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A stacked Late Quaternary fluvio-periglacial sequence from the Axe valley, Southern England with implications for landscape evolution and Palaeolithic archaeology

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Abstract

The current model of mid-latitudes late Quaternary gravel terrace sequences is that they are uplift-driven but climatically controlled terrace staircases relate to both regional-scale crustal and tectonic factors, and palaeohydrological variations forced by quasi-cyclic climatic catchment conditions in the 100 K world (post Mid Pleistocene Transition). This model appears to hold for the majority of the river valleys draining into the English Channel which exhibit 8-15 terrace levels over approximately 60-100m of altitudinal elevation. However, one valley, the Axe, has only one major morphological terrace and has long-been regarded as anomalous. This paper uses both conventional and novel stratigraphical methods (digital granulometry and terrestrial laser scanning) to show that this terrace is a stacked sedimentary sequence of 20-30m thickness with a quasi-continuous (i.e. with hiatuses) pulsed, record of fluvial and periglacial sedimentation over at least the last 300-400 K yrs as determined principally by OSL dating of the upper two thirds of the sequence. Since uplift has been regional, there is no evidence of anomalous neotectonics, and climatic history must be comparable to the adjacent catchments (both of which have staircase sequences) a catchment-specific mechanism is required. The Axe is the only valley in North West Europe incised entirely into the near-horizontally bedded chert (crypto-crystalline quartz) and sand-rich Lower Cretaceous rocks creating a buried valley. Mapping of the valley slopes has identified many large landslide scars associated with past and present springs. It is proposed that these are thaw-slump scars and represent large hill-slope failures caused by Vauclausian water pressures and hydraulic fracturing of the chert during rapid permafrost melting. A simple 1D model of this thermokarstic process is used to explore this mechanism and it is proposed that the resultant anomalously high input of chert and sand into the valley during terminations caused pulsed aggradation until the last termination. It is also proposed that interglacial and interstadial incision may have been prevented by the over-sized and interlocking nature of the sub-angular chert clasts until the lateglacial when confinement of the river overcame this immobility threshold. One result of this hydrogeologically mediated valley evolution was to provide a sequence of proximal Palaeolothic archaeology over two MIS cycles. This study demonstrates that uplift tectonics and climate alone do not fully determine Quaternary valley evolution and that lithological and hydrogeological conditions are a fundamental cause of variation in terrestrial Quaternary records and landform evolution.

Keywords: periglaciation, incision, chert, thermokarst, Quaternary hydrogeology, hydraulic fracturing, bifaces, Palaeolithic, Acheulian

1. Introduction

The typical configuration of Quaternary fluvial sediment bodies along the NW border of Europe is as river terrace staircases which decrease in age with decreasing altitude (Bridgland and Westaway, 2007) as is seen in the Severn, and Thames (UK, Bridgland et al., 2004), Seine and Somme (France; Antoine et al., 2000) and Middle Rhine (Germany; Westaway, 2002). This scenario would be expected in non-cratonic areas where regional uplift has occurred (Bridgland and Westaway, 2008). For example where, during the Quaternary, river systems are close to glacial margins or within permafrost-affected regions and have been subject to large fluctuations in sediment supply with or without uplift (Hancock and Anderson, 2002*).* Recent research and sediment dating has shown that this model is frequently complicated by intra-cyclic sediments forming compound terraces of two cold (stadial) phases (although rarely more) separated by channel fills, loess or landsurfaces (e.g. palaeosols) of interstadial or interglacial origin (Lewin and Gibbard, 2010). This staircase configuration is reversed below a hinge-line into subsiding basins, such as the southern North Sea (Rhine) and into lateral diachroneity in tectonically stable areas. Whilst this model was based upon the larger river systems in Europe it also holds for small river systems and for most of the rivers along the coast of England (Brown et al., 2010) and France which drain into the Channel River (English Channel/La Manche; Fig. 1a). The only exception appears to be the River Axe which, as mapped by the British Geological Survey (BGS; Edwards and Gallois, 2004), contains only one terrace at 14-30 m above the Holocene floodplain, small (unmapped) fragments of a lower terrace only 1-2m above the floodplain and spreads of ‘head’ or solifluction gravels on the upper slopes (Fig. 2). These two gravel bodies make up the Axe Valley Formation (Campbell et al., 1998a) which is known from three quarrying locations Kilmington, Broom and Chard Junction Quarry (henceforth, CJQ). To the west the Otter and Exe valleys (Fig. 1) have altitudinal staircases of 10 and 8 terraces respectively (Edwards and Gallois, 2004; Brown et al., 2009, 2010; Basell et al., 2011) and to the east the Frome/Piddle and Stour systems (Fig. 1) also have altitudinal staircases of 12-15 terraces (BGS 2000) as would be expected in a region that has undergone Quaternary regional-uplift (Westaway, 2010; 2011). The River Axe is also known for a remarkably rich intra-fluvial Lower Palaeolithic site at Broom (Reid Moir, 1936; Hosfield, 2008; Hosfield et al., 2011; Hosfield and Green, 2013) which has produced over 1800 bifaces and is only comparable to rivers to the east at Woodgreen on the River Avon, and Red Barns and Hill Head on the Solent River (Wenban-Smith and Hosfield, 2001). This paper presents the results of research at the only working quarry in the Axe valley which had the aim of explaining this anomalous situation (i.e. single compound terrace) and understanding its ramifications for both Quaternary landform evolution and Palaeolithic archaeology.

2. Previous Studies

The Axe is one of several catchments which since the breaching of the Weald-Artois anticline, have drained into the English Channel and southern North Sea but which lie just to the south of the maximum glacial extent of the British-Irish-Fennoscandian ice sheet (Fig. 1) and experienced periglacial conditions for most of the Late Quaternary (Mol et al., 2000; Renssen and Vandenberghe 2003). The Quaternary evolution of the River Axe has received considerable attention over the last 50 years due to its valley morphology and importance in Palaeolithic archaeology. Its atypical nature (single terrace) was noted by Green (1974; 2013) and Shakesby and Stephens (1984) and one of the aims of these studies was to test the hypothesis first proposed by Mitchell (1960) and later by Stephens (1977) that the anomalously thick gravels resulted from overflow through the Chard Gap (Fig. 3) from a ponded proglacial lake, Lake Maw, in the Somerset Levels (Fig. 1). The gravels at Chard do not support this hypothesis for two reasons. Firstly there are no clasts from the north Somerset area and secondly the gravels continue upstream of the entry point of the Chard gap into the Axe Valley, and into upstream tributaries

(Green, 1974; Campbell et al., 1998; Green, 2013). What is certain from these studies is that the Axe Valley and CJQ contains only one major morphological terrace and an anomalously thick sequence of locally derived gravels, principally Upper Greensand chert and flint. OSL dating at Broom also showed that the sequence younged upwards and is therefore a stacked or vertically aggraded gravel body of Late Pleistocene age (Hosfield et al., 2006, 2011). The quarry at Chard Junction which has been operating since the 1950s has produced occasional finds of Palaeolithic artefacts but these have been out of context (not in the gravel faces) such as the twisted ovate found by J. J. Wymer in 1959 and cordiform biface he also found in 1974. Wymer (1999) clearly thought that the site had considerable potential probably due to its proximity to the well-known sites at Broom (Hosfield et al., 2011; Hosfield and Green, 2013). Other than an isolated find out of sedimentary context there has been no archaeological recording of the sub-surface archaeology of the gravels at Chard Junction (Basell et al., 2007). Palaeolithic artefacts recorded in the county Historic Environment Records (HERs) supplemented by museum records were plotted onto the DEM/geology drape and it can be seen that there is a cluster of 11 in the CJQ area prior to this study (Fig. 2).

3. Catchment hydrogeology

The bedrock geology and hydrogeology of the Axe valley are of critical importance to its Quaternary evolution and so will be discussed in some detail. The English Channel cuts discordantly across the Cenozoic basins and axial structures (anticlines) that run from the Seine Basin to the Thames Basin and further west to the Wessex basin and Dorset plateaux (Fig. 1). This provides the well-known laterally time-transgressive Mesozoic section that is known as the Jurassic Coast. This mega-section youngs from the Upper Triassic at the west end (Exmouth Sandstone and Mudstone) to the Upper Cretaceous at the east end (Upper Chalk Group). The Axe catchment is located approximately mid-way along this sequence and is incised into a short outcropping section of mid-Cretaceous Upper Greensand and chalk which form the scarp slopes of the Blackdown Hills (Fig. 1c). The Upper Greensand is a sub-horizontal sequence of clays, weakly- and un-cemented sandstones, and tabular chert overlain by clay-with-flints of Eocene age. Large blocks of siliceous rock known as sarsens, are also found on the Blackdown plateau and it is believed that they are also of Eocene age along with the clay-with-flints formation (Isaac, 1979; Scrivener et al., 2011). The valley has incised through this sequence and is now floored by mudstones of Lower Jurassic age up to just above CJQ at Forde Abbey. This coincides with a nick-point at the upper end of the incised valley (Fig. 3) with the result that the valley-sides below this point are composed of a 120m thick 'layer-cake' of clay, sands and chert, sand and a basal mudstone of low permeability. In contrast the catchments to the west are underlain by only sandstones and mudstones (no chert) and to the east by chalk or Palaeogene sediments. A particularly unusual feature is the sand-chert-sand alternation which occurs in the CJQ area at 90 to 160 m OD (m above ordnance datum sea level) and which produces a lower and upper spring-line at the base of the two sandstone members (Foxmould Member and Bindon Sandstone Member, Fig. 1). These members are separated by mineralised erosion surfaces (hardground) forming hydrogeological discontinuities. Today minor seepage occurs from the upper spring-line but the lower spring-line has historically had enough discharge to power a number of mills and a gravity driven fountain at Forde Abbey. The chert is well exposed 5 km to the east of the Axe valley at Shapwick/Pinhay Quarry where it is a 30m thick bed of cryptocrystalline silicate fractured into tabular bedded blocks along the bedding which varies from 1cm to 40cm in thickness (Eggerton Grit). The quarry also reveals large phreatic tubes towards the base of this member (Brown et al., 2011a).

