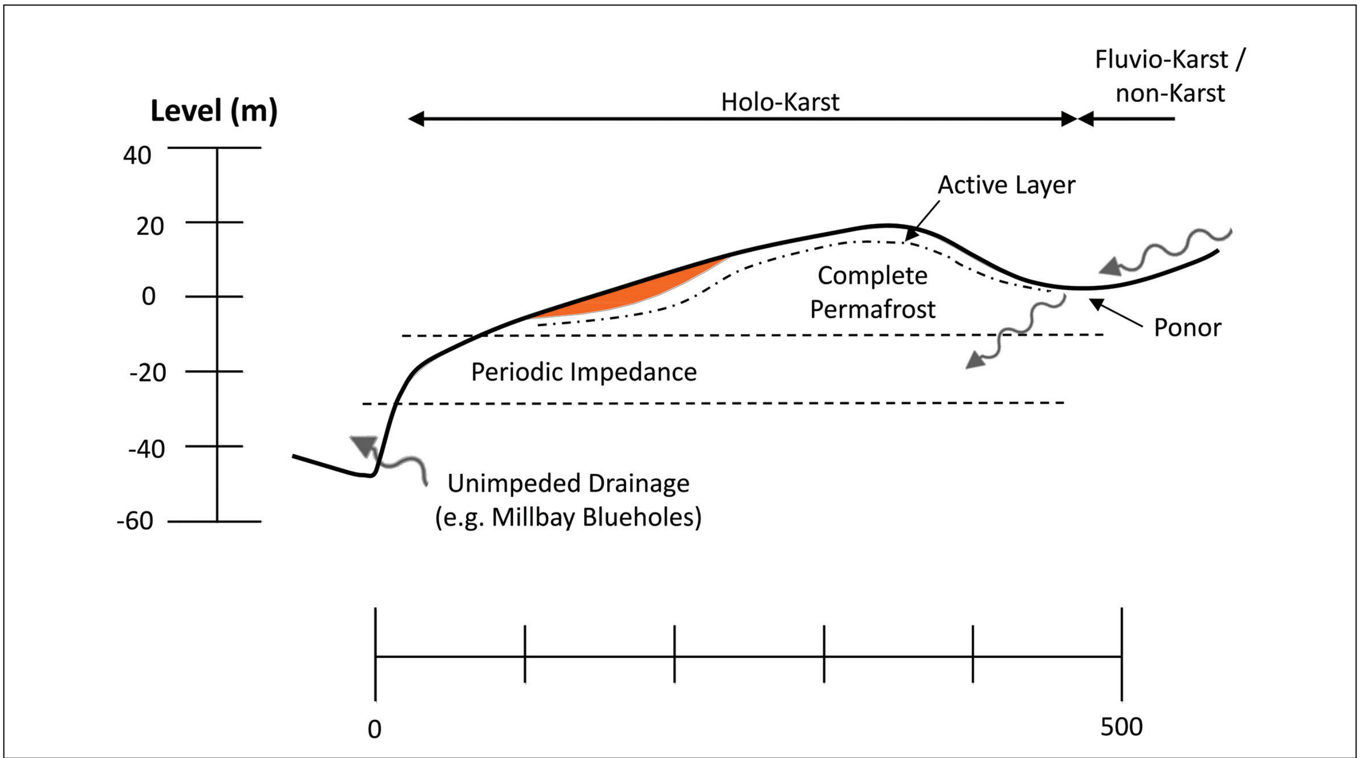

Figure 6. *Cold stage allogenic "B-type" karst model (modified from Ford, 1987).*

On the western side of the PCKA, more than one phase of fossil allogenic vadose engulfment is postulated to have existed on the northern flank of the limestone outcrop. The presence of such allogenic engulfment strongly suggests a switching of the PHCKA to a 'B-type' aquifer during the times represented by the two different phases. These phases relate to two different altitudes of around +25 m AOD and -20 m to -25 m AOD. The lower of these phases is associated with the large partially infilled depression which exists in this part of Plymouth and was known in Tudor times as Stinky or Sour Pool. This is an area of low-lying ground which has only been infilled relatively recently. In the past this area formed a tidal pool which was utilised to operate tidal Mills, from which the name Millbay probably derives. It extends along much of Plymouth's Union Street and Rendle Street to an area around Frankfort Gate. Much of this area was originally underlain by dark organic silts and clays, which are partly extant. To the eastern end of this area, alluvial depth increases locally to a maximum of 25 m. We believe that this increase in depth is the reason for the anomalous record on the BGS sinkhole database well to the north of the known limestone outcrop. It can be seen in Figure 5 that the elevation of the vadose engulfment where the inferred Millbay palaeo-channel crosses the northern limestone outcrop is significantly lower and forms a closed depression along the channel length, resulting in bathy-capture of the surface stream into the limestone outcrop.

A second allogenic vadose engulfment zone or ponor occurs to the north of the former West Hoe Quarries. This area was investigated during the construction works in the 1960s when convincing morphological evidence for the occurrence of a large abandoned and alluvial infilled allogenic ponor was obtained. The location and elevation of this ponor at around 25 m to 30 m AOD argues for the former presence of an associated allogenic stream originating in a similar area to that of the Sour Pool but prior to significant lowering of the Devonian slates to the north of the limestone outcrop and prior to development of the Millbay/Sour Pool channel, which would have led to its abandonment. It is possible that at this time, the Western section of the Hoe and former Battery Hill Plateau which, prior to early nineteenth-century quarrying, extended between the northern end of Durnford Street east to Bath Street, may have been joined as a single ridge. This ponor may have represented the only outlet for this source of allogenic water along the western end of Millbay at that time. Remnants of topographic ridges separating this area in a north to south direction from the Barbican area to the east and the Stonehouse Creek to the west are discernible from the current topography and would appear to delineate this area. Former inferred and recorded extents of the Sour Pool are shown in Figure 2.

