3. METHODOLOGY

3.1 INTRODUCTION

3.1.1 This project was designed to bring together geomorphological, palaeoenvironmental and archaeological expertise to produce an integrated model of the potential for archaeology, the present and future threat from fluvial change, and the suitability of the substrata for extraction in the Ribble Valley. The techniques used have included traditional desk-based data gathering, archaeological and geological fieldwork, geostatistical and spatial analysis, and geospatial modelling.

3.1.2 Previous projects have used some, but not all, of the techniques described (notably the Lynher Valley project (Cornwall Archaeology Unit 2002)). Assessment of the success of the methodologies has been a important element of the project, since some of the techniques did not prove to be successful, or did not produce usable results (see *Sections 4.1-3*).

3.2 STRUCTURAL OVERVIEW OF THE GIS

3.2.1 Initially, separate GIS systems were constructed for the archaeological and geological aspects of the project; but both were constructed in ArcGIS 9.0 to maintain full compatibility. In the data gathering phase of the project, the datasets were constructed separately, but in the analytical phases theSE were combined into a single geodatabase, compatible with Microsoft Access 97. This format allows the spatial data normally held in a shape file, and the attribute data normally held in a database table, to be combined into a single Feature Class. By incorporating the geomorphological, environmental and archaeological datasets into the same geodatabase, they could be interrogated and analysed together, and distributed as a single combined file rather than separately.

3.2.2 The datasets included in the geodatabase are described in Table 1, and the flow diagram describing the process of constructing these feature classes is shown in Figure 28.

Feature class	Data type	Features included
Archaeological Events	Points	All archaeological interventions such as excavations, watching briefs and so on
Archaeological Events	Polygons	The actual extent of all archaeological interventions, where available
Archaeological Monuments	Points	All archaeological features within the study area
Archaeological Monuments	Polygons	The actual extent of all archaeological features, where available
Enhanced Historic Landscape Characterisation	Polygons	Quantity and density of archaeological events and monuments within each polygon
Potential for prehistoric Activity	Polygons	Areas of high, medium and low potential for activity
Potential for Roman Activity	Polygons	Areas of high, medium and low potential for activity
Potential for medieval Activity	Polygons	Areas of high, medium and low potential for activity
Palaeoenvironmental Events	Points	All palaeoenvironmental work within the study area such as boreholes, coring and so on
Palaeoenvironmental Monuments	Points	Data resulting from palaeoenvironmental events, such as radiocarbon dates and so on

Feature class	Data type	Features included
Glacial Landforms	Polygon	Moraine ridges, drumlins, deltas, kettle basins, sandur flats
Glacial Lines	Lines	Channels, ridge crests, ice-flow directions, ice divides
Glacial Point Features	Points	Mound summits, section locations
River Terraces	Polygons	River terraces, alluvial fan surfaces
Fluvial Lines	Lines	Palaeochannels
Fluvial Points	Points	Core sites, section sites
Potential for Present Fluvial Change	Polygons	
Potential for Future Fluvial Change	Polygons	
Suitability for Aggregate Extraction	Polygons	

Table 1: Datasets included in the Ribble ALSF project geodatabase

3.3 CHARACTERISING THE GEOLOGICAL AND GEOMORPHOLOGICAL RESOURCE

3.3.1 ***Previous Research and Investigations:*** prior to this project, knowledge of the Quaternary geology and geomorphology of the Ribble Valley was patchy and of variable quality. Mapping of the drift geology by the British Geological Survey (BGS) has resulted in five 1:50,000 sheets (Fig 29), only two of which are recent revisions, Garstang (BGS 1990) and Settle (BGS 1991). The other sheets, Rochdale (BGS 1974), Preston (BGS 1982) and Clitheroe (BGS 1975), are more dated, and there is considerable difference in nomenclature and detail between the sheets. The BGS are in the process of revising the Preston sheet, and the present project will contribute directly to that revision (AJ Humpage and RG Crofts (BGS) *pers comm*).

3.3.2 Further data on the Quaternary geology were available from research investigating the sand and gravel reserves within Lancashire. Three reports have been commissioned by Lancashire County Council's (LCC) Minerals and Waste Group. The first was a Department of the Environment-commissioned report (*Sand and Gravel Resources of Lancashire* (Allot and Lomax Ltd 1990)) and the second was by Entec UK Ltd (2005) in partnership with the British Geological Survey (BGS). The general consensus (LCC and Minerals' Operators) was that the Entec report represented a helpful start and provided a better identification of potential targets for high-grade sand and gravel deposits than the Allot and Lomax report. Few of the areas identified in the Entec report have been assessed using borehole investigations to test the quality of the resource available, and were identified solely on the basis of the available data. As it stood there was a paucity of high-quality published information relating to Lancashire's sand and gravel geology and resources, and what did exist was largely underpinned by the BGS mapping (Fig 30). A third report, commissioned by LCC from Geoplan Ltd (2006), provided a more targeted and detailed investigation with an assessment of mineral quality. The Geoplan Ltd study drew upon a wider range of sources, including some confidential, and whilst focusing on study areas delimited during the Entec study (Fig 31) had a wider brief to look at new areas for which there was extant geological data. The Geoplan and Entec reports were the best available assessment of sand and gravel aggregate reserves within Lancashire. Further information about the late Quaternary evolution of the Lower Ribble

Valley was available from the PhD research by Bernardo Chiti at the University of Stirling (Chiti 2004).