4. Methodology

The research at the recent extraction phases of CJQ (Hodge Ditch Phases I-III) was partly designed to allow the testing of novel techniques with potential for the monitoring of difficult Palaeolithic sites where there is a low density of lithic remains and an unknown potential for environmental information (Brown et al., 2011b). To this end the study involved not only standard lithological recording of gravel faces, but also geomorphological mapping, the analysis of borehole and gamma cps logs, digital granulometry (DG) and terrestrial laser scanning (TLS). Pre-extraction borehole records and gamma cps logs (Slatt et al., 1992) were used to derive a stratigraphic cross-section of the terrace gravels at Hodge Ditch (Fig. 4). Although the lithological descriptions did not reliably distinguish between the sandy gravels and other diamictons it was found that matrix-rich diamicton had a consistently higher relative gamma cps values (50+) allowing its differentiation from chert gravels and sands which both had low gamma cps values (c. 10), due to the inherited mineralogy from the Eocene clays and the mudstones (Brown et al, 2011b). The second novel methodological element of this project was the application of DG. The method is common in the analysis of sediment thin sections and geomorphology (Butler, et al. 2001; Graham et al. 2005a, 2005b; Strom et al. 2010) where it is used for the determination of the grain size distribution of river gravels. The application here uses a commercially available software (Sedimetrics®, Graham et al., 2005b) on vertical faces of gravel to generate grain size distribution curves. A 10 mega pixels camera was used (Canon Powershot 10XIS with a 20x optical zoom) give a minimum measurable grain size (MMGS) of approximately 4 mm for a 0.3 m^2 frame area. Testing has shown that there is a linear relationship between DG results and descriptive results derived from traditional sieving (Brown et al., 2011b; Basell et al. subm.). The TLS system used was a Leica ScanStation HDS3000 at typical ranges of 10-200m. A semi-permanent dGPS grid (using a Leica RX1250Xc GPS & GLONASS SmartRover), was established with a network of 12 temporary benchmark (TBM) targets which allowed any TLS position in the quarry to incorporate at least 3 reference targets. After processing (including cleaning), registration using Leica GeoOffice Combined v7 x,y,z data were exported and input into ArcGIS for solid model rendering used here and experimentally to generate grain size data (Basell et al.subm.).

All the gravels investigated were fully decalcified due to the acidic nature of the majority of the lithologies making up the catchment and so dating employed OSL initially as part of a wider dating programme of South West British river deposits (Toms et al., 2008, 2013). For the OSL dating, samples were collected in daylight from sections by means of opaque plastic tubing (150 x 45 mm) hammered into each face. In order to attain an intrinsic metric of reliability and where possible, multiple samples were obtained from stratigraphically equivalent units targeting positions likely to be divergent in dosimetry on the basis of textural differences. A measure of γ dose rate was made in situ using an EG&G μNomad portable NaI gamma spectrometer. To preclude optical erosion of the datable signal prior to measurement, all samples were prepared under controlled laboratory illumination provided by Encapsulite RB-10 (red) filters. Following segregation of material potentially exposed to light during sampling, fine sand sized quartz was isolated by means of acid and alkaline digestion (10% HCl, 15% H_2O_2) to attain removal of carbonate and organic components; a further acid digestion in HF (40%, 60 min) to etch the outer 10–15 mm layer affected by a radiation and degrade each samples' feldspar content; 10% HCl was then added to remove acid soluble fluorides. Each sample was re-sieved and quartz isolated from the remaining heavy mineral fraction using a sodium polytungstate density separation at 2.68 g cm^3. Equivalent dose (D_e) values were acquired using a Risø TL-DA-15 irradiation-stimulation-detection system (Markey et al., 1997; Bøtter-Jensen et al., 2003) and single-aliquot regenerative dose protocol (Murray and Wintle, 2000; 2003). Optimal thermal treatment was evaluated from measures of D_e and dose recovery preheat dependence. Dose rate (D_r) values were estimated through a combination of *in situ* γ spectrometry (γ D_r), Neutron Activation

Anlysis (β Dr) and geographical position and overburden thickness (Cosmic D_r; Prescott and Hutton, 1994). Disequilibrium in the U-series was monitored by means of *ex situ* gamma spectrometry using an Ortec GEM-S high purity Ge coaxial detector system.

5. Results: Stratigraphy, Sedimentology and Lithology

Borehole logs reveal that the full sequence of deposits on the southern side of Hodge Ditch extends from 79m to 47m OD at the thalweg of the buried valley although only the upper 23m has been exposed by quarrying above the present water table. The general sequence across the entire pit is typically tripartite above the mudstone bedrock head. A pit was dug in the quarry floor to inspect the bedrock-sediment junction at c. 55m OD on the slope of the buried valley, although boreholes indicate that the gravels extend to 47m OD. This pit revealed up to 1m of highly fractured brecciated Charmouth Mudstone (Unit C, Fig. 4g) with a disrupted contact exhibiting festoons and flame structures. Above the junction up to 64.4m OD are horizontally bedded clast-supported medium to well sorted gravels, with occasional shallow cross-bedding which includes trough-bedding varying between a SE to SW flow direction as would be expected in braided river with a N-S orientated valley. Overlying these gravels is a thick but highly variable unit of bedded fine to medium gravels (71-64.5m OD) with the development of large sand-filled channels bisecting the site approximately from east to west. To the north and south the channel is cut into horizontally bedded gravels. The sands display well-developed frost cracks (Fig. 4c), micro-joints and normal faults with minor displacement (Grubbenvorst type *sensu* Mol et al., 1993) and the gravels show features typical of cryoturbation including overturning, *in-situ* shattered clasts and transported angular clasts of silty-sand. These deposits are highly laterally variable as recorded by conventional logging (Fig. 4) and ground laser scanning (Fig. 5). At one location in Hodge Ditch III a thin and reworked slightly organic clay palaeosol was observed (Fig. 4b). Above an abrupt but irregular unconformity an upper matrix-rich, massive, poorly sorted, dark-red gravel-rich diamicton formed the sloping superficial unit (unit A in Fig. 4) from 79m to 71m OD at its maximum thickness. This thins from the bedrock valley sides to the NE of the site towards the valley axis. This unit has a high gamma cps values typical of a mixture of the underlying weathered Lower Lias (including Charmouth Mudstones) and chert clasts. TLS of 23 faces one of which is shown in Figure 5, were integrated and used to generate a solid model (Fig. 6). Due to the high variability of the gravels both laterally and vertically only the sand channel and the upper diamicton unit are differentiated in this model but it shows a former channel of the Axe buried by renewed gravel deposition prior to the deposition of the palaeosol (Fig. 4) and the diamicton.

Lithological analysis shows that the clasts throughout are overwhelmingly composed of sub-rounded to angular chert typical of the Whitecliff Chert Member (70-80%) with 30-20% flint although 0-2% of the clasts are quartz, quartzites and metamorphic rocks (Brown et al., 2011b). Some of the chert clasts reach boulder size (>256mm long axis) and are typically sub-angular with one or two faces showing a pre-weathered surface. This 'tabular' chert has probably been derived from fractures and weathered scarp faces on the middle to upper valley-side slopes and has undergone relatively little fluvial transport as the overwhelming majority of clasts were angular to sub-angular (75-80%). The quartzites are all well rounded and originally derived from Palaeozoic sources to the west later incorporated into a conglomerate within the Upper Greensand cherts at Snowdon Quarries, near Chard, or the Trias Pebble Beds (Budleigh Salterton Pebble Beds) which outcrop immediately to the west of the present Axe catchment. Alternatively they could have been derived from an upper plateau gravel. Support for this origin comes from the occurrence of some large pebbles and small boulders with thick grey weathering rinds, solution pits and the occurrence at the site of occasional small 'sarsens' which are blocks of silicified sandstone (silcretes) found on the Blackdown Plateau (Fig. 4). The grain size envelope reveals the gravels beds to be very poorly sorted medium gravels to cobbles with a secondary mode in the medium-coarse sand sized fraction (-1 phi). The lithic artefacts all fall into the upper part of the range but none lie outside the D_{95} of the gravel beds. However, the small sarsens lie well outside the gravel range and are therefore very unlikely to have been transported into the reach by fluvial processes. Although the bifaces are within the transported size-ranges their condition varied from rolled (highly abraded) to fresh (unabraded with sharp edges).

6. Results: archaeology and dating

As part of the ad-hoc monitoring in 2008 two lanceolate bifaces were discovered (2°55'21" W 50°50'17" N) in close proximity and from the basal strata of the Hodge Ditch Phase I extraction area (Brown and Basell, 2008). During continued recording of the site a further biface was found during 2008. Further finds included a biface (broken in antiquity), a very small biface (found in 2013), a flake and a core in Hodge Ditch Phase II. Although none of these finds were discovered embedded in a gravel face) they can all be confidently associated with specific areas and stratigraphic units within the pit (Hodge Ditch II) and particular working levels at or below 56m OD. They have been found on the southern areas of Hodge Ditch I and II and within the lower gravels. These lithics vary from fresh with sharp edges, to moderately rolled and one is unusually large (22 cm length and 1.1 kg in weight) suggesting two-handed use, probably for the butchery of large herbivore carcasses (Schick and Toth, 1993). Given the large quantity of gravels removed from Hodge Ditch I-III (over 1.8 M tons) and frequent monitoring throughout this represents a low 'background' density probably related to hominin activity along the floodplain and at the nearby high concentration site at Broom (Hosfield and Green, 2013).

Thirty three optical age estimates from Hodge Ditch I are outlined in Table 1 and illustrated in Fig. 7. All but four samples (GL08047, GL09117, GL09118, GL10066) have D_e values of less than 600 Gy, the maximum dose so far verified to produce accurate age estimates in the UK (Pawley et al., 2010). Excluding those samples that failed analytical diagnostics (Table 1 and Fig. 7), sedimentation between 55.8m and 66.5m OD appears centred upon a geometric mean age of 259±10 ka (MIS 7) but samples associated with the artefact level (GL08043, GL08044, GL08046 but excluding GL08047) show convergent age estimates from divergent dosimetry (Toms et al., 2005) providing an intrinsic measure of reliability and a weighted mean age of 326 ± 22 ka (MIS 9) but this should be considered as a minimum estimate for artefact age.

Additional dating evidence came from an exposure in Hodge Ditch III in 2011 when quarrying revealed a small lens of dark-grey clay with associated mottling of the underlying sands at 0.8m below the junction with the superficial diamicton. Analysis of the lens revealed it to be a low organic content sandy silty-clay with unidentified small rootlets. Its thinness (1-4 cm) and the minimal soil formation below it (no B horizon), suggest it is a re-worked organic channel fill. Pollen analysis was undertaken on one large sample (100g) and despite the low sample counts (Table 2) it is clear that the assemblage is dominated by tree pollen and particularly *Alnus*. The presence of *Alnus* and other thermophilious trees (*Quercus*, *Fraxinus* and *Corylus*) clearly indicates that this is from an interglacial rather than an interstadial and the presence of *Carpinus* and *Taxus* and the sedimentary context below the upper diamicton unit the most likely ascription is to some time in MIS5 and most likely 5e. The retained fraction from sieving produced very little organic residue and no insect (coleoptera, diptera or chironomid) remains were found. The plant material consisted only of unidentified fine root or stem material probably of monocotyledonous origin, black humic matter and very small lignified fragments of stem. Some small fragments of charcoal were present (under 2mm) and material including a few whole leaves of bryophytes. Comparison with type material and reference to Smith (2004) showed them to be typical of *Sphagnum* sp.. Studies using an environmental scanning electron (ESEM) revealed chains of cubic crystals within carbonised plant tissues within a predominantly quartz matrix. The individual crystals are 0.5-1 micron in size and typical of magnetotactic bacteria that require molecular oxygen to produce magnetic minerals intracellularly in the form of a chain within a magnetosome (Stolz et al., 1990). Microbial activity under conditions of low and alternating redox potential is known to produce both spherules (Ariztegui and Dobson 1996; Brown et al. 2010) and chains (Stolz et al., 1990). Given the lack of soil structure and no B horixon, the carbonised rootlets and the evidence of reducing conditions from the magnetobacteria we conclude that this is the remains of a shallow pool or pond smeared-out probably by the deposition of the overlying sand and gravel and possibly the deposition of the superficial diamicton. It illustrates that there was a hiatus in floodplain aggradation and the floodplain supported at least herbaceous vegetation growing in shallow pools during the last interglacial.