Evidence from both within adjacent accessible caves and from the adjacent palaeo-Tamar strongly suggests that these phases of allogenic engulfment were associated with appreciable vadose cave development grading to a base level of erosion significantly below the level of engulfment.

Summary and Conclusions

A model for the exposure and subsequent development of the PCKA is presented and a chronology for the development of the PCKA caves can be tentatively linked to this development and the development of the major gorge complex it contains. This chronology suggests that the initial exposure of the limestone to its most recent phase of subaerial weathering would not have occurred much before the late Anglian MIS12 when regional uplift would have been sufficient to raise the top of the present limestone outcrop to be exposed as the tentative channel base of an earlier Tamar/Plym catchment system. We suggest that the dispersed rounded quartzite gravel deposits recorded from the summit of the Plymouth Hoe Plateau and the Shapter's Field gravel deposits were deposited at this time and could represent the oldest Pleistocene deposits present within the PCKA. Remains of these deposits may still be preserved in karst solution dolines and other fissures elevated around 30 m to 35 m AOD.

Halocline cave development related to high sea-level during the Hoxnian, MIS11 is present in the eastern section of the aquifer and is represented by caves in the former Fison's Quarry at Cattedown. Later phases of halocline cave development are represented by extensive development below present sea-level in the western portion of the aquifer from Mount Wise, Plymouth Hoe and to the East of the Barbican. Assuming that these occurred during an extended period of high sea level under an ameliorated climate it is probable that they date from between the late Ipswichian to Early Devensian, MIS5e to MIS5a.

Allogenic ponor-type cave development is known to have occurred during at least two phases of vadose development of the aquifer. The earlier phase, with an input elevated at around +25 m AOD could have occurred during a period of low sea level from MIS10 or later. An earlier date is favoured given the subsequent erosion between this level and the latest ponor input level inferred at around -25 m AOD. This latest ponor phase is likely to be Devensian in age. It is suggested that these phases of allogenic vadose development occurred during periods of low sea level as both phases appear from related evidence to be graded to base levels significantly below their input elevation.

The above chronology suggests the potential for karst features within the PCKA to be preserved and to preserve archives of sediment which date from a maximum of around 400 to 500 kyr. The greater elevation of the surface of the BHCKA indicate potential for the preservation of significantly older features, which is supported by the records of cave deposits in the adjacent Berry Head and Torquay limestones whose maximum ages date to at least 800 kyr.

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Appendix 1 Data used to create overall Digital Elevation Model (DEM) for the Plymouth Limestone and its visualisation Figure 2

Data for the elevation above sea level was obtained from the open source Open Government data.gov web site. Publicly available bathymetric data was obtained from the United Kingdom Hydrographic Office. As the smallest grid size of the available bathymetric data was 2 m x 2 m, similarly detailed above sea level Digital Elevation Model (DEM) data were obtained. The LIDAR DEM data is available from the Open Government Website in several formats. All data formats are georeferenced. The Digital Terrain Model (DTM) data was used in the model whereby building and other man-made structures and vegetation have been removed.

Raster data manipulation was carried out in either the open source GUI based GIS software program QGIS or directly from Windows based command line software program GDAL. Manipulation directly within GDAL rather than the GDAL implementation within QGIS allowed for greater processing flexibility and showed noticeably enhanced processing speed. Vector data manipulation or editing was carried out in QGIS.

To produce a single raster from both the DEM data sets mutually exclusive null data from both original data sets was set to a numerical value of 0. This allowed combination of the two data sets by simply creating a raster equal to the additional sum of the two modified data sets. Where data is absent from both the original data sets, this is represented in the final combined raster as an elevation of zero.

The combined DEM was hill-shaded using a combination of techniques. Initial hill-shading was carried out using the default GDAL hill-shading algorithm implemented through the standard QGIS terrain analysis using default GDAL settings. This sets azimuth and inclination at a standard inclination of 40 degrees and azimuth of 300 degrees. Whilst it is possible to vary these parameters in QGIS and to choose an alternative Zevenbergen and Thorne (1987) algorithm further hill-shading was carried out using the multidirectional weighted lighting directions as described in Mark (1992). This method is only available when running GDAL from a command line. Final hillshading combined both hill-shading technques by sequentially rendering a 25% transparent multidirectional hill-shade model and a 75% transparent hill-shade model lit from a azimuth of 300o and an inclination of 40°. Multidirectional hill-shading was considered particularly effective for highlighting parts of deep channel which extends along Western Kings Point, the Hoe Foreshore and the Cattewater, where due to the steep significant changes in topography on either side of the channel, hill-shading from a single direction would have resulting in faces of the channel not being illuminated.

In the final DEM colour shading a combination of scales were used to highlight regions of interest. It was considered that due to the significant differences in topography between the underwater channel and the gentler land topography, it was considered that a single scaled colour scheme would not be adequate. In the final image the bathymetry is linearly scaled with a range of blue tones, while the land topography is scaled using the algorithm given in Florinsky (2016) as follows;

Sign (Elevation)*ln(1+10expnm*(Elevation)

where n and m are constants, n being related to the cell size of the DEM and m varying between 1 and 9. In this instance the value of 2 was used.