7. Discussion: Geomorphological mapping and thermokarst formation

This and other studies in the Axe valley have shown that the vast majority of the compound terrace is locally derived chert from the Whitecliff Member and sand from the Greensand Members (Foxmould and Bindon Sandstone) which outcrop on the valley sides (Fig. 1). Given the thickness of gravels over a reach of approximately 25 km and the stratigraphy of the superficial diamicton geomorphological mapping was undertaken in order to identify proximal chert sources. An area of 6 km^2 upslope of the diamicton cone and the Hewood Bottom tributary was mapped (Fig. 9). The valley-side slope above the quarry (NW corner of Fig. 9) which has an average gradient (0.015 m m^{-1}), has a structurally controlled form reflecting the near horizontal clay-with-flints, sandstone and chert stratigraphy. This produces an upper plateau, shallow ridges and convex slopes, and lower chert-underlain rectilinear or concave slopes with alternating spurs and shallow valleys. Descending from the springs along these valleys are a series of steep sided gullies many of which have pronounced concave headwalls at or below the springs. These features (Fig. 9 A-E) have arcuate to horseshoe-shaped planforms and are amphitheatre-like. The most pronounced which is located at the lower spring-line is 187 m across and 5 m deep. They are easily distinguished from quarries by their regular bowl-shape and locations on spring-lines. These features are remarkably similar to the scars left by ground-ice slumps or retrogressive thaw-slumps in areas undergoing rapid permafrost melting (Lewkowicz, 1988; Froese et al., 2008) such as the well-studied examples in the Yukon (Lantuit et al., 2012) (Fig. 9). Active retrogresive thaw-slumps consist of a steep (20° –90°) headwall of ice-rich permafrost and a more gentle (3°–10°) foot slope of thawed rock and soil (Burn and Lewkowicz, 1990) and in planform they can be vary from open-arcuate/D shape to lemniscate/teardrop shape. These slumps would have fed a slurry of sand and chert directly onto the floodplain via the tributary.

Following from the identification of these features along with many indications of periglacial conditions affecting the palaeo-floodplain, it was decided to examine the implications of simple permafrost melt model on these slopes. In order to keep the model requirements as minimal as possible the model used was the simple surface temperature driven TTOP model (Fig. 10) from Wright et al. (2003):

$$\mathbf{TTOP} = \frac{K_t K_f (n_t.DDT - n_f.DDF)}{P} \qquad \textbf{Eqn. 1}$$

Where TTOP is the temperature (°C) at the top of the permafrost, K_t is the thermal conductivity of the unfrozen ground, K_f is the thermal conductivity of the frozen ground, DDT is the air thawing index (degree days), DDF is the air freezing index (degree days), n_t is the thawing n-factor (vegetation), n_f is the freezing n-factor (vegetation) and P is the annual period (365 days). From the estimation of TTOP and assuming a linear profile (so assuming a homogenous substrate at that point on the slope) an estimate of permafrost thickness can be calculated by extrapolating along the geothermal gradient to 0°C. The values used were taken from Lebret et al. (1994) for K_t and K_f but with no correction for soil mineralogy as this has been found to be insignificant in its effect (Riseborough and Smith, 1998). The values used are given in Table 3 and the surface vegetation was assumed to be tundra. TTOP was generated from the estimated mean annual temperature for southern England during the late glacial maximum (Atkinson et al. 1987) and a sinusoidal annual temperature amplitude of 26°C which is slightly higher than a typical value for modern arctic Canada (23°, Wright et al., 2003). When applied using these values the result is a winter permafrost thickness varying from 88m to 122m with lithology (greater on the chert and mudstone and less on the clays and sands) and deep enough to freeze the entire sedimentary sequence outcropping on the slopes (Table 3; Fig. 10). Thawing was rapid and would have been fastest on the sands, and clay with flints, and with the deepening of the active layer the sand members would have been saturated but vertical drainage would be prevented by the aquicludes (impermeable rocks) and any remaining permafrost in the chert and mudstones. If thawing of bedrock and soil ice releases water faster than it can drain porewater pressures will rise, effective rock stress fall, and frictional strength is reduced (Morgenstern and Nixon, 1971; Harris et al. 1995). The result would high pore-water pressures within the sand units and the chert, and very high seepage pressures at both the upper and lower spring-line. Given the impermeable nature of the chert this may have caused hydraulic fracturing of the chert, reduced frictional strength and induced slope failure. In other words, ideal conditions for thaw-slump generation at these points on the slopes, with the resultant mass failure of sand and chert in the form of debris-flows and slumps with shear planes in the lower saturated Foxmould sand over the Gault and Eype Clay. Under this scenario the chert would be transported as coarse clasts within a saturated sand matrix in non-Newtonian flows even on low slopes, here typically 1-2°. These debris flow injections onto the floodplain (similar to the upper diamicton) were reworked and sorted by the river until

MIS 4-2 when the river was confined by the debris-cone on the north side of the floodplain and incised through the gravel stack. Reworking of the debris flows must have taken place when the surface was unfrozen including under interstadial and interglacial periods. This is a process-based version of the 'fluvioperiglacial' models of both Castleden (1980), Bryant (1983) and Shakesby and Stephens (1984) and explains the anomalous accumulation of gravels from the Upper Greensand slopes down to the buried valley at the present river mouth (Fig. 3). A possible alternative model could be active layer saturation causing the retrogressive thaw slumps during full periglacial conditions, however, these be so located at the bedrock junctions and springs – hence our view that the cause is melting of the permafrost at cold period terminations.

8. Discussion: Terrace formation

Combining the stratigraphy and the OSL dating we suggest that the uppermost unit at Chard Junction Quarry is solifluction and thaw-slump derived debris-flow deposits which accumulated during the Devensian post MIS 5a. The uppermost OSL dates on the underlying bedded sand and gravel suggest accumulation during the early Devensian MIS 5a-d and an MI5e date for the organic deposits is consistent with the palynology. The middle bedded units of bed D appear to have accumulated in cold stages MIS 6 and this is in agreement with the sedimentological evidence of freezing of the floodplain surface. These sediments closely resemble the periglacial alluviation model of Bryant (1983) with an abundant supply of sand and chert gravel deposited as medial and lateral bars in a braided channel-system. The lowest accessible beds (i.e. those above the present water table) may pre-date MIS 7 but confirmation of this is underway using post-IR IRSL dating (Thomsen et al., 2008). The gravel-bedrock contact shows strong development of brecciation which is interpreted here and elsewhere in southern England as being due to permafrost ice-segregation and which made bedrock vulnerable to thermal erosion (Murton and Lautridou, 2003; Murton and Belshaw, 2011). It follows that the incision of the buried valley within which this sediment stack has accumulated was pre MIS 9-10 and given the deep buried valley from CJQ to the coast it is most likely that it represents incision to the low Mid-Pleistocene sea level during MIS 12 (Fig. 2). This accommodates additional incision of the English Channel River due to breaching during at this time (Gupta et al., 2007). This does not conform to the standard model (Bridgland and Westaway, 2007; Bridgland, 2000) and we suggest this is because the Upper Greensand being highly erodible was deeply incised in the early Pleistocene and incision, although slowed once the mudstones were encountered, was after MIS 12, prevented by sediment oversupply and the nature of the chert as bed material. It is also possible that a threshold for incision reached after MIS 12 was not reached again until the termination of the last glacial cycle.

This study has confirmed that the stone artefacts discovered at Chard come from the basal 10m of the sequence and that the site has a low or background-level density, but that the lithics have probably not travelled far from their point of discard. At Broom, and particularly the Ballast or Railway Pit the stratigraphy and the archaeology differs significantly from that at Chard. In particular at Broom there is the development of a laterally extensive pollen-bearing clays and silts or a subaerial loam that was deposited in a temperate stage possibly during an interstadial within MIS 8, or in MIS 9 (Hosfield et al., 2011; Hosfield and Green, 2013) and this is not the case at CJQ which is a more active reach. The archaeology, which was an initial justification for the study, is also different because the total number of finds from Chard is c. 23 (including local surface finds), while Broom produced over 1800 stone tools. This study shows that this massive difference is the result of a concentration of lithics at Broom probably due to nearby working of chert vs low density probably discarded lithics at CJQ. Although the majority of the bifaces at Broom are ovates and cordates, although pointed forms are known, the biface finds reported here are similar being lanceolate (corresponding to Hosfield and Chamber's "pointed" categorization) and cordate in form. Our research suggests that the biface-bearing gravels at CJQ are broadly contemporaneous with the assemblage at Broom although at neither site has it been possible to directly date a bed containing an *in-situ* artefact assemblage. This confirms that Broom is a 'super-site' probably due to the reworking into the channel of a proximal archaeological context, possibly even a biface pavement (Brown et al., 2013).

Taken together the sites at CJQ, Broom and Kilmington reveal episodic cold-stage fluvioperiglacial aggradation during the Middle-Late Pleistocene. In being a stacked sequence the Axe Valley is exceptional in southern England and this requires explanation. The typical geophysical context for terrace staircases is relative uplift with repeated down-cutting to low base levels as provided by cold-period sea levels whereas stacked sequences are typical of subsiding basins such as the lower Rhine sequence under the Netherlands (Peeters et al., 2014). Although the area is affected by faults which may have been active into the Quaternary (Gallois, 2006) there is no evidence that the Axe valley was part of a subsiding block relative to the catchments each side of it. Indeed the whole Blackdown block, SW peninsula and South Coast has undergone variable uplift during the Quaternary (Westaway, 2010; 2011). It is also self-evident that the climate of this catchment must have been similar to its surrounding areas throughout the Quaternary. An alternative explanation is that the catchment has, at some stage in the later Quaternary, been reduced in size by river capture, thus reducing its discharge but not reducing the sediment input from main valley slopes. Such a possibility has been postulated by Gallois (2006) with capture of part of the adjacent proto-Otter by the Exe/Culm system but this did not affect the Axe catchment. Shakesby and Stephens (1984) suggested that high rates of sediment availability and periglacial transport produced the thickened Axe Valley Formation and Hosfield and Green et al (2013) stress the erodible nature of the Upper Greensand lithologies. Whilst this is undoubtedly correct we argue this is not enough, as similar conditions pertained in the adjacent

Otter Valley and the rivers draining the north and eastern edges of the Blackdown Plateau, all of which exhibit terrace staircases. The mapping of the slopes above Chard Junction suggest that the entire catchment was highly susceptible to thermokarstic melt-out processes at terminations due fundamentally to its layered stratigraphy of highly permafrost-sensitive rocks i.e. sand with fractured chert over a basal aquiclude. The pronounced spring-lines of the hills is seen largely as a relic of the operation of a pressurised groundwater system during periglacial melting and associated retrogressive thaw-slumping. Modelling has suggested that the occurrence of pressurised groundwater systems was common in northwest Europe in areas of discontinuous permafrost including river valleys and would have had its maximum effect in lithologies with high effective porosities and permeabilities (van Weert et al., 1997).

The pre-fractured nature of the chert and the bimodal grain size of sediment (cobbles vs fine-medium sand) may also be important for the lack of incision between stadials until the later Devensian. The pre-fractured chert forms sub-angular blocks of cubic to tetrahedron shape which after winnowing of the sand matrix have a tendency to lock together forming a pavement, especially as upstream bedload input reduces (Dietrich et al., 1989). A simple calculation using the grain size distribution envelope (Fig. 8) of the Shields stress required to move the D_{50} of the gravels and the D_{95} suggests a 44% higher critical shear stress would be required to disrupt an armoured bed and this takes no account of any imbrication and interlocking which would increase this value further. Armouring and the thick gravel body would have increased hyporheic flow during temperate conditions and reduced the likelihood of bed incision. This mechanism is supported by the high lateral variability of the gravels formed as a result of laterally shifting channels and bars and the common occurrence of small lenses of framework gravels. The Devensian incision took place prior to the deposition of the lower inset terrace. Although not dated in this study it is comparable in height and extent with the lowest terrace in the Exe system which has been dated to the lateglacial stadial (Younger Dryas; Bennett et al., 2011). The sloping surface of the terrace throughout the valley suggests the possibility that the solifluction/debris flow unit was so extensive that it confined the channel to a small part of the floodplain. This would have promoted incision when vegetation had stabilised valley slopes although this process may have started as hyporheic in the depressed thaw zone under the floodplain under warming climate conditions (Zarnetske, et al., 2008; Murton and Belshaw, 2011). This mechanism may also provide an explanation for the prior incision of the valley floor which initiated the stacked sequence post MIS 12 as suggested by the bedrock brecciation. It must also have been important in increasing the erodibility of bedrock at floodplain edges thus facilitating lateral expansion of the braidplain and what has been termed in the past fluvioperiglacial pedimentation *sensu* Castleden (1980).

10. Conclusions

1. The chronostratigraphic data presented in this paper reveals that the Axe, a tributary valley of the Channel River in southern England, has undergone quasi-continuous fluvial aggradation - with hiatuses and lateral reworking - from MIS 10 and possibly MIS 12 until MIS 2 when it underwent an incision and then a minor aggradational phase. The sediment-stack up to 32m in total thickness is preserved in one major compound terrace with a sloping surface formed by debris-flow deposits which is particularly well-developed at tributary junctions.

2. This morphology and developmental history is in stark contrast to all the other fluvial systems draining into the English Channel/La Manche system in southern England and northern France which are all terrace staircase systems regarded as typical of non-cratonic areas close to Quaternary glacial margins. Such an anomaly requires an explanation within or outside the current conceptual model of terrace formation. However, the Axe is also unusual in being entirely incised into a near-horizontally bedded alternating sequence of weakly cemented sands and

cherts over mudstones of Mesozoic age. Geomorphological mapping of the valley slopes has revealed features along prominent spring-lines which on morphological grounds are very similar to modern retrogressive thaw slumps found in areas of melting permafrost.

3. A simple 1D model (TTOP) is used to test this hypothesis and it suggests that that permafrost differentially melted in non-cemented sands both below and above the chert beds producing a pressurised groundwater system which instigated hydraulic fracturing of the chert and retrogressive thaw slumping. This liberated the pre-fractured chert in debris-flows providing a high input of both sub-angular chert within fluidized sand onto the floodplain. This input was locally reworked by fluvial activity but not incised into until the lateglacial. The reasons for this change in fluvial behaviour are not known but may be due to a combination of the confinement of the river by debris flow deposits and thermokarst induced down-cutting after reduced sediment supply.

4. One result of this hydrogeologically mediated valley evolution was to provide a record of both proximal (near-site) and background Lower Palaeolithic archaeological activity. The similarity between the artifact typologies at CJQ and nearby Broom and the OSL dating at both sites suggests a common age of either MIS 9 or 7, and the low-density of artefacts at CJQ confirms the importance of Broom as a 'super-site' (*sensu* Ashton and Hosfield 2010 and Brown et al 2013) and its likely proximity to an *in-situ* assemblage reworked into an adjacent channel.

5. Most importantly this study demonstrates that uplift tectonics and climate alone do not fully determine Quaternary valley evolution and that lithological and hydrogeological conditions are a fundamental cause of variation in terrestrial Quaternary records.

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Tables

Table 1. Dose Rate (D_r), Equivalent Dose (D_e) and Age data of samples from Hodge Ditch I-III (51°N, 3°W, 75 m O.D.). Uncertainties in age are quoted at 1σ confidence, are based on analytical errors and reflect combined systematic and experimental variability and (in parenthesis) experimental variability alone. All ages are expressed in thousands of years before 2010.

Table 2. Pollen count data from large sub-sample from the Hodge Ditch III organic silty clay.

Table 3. Parameters used in TTOP modelling of permafrost freezing.

Figure captions

Fig. 1. (a) Location of the Axe valley catchment in southern England with catchments coded by the number of BGS terraces recognised (after Brown et al., 2009) and ice limits , (b) generalised geological section of the Jurassic Coast, (b) a simplified geological cross-section along the Jurassic Coast with the Axe valley shown, and (c) a GIS derived drape of the superficial geology of the Axe catchment. Data derived from BGS mapping.

Fig. 2. Drape of Quaternary deposits, archaeological (Palaeolithic) finds and sites mentioned in the text over a DEM derived from IFSAR data.

Fig. 3. The long profile is re-drawn using some data from Campbell et al. (1998b), Basell et al., (2007), Brown et al. (2010) and this paper. Only the OSL dates with no analytical caveats are plotted for CJQ. Upper stippling is Upper Greensand lithologies and below Triassic Mudstones with the junction generalised from BGS mapping.

Fig.4. Generalised stratigraphic section from CJQ Hodge Ditch Phases 1-3 with insets of sedimentological features (a) upper diamicton unit, (b) organic-rich clay in upper part of Unit B, (c) channel sands with frost cracks between unit B and C, (d) sand lenses within Unit C, (e) clast-supported horizontally bedded gravels in Unit C, (f) a sarsen from Unit B showing surface weathering pits, (g) the brecciated and disrupted bedrock-gravels interface in Hodge Ditch II.

Fig. 5. Scanned face of a section in with Scan data draped Hodge Ditch 3 with photos taken using the ScanStation and then processed using different image texture settings (upper gamma 2 and lower using a colour classification of the intensity of return).

Fig. 6. (A) HD I, II and III point data interpolated in ArcMap 10 using inverse distance eighting and displayed using height colour values. Displayed in ArcMap (2D) using a pseudo-3D image. Red high, blue low. Red points show distribution of OSL locations labelled according to GL-number. (B) Model with OSL sample locations (black), bedrock from bore hole data, location of one of the scanned faces (pale mauve) inserted from scanned grid co-ordinates as an example, palaeosol (bright pink line in HD3) and location of major sand units derived from scan data and photographs. Artefact locations are shown in bright pink. The apparent position of some of the OSL sample locations within mounds of gravel is because following standard gravel extraction during which samples were taken and sections recorded, the area was

subsequently used to dump spoil mounds which were captured by a later scan. 5 x vertical exaggeration.

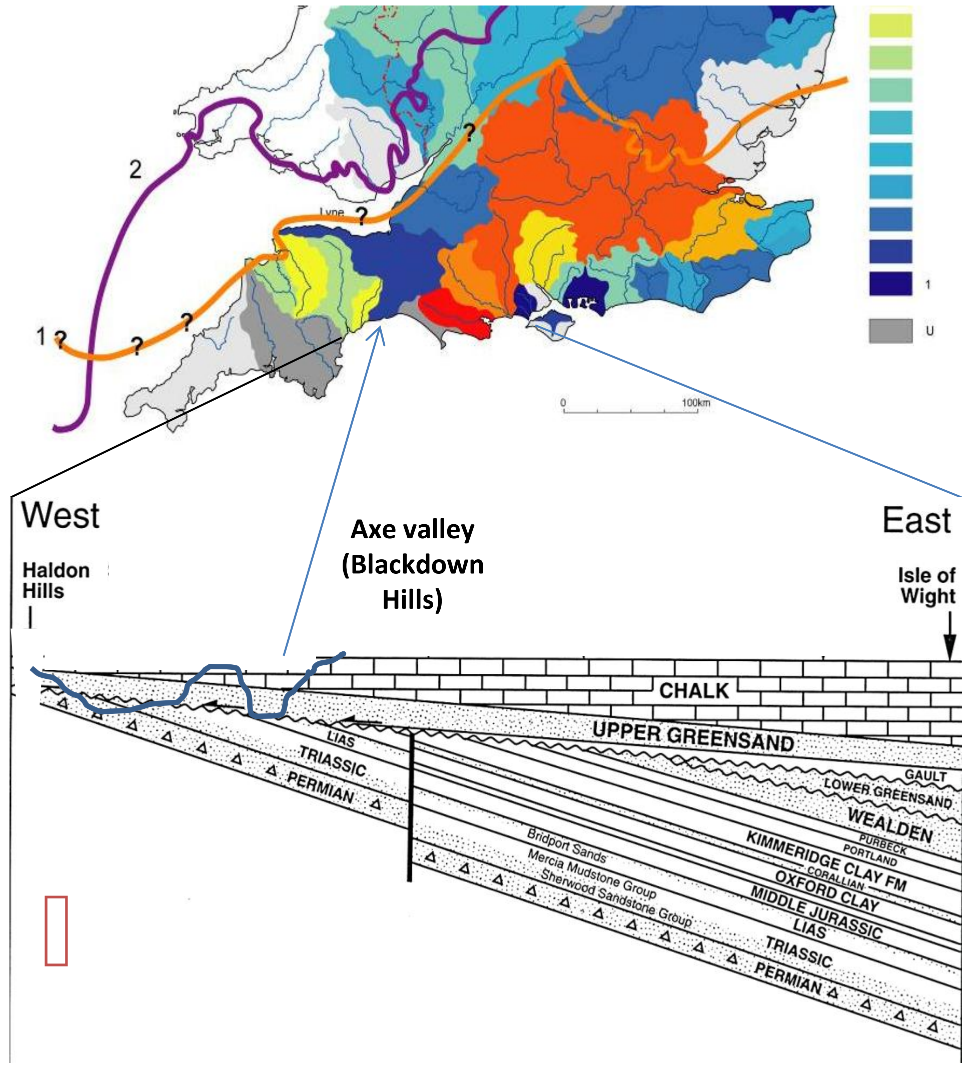
Fig. 7. Age depth model derived from OSL and bio-correlation dates. Solid red line signifies the depth of the thin palaeosol. Dashed grey line indicates the level at which artefacts were found. Diamonds represent OSL age estimates, with red fill used to highlight those with analytical caveats. The blue line shows the oxygen isotope curve from ODP 677 along with temperate (red numbered) and cool (blue numbered) MIS.

Fig. 8. Grains size envelope for CJQ fluvial gravels from Hodge Ditch I-III with moment statistics and size range of the bifaces found during this research.

Fig.9. GIS DEM of the mapped area around the CJQ showing spring-related thaw-slump landforms (marked by break of slopes as mapped and by symbols A-E). The map uses standard geomorphological symbols as recommended by the Geological Society Engineering Working Party (1972) and reproduced in Gardiner and Dackombe (1983).

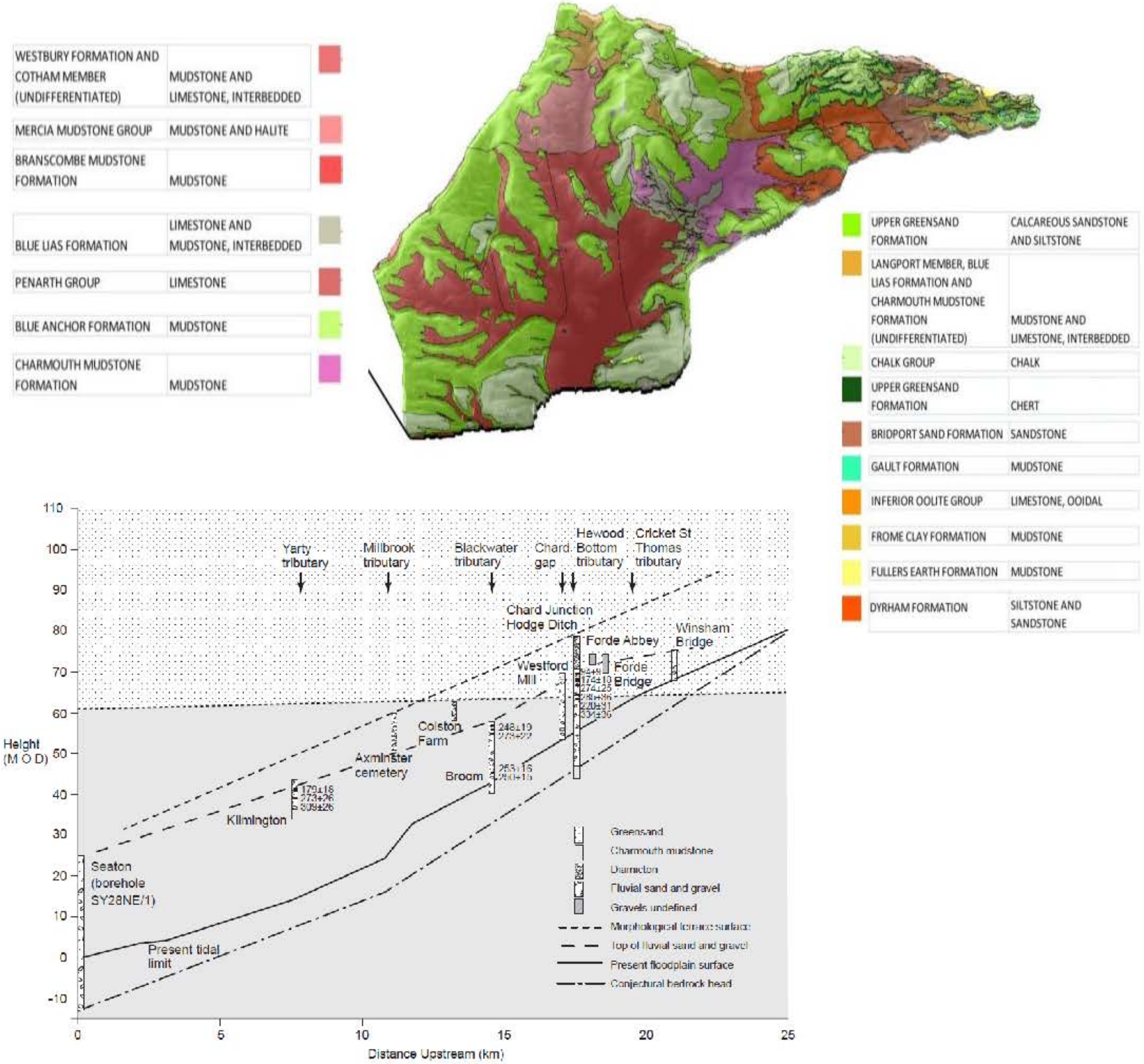
Fig. 10. Simplified model of para-fluvioperiglacial sediment input forced by permafrost melting of the Upper Cretaceous (Greensand) lithological sequence, (a) model representation, (b) the valley-side cross-sectional geology used in the model with present water table and (c) the model with frozen layer and flowlines after sequential melting.

Fig 1



2
1
Lyne
0
100km
1
U
West
Haldon Hills
Axe valley (Blackdown Hills)
East
Isle of Wight
CHALK
UPPER GREENSAND
GAULT
LOWER GREENSAND
WEALDEN
PURBECK
PORTLAND
KIMMERIDGE CLAY FM
CORALLIAN
OXFORD CLAY
MIDDLE JURASSIC
LIAS
TRIASSIC
PERMIAN
Bridport Sands
Mercia Mudstone Group
Sherwood Sandstone Group

Fig 2



WESTBURY FORMATION AND COTHAM MEMBER (UNDIFFERENTIATED) | MUDSTONE AND LIMESTONE, INTERBEDDED
MERCIA MUDSTONE GROUP | MUDSTONE AND HALITE
BRANSCOMBE MUDSTONE FORMATION | MUDSTONE
BLUE LIAS FORMATION | LIMESTONE AND MUDSTONE, INTERBEDDED
PENARTH GROUP | LIMESTONE
BLUE ANCHOR FORMATION | MUDSTONE
CHARMOUTH MUDSTONE FORMATION | MUDSTONE
UPPER GREENSAND FORMATION | CALCAREOUS SANDSTONE AND SILTSTONE
LANGPORT MEMBER, BLUE LIAS FORMATION AND CHARMOUTH MUDSTONE FORMATION (UNDIFFERENTIATED) | MUDSTONE AND LIMESTONE, INTERBEDDED
CHALK GROUP | CHALK
UPPER GREENSAND FORMATION | CHERT
BRIDPORT SAND FORMATION | SANDSTONE
GAULT FORMATION | MUDSTONE
INFERIOR OOLITE GROUP | LIMESTONE, OOIDAL
FROME CLAY FORMATION | MUDSTONE
FULLERS EARTH FORMATION | MUDSTONE
DYRHAM FORMATION | SILTSTONE AND SANDSTONE
Height (M O D)
110
100
90
80
70
60
50
40
30
20
10
0
-10
Yarty tributary
Millbrook tributary
Blackwater tributary
Chard gap
Hewood Bottom tributary
Cricket St Thomas tributary
Chard Junction Hodge Ditch
Winsham Bridge
Forde Abbey
Westford Mill
Forde Bridge
Colston Farm
Axminster cemetery
Broom
Kilmington
Seaton (borehole SY28NE/1)
Present tidal limit
Greensand
Charmouth mudstone
Diamicton
Fluvial sand and gravel
Gravels undefined
Morphological terrace surface
Top of fluvial sand and gravel
Present floodplain surface
Conjectural bedrock head
0
5
10
15
20
25
Distance Upstream (km)

Fig 3

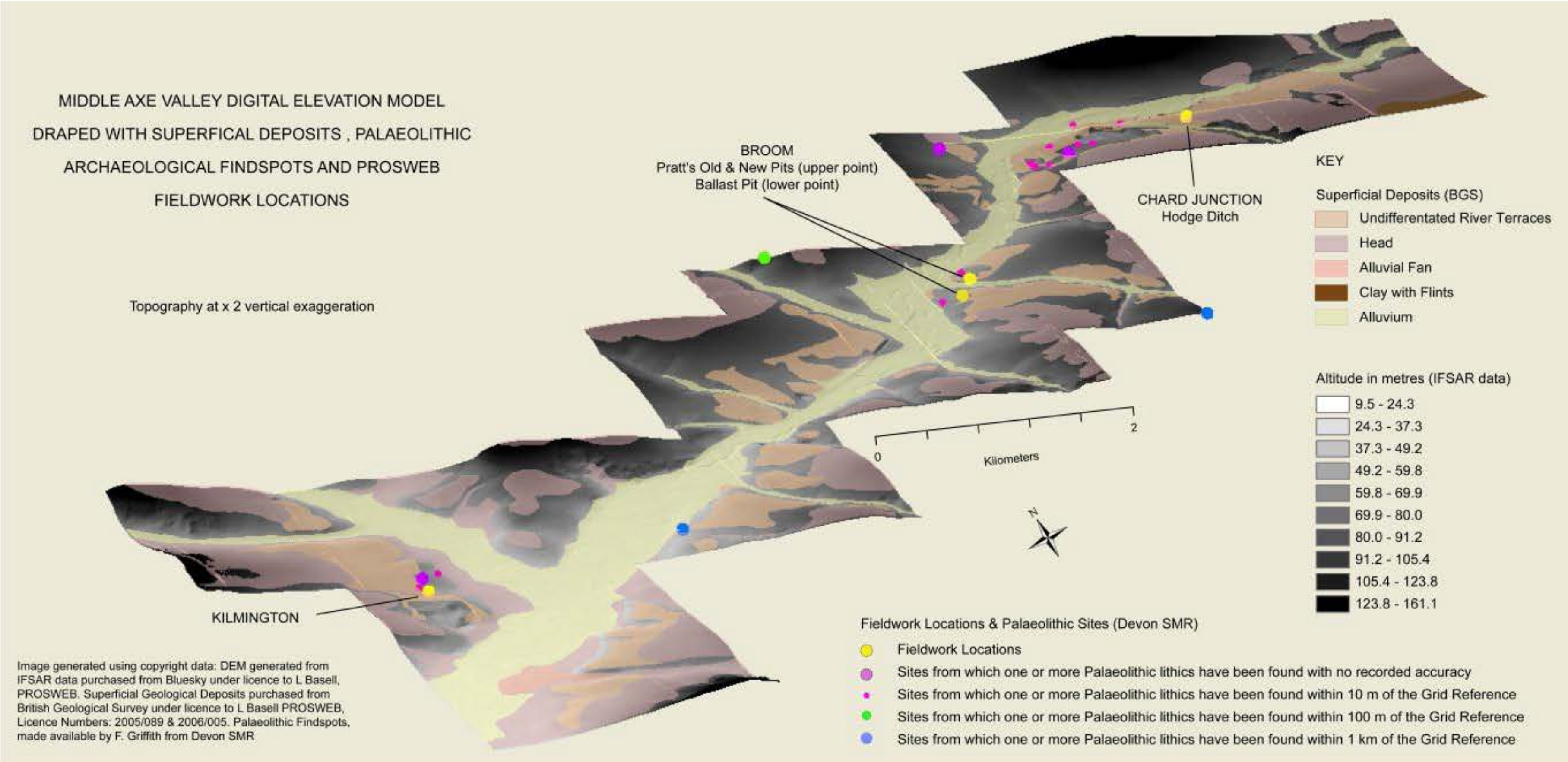
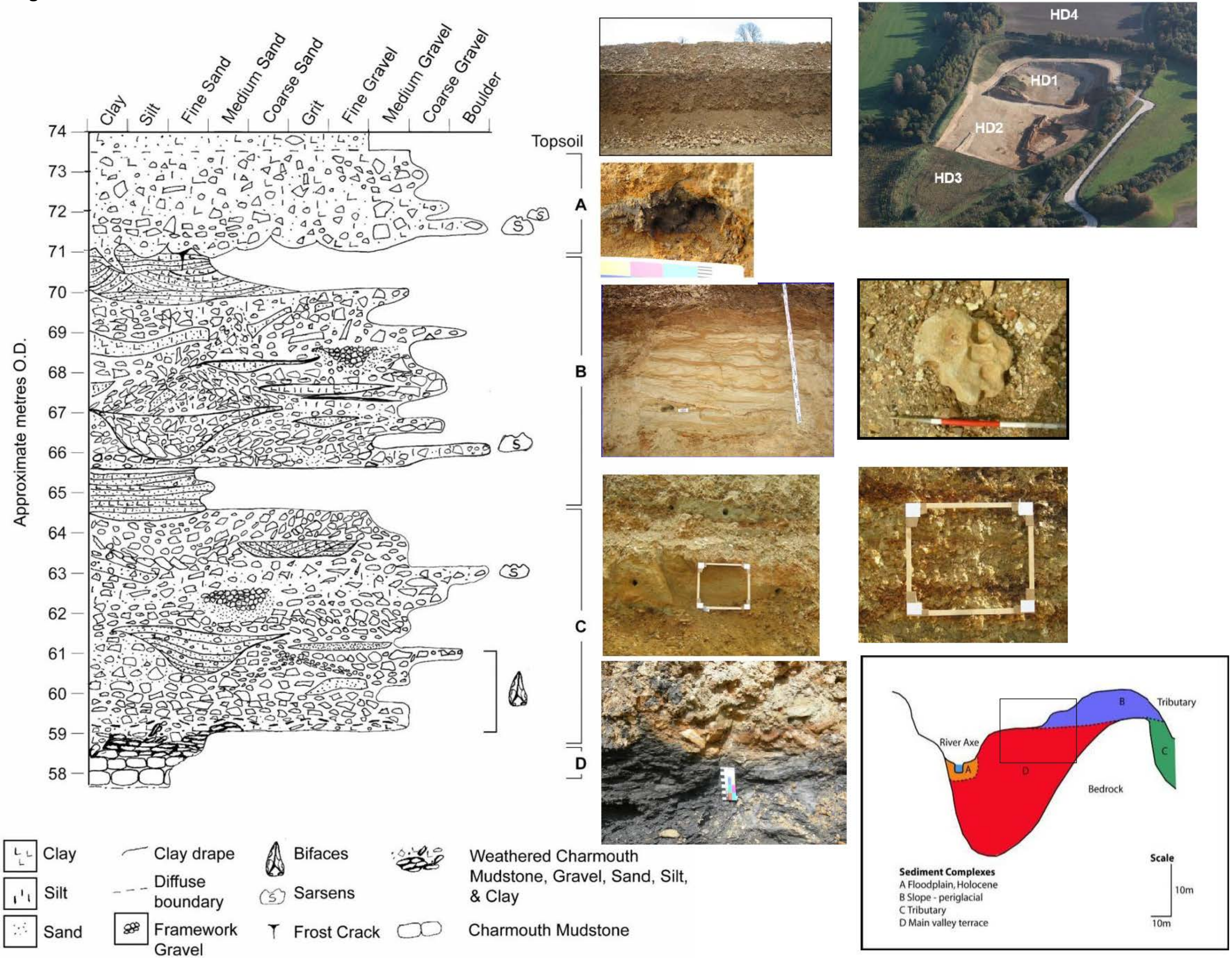

MIDDLE AXE VALLEY DIGITAL ELEVATION MODEL
DRAPED WITH SUPERFICAL DEPOSITS , PALAEOLITHIC
ARCHAEOLOGICAL FINDSPOTS AND PROSWEB
FIELDWORK LOCATIONS
Topography at x 2 vertical exaggeration
BROOM
Pratt's Old & New Pits (upper point)
Ballast Pit (lower point)
CHARD JUNCTION
Hodge Ditch
KILMINGTON
0
2
Kilometers
N
KEY
Superficial Deposits (BGS)
Undifferentated River Terraces
Head
Alluvial Fan
Clay with Flints
Alluvium
Altitude in metres (IFSAR data)
9.5 - 24.3
24.3 - 37.3
37.3 - 49.2
49.2 - 59.8
59.8 - 69.9
69.9 - 80.0
80.0 - 91.2
91.2 - 105.4
105.4 - 123.8
123.8 - 161.1
Fieldwork Locations & Palaeolithic Sites (Devon SMR)
Fieldwork Locations
Sites from which one or more Palaeolithic lithics have been found with no recorded accuracy
Sites from which one or more Palaeolithic lithics have been found within 10 m of the Grid Reference
Sites from which one or more Palaeolithic lithics have been found within 100 m of the Grid Reference
Sites from which one or more Palaeolithic lithics have been found within 1 km of the Grid Reference
Image generated using copyright data: DEM generated from IFSAR data purchased from Bluesky under licence to L Basell, PROSWEB. Superficial Geological Deposits purchased from British Geological Survey under licence to L Basell PROSWEB, Licence Numbers: 2005/089 & 2006/005. Palaeolithic Findspots, made available by F. Griffith from Devon SMR

Fig 4



Clay
Silt
Fine Sand
Medium Sand
Coarse Sand
Grit
Fine Gravel
Medium Gravel
Coarse Gravel
Boulder
74
73
72
71
70
69
68
67
66
65
64
63
62
61
60
59
58
Approximate metres O.D.
Topsoil
A
B
C
D
HD4
HD1
HD2
HD3
B
Tributary
River Axe
A
D
C
Bedrock
Scale
10m
10m
Sediment Complexes
A Floodplain, Holocene
B Slope - periglacial
C Tributary
D Main valley terrace
Clay
Silt
Sand
Clay drape
Diffuse boundary
Framework Gravel
Bifaces
Sarsens
Frost Crack
Weathered Charmouth Mudstone, Gravel, Sand, Silt, & Clay
Charmouth Mudstone

Fig 5

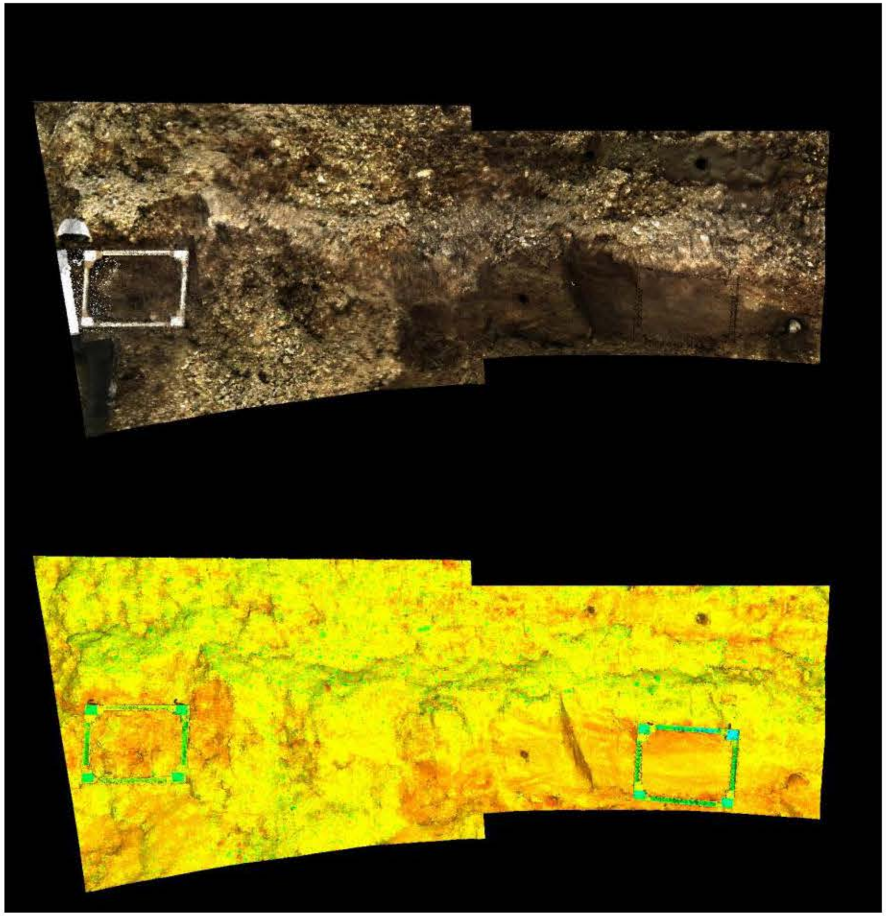


Fig 6

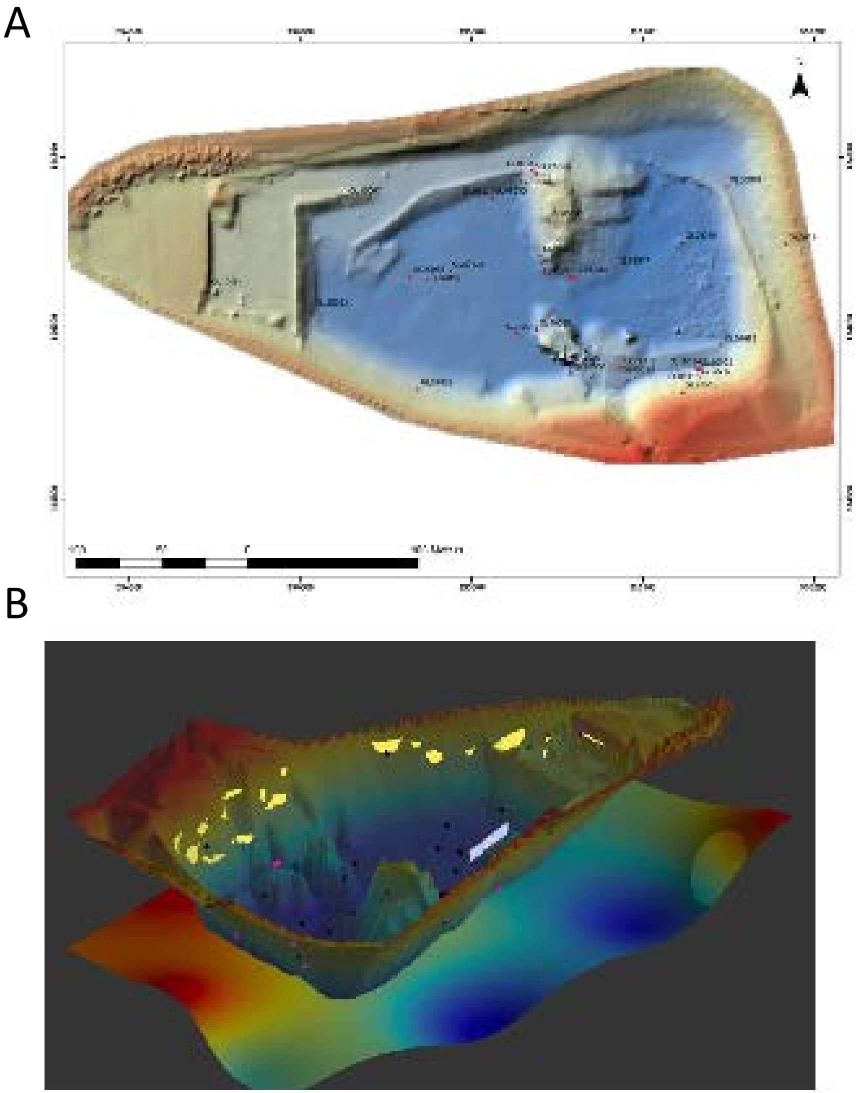
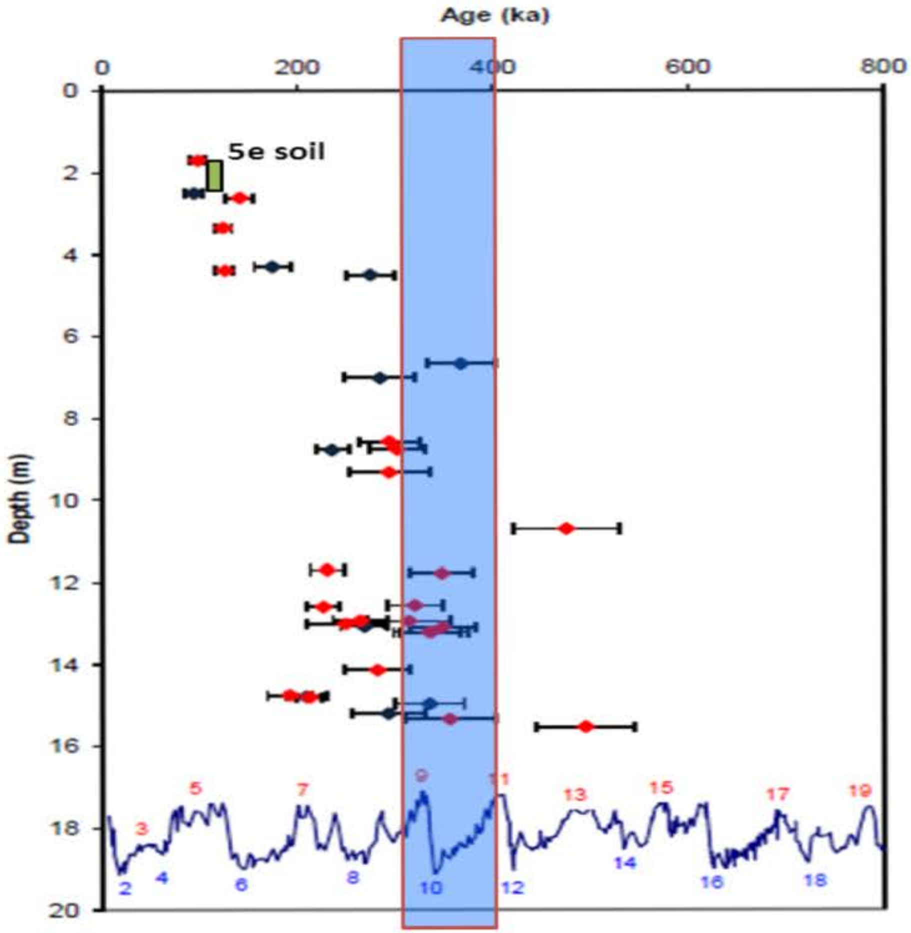
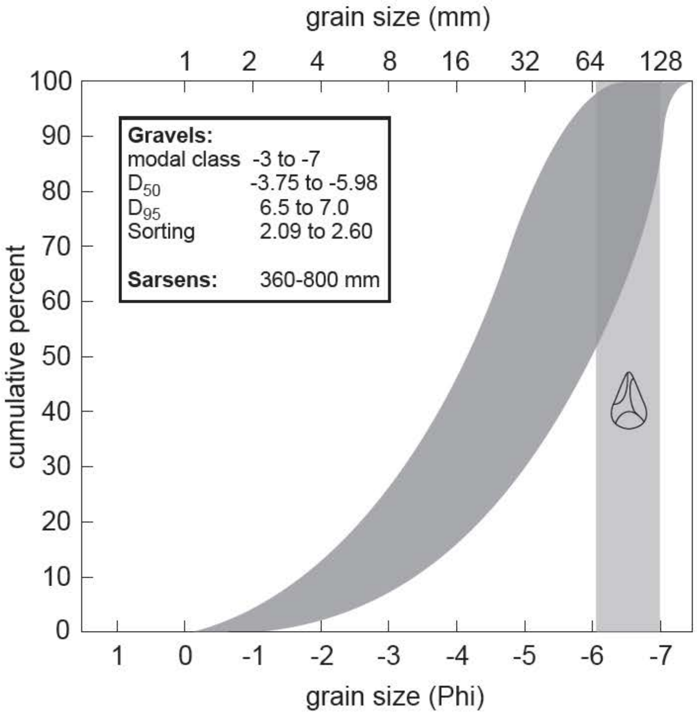


Fig 7



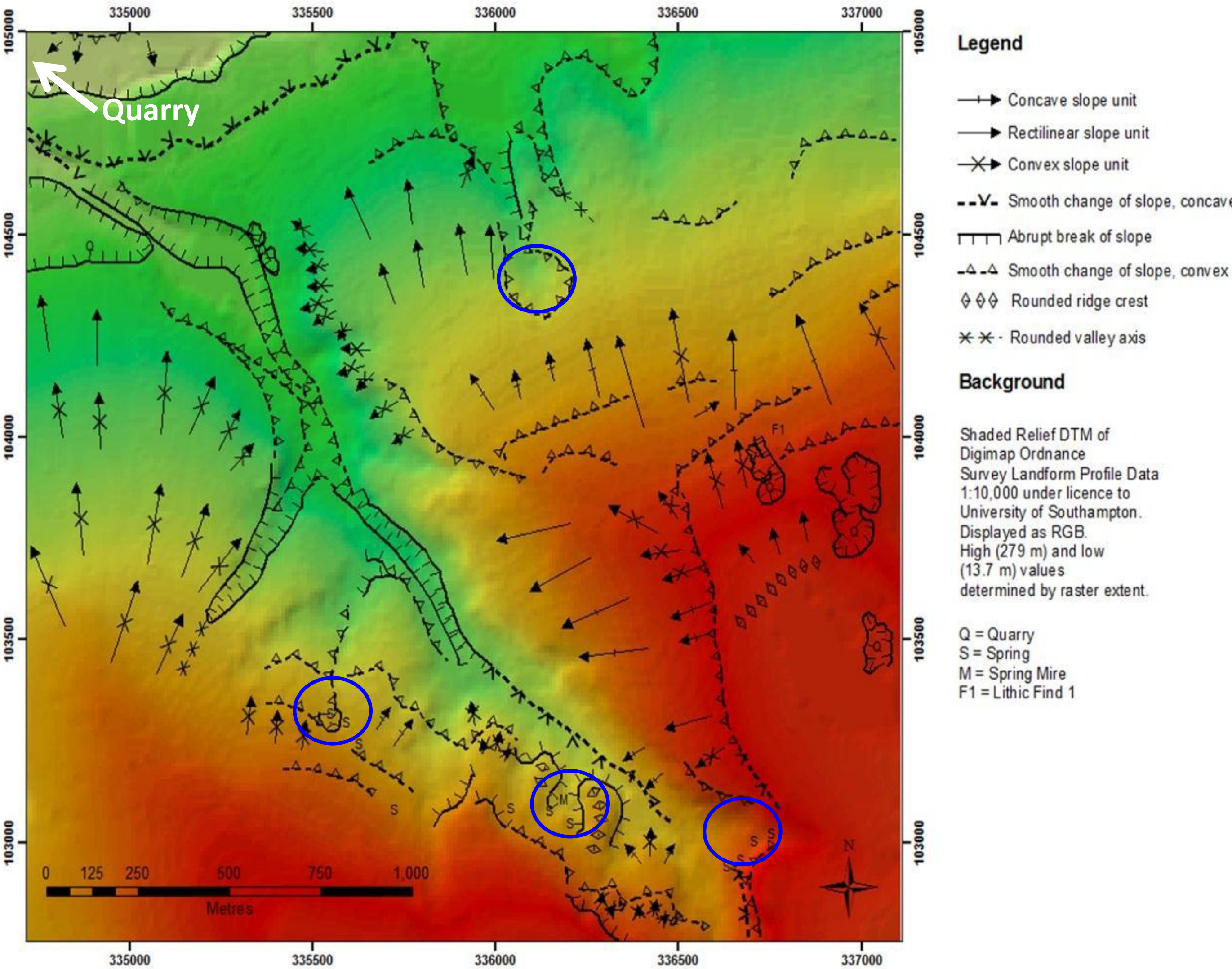
Age (ka)
0
200
400
600
800
5e soil
Depth (m)
0
2
4
6
8
10
12
14
16
18
20
3
5
7
9
11
13
15
17
19
2
4
6
8
10
12
14
16
18

Fig 8



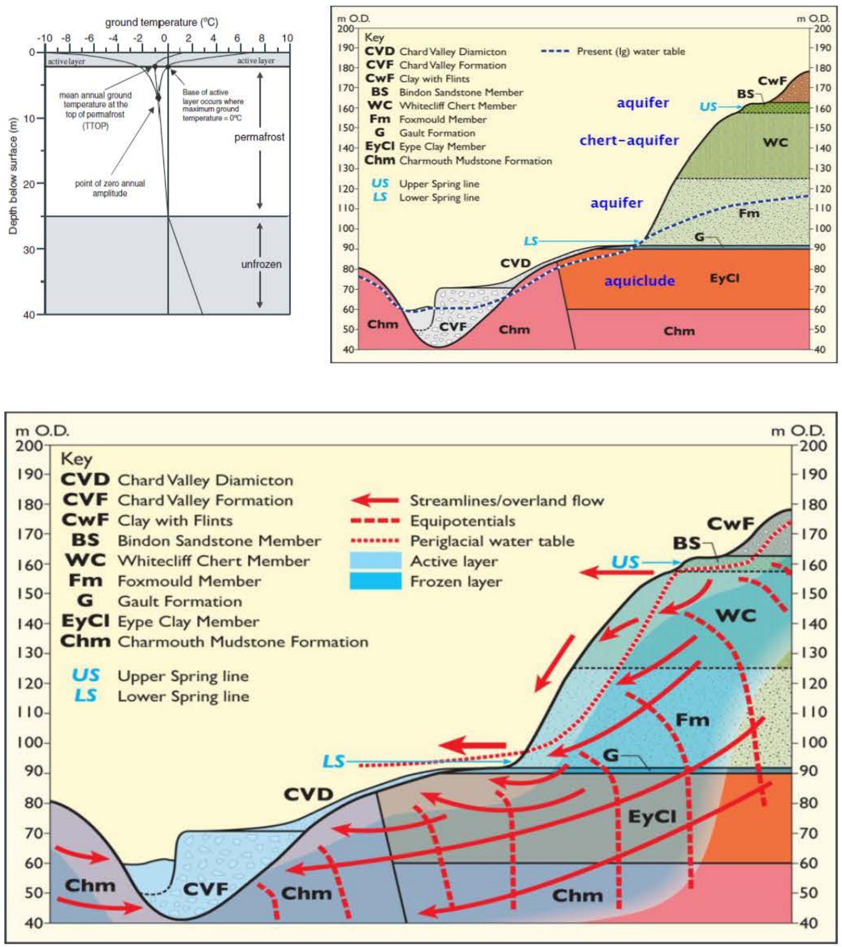
grain size (mm)
1
2
4
8
16
32
64
128
100
90
80
70
60
50
40
30
20
10
0
cumulative percent
Gravels:
modal class -3 to -7
D50 -3.75 to -5.98
D95 6.5 to 7.0
Sorting 2.09 to 2.60
Sarsens: 360-800 mm
1
0
-1
-2
-3
-4
-5
-6
-7
grain size (Phi)

Fig 9



Quarry
335000
335500
336000
336500
337000
105000
104500
104000
103500
103000
F1
0 125 250 500 750 1,000
Metres
N
Legend
Concave slope unit
Rectilinear slope unit
Convex slope unit
Smooth change of slope, concave
Abrupt break of slope
Smooth change of slope, convex
Rounded ridge crest
Rounded valley axis
Background
Shaded Relief DTM of Digimap Ordnance Survey Landform Profile Data 1:10,000 under licence to University of Southampton. Displayed as RGB. High (279 m) and low (13.7 m) values determined by raster extent.
Q = Quarry
S = Spring
M = Spring Mire
F1 = Lithic Find 1

Fig 10


ground temperature (°C)
Depth below surface (m)
active layer
mean annual ground temperature at the top of permafrost (TTOP)
Base of active layer occurs where maximum ground temperature = 0°C
point of zero annual amplitude
permafrost
unfrozen
m O.D.
Key
CVD Chard Valley Diamicton
CVF Chard Valley Formation
CwF Clay with Flints
BS Bindon Sandstone Member
WC Whitecliff Chert Member
Fm Foxmould Member
G Gault Formation
EyCl Eype Clay Member
Chm Charmouth Mudstone Formation
US Upper Spring line
LS Lower Spring line
Present (Ig) water table
aquifer
chert-aquifer
aquifer
aquiclude
Streamlines/overland flow
Equipotentials
Periglacial water table
Active layer
Frozen layer

Lab Code	Overburden (m)	Grain size (μm)	Moisture content (%)	α D_r (Gy.ka^{-1})	β D_r (Gy.ka^{-1})	γ D_r (Gy.ka^{-1})	Cosmic D_r (Gy.ka^{-1})	$^{226}Ra/^{238}U$	Total D_r (Gy.ka^{-1})	Preheat (°C for 10s)	D_e (Gy)	Age (ka)
GL06010	4.3	125-180	16 ± 4	-	1.09 ± 0.10	0.34 ± 0.02	0.11 ± 0.01	1.25 ± 0.27	1.54 ± 0.10	240	268.5 ± 22.0	174 ± 18 (16)
GL06011	2.5	125-180	13 ± 3	-	0.53 ± 0.04	0.29 ± 0.01	0.14 ± 0.01	0.76 ± 0.12	0.96 ± 0.05	260	90.2 ± 6.8	94 ± 9 (7)
GL06012	1.7	125-180	14 ± 3	-	1.28 ± 0.11	0.53 ± 0.02	0.16 ± 0.02	1.07 ± 0.22	1.97 ± 0.11	260	193.7 ± 11.0	98 ± 9 (6) [a,b]
GL06013	4.5	125-180	15 ± 4	-	0.72 ± 0.07	0.26 ± 0.01	0.10 ± 0.01	0.96 ± 0.25	1.09 ± 0.07	240	298.6 ± 19.2	274 ± 25 (20)
GL06057	6.7	125-180	16 ± 4	-	0.75 ± 0.07	0.20 ± 0.01	0.08 ± 0.01	1.04 ± 0.17	1.02 ± 0.07	240	375.3 ± 24.6	367 ± 35 (29)
GL06058	7.0	125-180	15 ± 4	-	0.84 ± 0.08	0.21 ± 0.01	0.07 ± 0.01	0.78 ± 0.12	1.12 ± 0.08	280	318.3 ± 33.3	284 ± 36 (32)
GL08043	15.3	125-180	17 ± 4	-	0.54 ± 0.05	0.22 ± 0.01	0.03 ± 0.00	0.88 ± 0.16	0.80 ± 0.6	280	284.9 ± 31.9	355 ± 47 (43) [c]
GL08044	15.2	125-180	21 ± 5	-	1.22 ± 0.13	0.38 ± 0.02	0.03 ± 0.00	1.03 ± 0.14	1.63 ± 0.14	280	477.2 ± 45.1	292 ± 37 (33)
GL08045	12.9	125-180	17 ± 4	-	0.97 ± 0.09	0.26 ± 0.01	0.03 ± 0.00	0.99 ± 0.16	1.26 ± 0.10	280	332.7 ± 23.8	264 ± 28 (23) [c]
GL08046	15.0	125-180	20 ± 5	-	1.04 ± 0.11	0.48 ± 0.02	0.03 ± 0.00	1.00 ± 0.12	1.56 ± 0.11	260	521.4 ± 41.5	334 ± 36 (31)
GL08047	15.5	125-180	20 ± 5	-	1.03 ± 0.11	0.42 ± 0.02	0.03 ± 0.00	0.79 ± 0.09	1.49 ± 0.11	280	736.8 ± 51.7	494 ± 50 (43) [c,d]
GL09029	3.3	125-180	13 ± 3	-	0.54 ± 0.05	0.41 ± 0.02	0.12 ± 0.01	0.87 ± 0.16	1.07 ± 0.05	260	132.1 ± 7.0	124 ± 9 (7) [e]
GL09030	8.1	125-180	13 ± 3	-	0.53 ± 0.05	0.22 ± 0.01	0.06 ± 0.01	0.87 ± 0.22	0.82 ± 1.43	250	247.4 ± 18.9	302 ± 29 (25) [c]
GL09031	9.6	125-180	15 ± 4	-	1.09 ± 0.10	0.28 ± 0.01	0.05 ± 0.01	0.91 ± 0.12	1.43 ± 0.10	230	419.8 ± 31.7	294 ± 30 (26) [c]
GL09117	11.8	5-15	21 ± 5	0.38 ± 0.04	1.44 ± 0.14	0.81 ± 0.03	0.04 ± 0.00	1.21 ± 0.14	2.67 ± 0.15	210	928.1 ± 64.8	347 ± 31 (28) [d]
GL09118	11.7	5-15	19 ± 5	0.35 ± 0.04	1.48 ± 0.14	0.79 ± 0.03	0.04 ± 0.00	0.83 ± 0.10	2.67 ± 0.15	250	614.0 ± 30.6	230 ± 17 (14) [d]
GL09119	8.8	5-15	19 ± 5	0.35 ± 0.04	1.23 ± 0.12	0.61 ± 0.02	0.06 ± 0.01	1.07 ± 0.14	2.26 ± 0.12	260	529.9 ± 24.5	235 ± 17 (14)
GL09120	10.7	125-180	8 ± 2	-	0.59 ± 0.04	0.24 ± 0.01	0.05 ± 0.00	0.90 ± 0.16	0.88 ± 0.05	240	419.1 ± 41.5	475 ± 53 (48) [e]
GL10001	2.6	180-250	9 ± 2	-	0.57 ± 0.04	0.46 ± 0.02	0.14 ± 0.01	0.88 ± 0.14	1.17 ± 0.05	280	164.9 ± 15.6	141 ± 14 (14)[b]
GL10002	13.1	180-250	13 ± 3	-	0.51 ± 0.05	0.31 ± 0.02	0.04 ± 0.00	1.05 ± 0.24	0.86 ± 0.05	240	229.4 ± 16.2	268 ± 25 (21)
GL10013	13.1	125-180	21 ± 5	-	0.50 ± 0.05	0.27 ± 0.01	0.04 ± 0.00	0.96 ± 0.30	0.80 ± 0.06	240	279.4 ± 18.0	348 ± 34 (14) [c]
GL10014	12.9	125-180	12 ± 3	-	0.56 ± 0.05	0.31 ± 0.02	0.04 ± 0.00	0.97 ± 0.25	0.91 ± 0.05	260	284.4 ± 34.1	313 ± 42 (21) [b]
GL10015	14.7	125-180	16 ± 4	-	1.02 ± 0.10	0.50 ± 0.02	0.03 ± 0.00	1.13 ± 0.16	1.55 ± 0.10	260	298.3 ± 30.2	192 ± 23 (40) [b]
GL10016	14.8	125-180	18 ± 4	-	0.84 ± 0.08	0.37 ± 0.02	0.03 ± 0.00	0.98 ± 0.13	1.24 ± 0.09	260	257.7 ± 19.0	208 ± 21 (44)
GL10019	13.0	125-180	15 ± 4	-	0.82 ± 0.08	0.20 ± 0.01	0.04 ± 0.00	0.99 ± 0.17	1.06 ± 0.08	240	262.5 ± 37.9	249 ± 40 (38) [c]
GL10020	14.1	125-180	15 ± 4	-	0.92 ± 0.08	0.35 ± 0.02	0.03 ± 0.00	0.93 ± 0.12	1.30 ± 0.09	240	366.8 ± 37.2	281 ± 34 (31) [b,c]
GL10055	13.2	125-180	6 ± 2	-	0.52 ± 0.04	0.28 ± 0.01	0.04 ± 0.00	-	0.84 ± 0.04	260	281.7 ± 21.2	335 ± 31 (26) [b]
GL10063	12.6	125-180	19 ± 5	0.32 ± 0.04	1.33 ± 0.13	0.17 ± 0.01	0.04 ± 0.00	0.98 ± 0.12	1.85 ± 0.13	240	592.7 ± 38.5	320 ± 31 (27)
GL10064	14.8	125-180	11 ± 3	-	0.56 ± 0.05	0.26 ± 0.01	0.03 ± 0.00	0.95 ± 0.24	0.85 ± 0.05	240	180.4 ± 9.5	212 ± 17 (13) [c]
GL10065	12.6	125-180	17 ± 4	-	0.78 ± 0.08	0.41 ± 0.02	0.04 ± 0.00	0.98 ± 0.19	1.24 ± 0.08	240	280.0 ± 17.5	226 ± 20 (17) [c]
GL10066	13.2	125-180	17 ± 4	-	1.11 ± 0.12	0.72 ± 0.08	0.04 ± 0.00	1.17 ± 0.16	1.87 ± 0.15	240	627.2 ± 58.1	336 ± 42 (38) [a,d]
GL10067	9.3	125-180	17 ± 4	-	0.98 ± 0.09	0.27 ± 0.01	0.06 ± 0.01	1.01 ± 0.16	1.31 ± 0.10	240	384.8 ± 50.1	293 ± 44 (41) [c]
GL10084	4.4	125-180	19 ± 5	-	0.62 ± 0.05	0.49 ± 0.02	0.10 ± 0.01	1.01 ± 0.16	1.21 ± 0.06	240	152.1 ± 10.4	126 ± 11 (9) [a]

Analytical Caveats: [a]Significant feldspar contamination, [b]Failed dose recovery test, [c]Failed repeat dose ratio test, [d]D_e exceeds 600 Gy, [e]Potential partial bleaching, [f]Limited sample mass