3.3.3 The BGS mapping varies in precision between map sheets; it identified a maximum of three river terraces (Fig 32), but their location, extent and the consistency of nomenclature between map sheets were difficult to gauge. Chiti (2004) on the other hand mapped in some detail a comparatively short reach between Preston and Ribchester (Fig 33), and identified four river terraces and the modern floodplain. Chiti (2004) supported his mapping of the geomorphology with some detailed stratigraphic investigation, accurate height-range correlation between terraces, some geochronological control, and palaeoenvironmental investigation. The research by Chiti and the BGS was a starting ground for investigation of the fluvial geomorphology presented in this report. Digital copies of the BGS 1:50,000 series (LCC licence) and Entec Sand and Gravel Study digital data were obtained, whereas the maps presented in Chiti (2004) were digitised from a paper copy.

3.3.4 Boreholes clearly provided the ready means of confirming the geology depicted on published maps and they contributed significantly to the identification of potential aggregate resources. The BGS holds copies of all deposited borehole records at their national headquarters and summary data, including borehole number, location and depth, are available on their website (www.bgs.ac.uk). This facility provided a useful first search capability for identifying boreholes of use in this project and over 8000 boreholes were originally identified in the area of the Ribble catchment. This number was reduced considerably by firstly filtering out all the boreholes that were not in areas underlain by potential aggregate groups (principally glacial sand and gravel and alluvium). A second filter was then applied that excluded all boreholes of less than 5m depth (the minimum commercially useful thickness of potential aggregate resources) and those identified as confidential. Further filtering was applied based, on the selective sampling of boreholes in areas (such as motorway developments) where the very close spacing of boreholes contained redundancy. Together this was able to reduce the number of boreholes to only 600. To date, some 250 of these boreholes have been catalogued from BGS records, mainly in aggregate priority areas in the Lower Ribble Valley (Fig 34). Further boreholes were available for the drift plain to the north of the Ribble, which also has considerable potential for sand and gravel production. In this project the aim of the borehole analysis was to construct, where distribution and density permitted, two- or three-dimensional models of aggregate distribution in order to assess the potential resources.

3.4 INTERROGATION OF REMOTELY SENSED DATA

3.4.1 ***Introduction:*** the principal aim of geomorphological mapping as a tool for sand and gravel survey was to identify by rapid, accurate and cost effective means, and to delimit and characterise the potential reserves of aggregate. Conventionally, geomorphological mapping has been a field exercise, recording the location and dimensions of landforms onto base maps of varying scales (typically 1:10,000). Geomorphologists have long made use of available technologies, with aerial photography, particularly where stereoscopic coverage was available, being invaluable for desk-based recognisance of landscapes and landforms. The routine use of Geographical Information Systems (GIS) and parallel developments in remotely-sensed accurate digital elevation models (DEM) has radically altered the approach of the geomorphologist. Smith *et al* (2006) have reviewed the comparative merits of a set of various remotely sensed data in discerning the geomorphology of glacierised terrain in central Scotland. They found, through comparison against conventional field mapping, that Light Detection and Ranging (LiDAR) imagery appeared extremely reliable, although only a limited dataset was available. NextMAP Great Britain™ performed well, and the lower resolution Ordnance Survey products (OS Profile® and OS Panorama®) performed poorly. In this project, the value of LiDAR, NextMAP and OS Profile have been assessed for a broader range of geomorphic settings, both fluvial and glacial, as has the role of these data sources in identifying, characterising and quantifying potential reserves of sand and gravel.

3.4.2 ***Data Sources***: three types of remotely sensed data are utilised in this report. LiDAR data were available for all of the Ribble Valley catchment with the exception of the reach around Brockholes, from Sunderland Hall and the M6 motorway. The LiDAR data were generated using an airborne laser to measure the distance between the aircraft and the ground, and was provided by the Environment Agency. The data were collected with the principal aim of generating cost-effective terrain maps suitable for assessing flood risk, and have a spatial resolution of 2 x 2m and vertical accuracy of *c*0.15m. The data were supplied in three forms: the first as a raw unprocessed surface; the second as a surface corrected for buildings and vegetation; and a third showing the residuals between the first and second surfaces. The relatively fine spatial scale (*c*2 x 2m) means that LiDAR can penetrate vegetation canopies, more so during winter conditions (Dowman *et al* 2003; Smith *et al* 2006), which improve the accuracy of the bare ground correction.

3.4.3 NextMAP is a digital terrain model produced by Intermap Technologies and commissioned by Norwich Union Insurance to assist with flood risk mapping. NextMAP data were also generated by airborne survey using synthetic aperture radar (SAR), and employed single-pass interferometry (IfSAR) (Dowman *et al* 2003; Smith *et al* 2006). The principal differences between LiDAR and NextMAP digital elevation data were the flight height in the survey methodology: 800m for LiDAR and *c*6500m for IfSAR, with accordingly the lower precision and accuracy of the NextMAP data having a 5 x 5m spatial precision and a 0.5-1m vertical accuracy (Dowman *et al* 2003). However, the NextMAP methodology is more cost effective, and there is comprehensive coverage for the United Kingdom, whereas there is currently only *c*60,000 km^2 of LiDAR coverage. NextMAP includes two data products: the raw IfSAR product (DSM) which records all ground surface features, including buildings and vegetation; and a product corrected to produce a bare ground model (DTM). Dowman *et al* (2003) and Smith *et al* (2006) highlight two further limitations to NextMAP data; the first is that it struggles to penetrate vegetation canopies, and secondly, there is a shadow effect behind tall structures, vegetation and landforms. Both LiDAR and NextMAP data appear to perform better in flatter rural terrain that is not forested (Dowman *et al* 2003; Smith *et al* 2006).

3.4.4 The next best available national scale DEM is the Ordnance Survey (OS) Profile® dataset, which is a contour-based dataset compiled by stereo-interpretation of aerial photographs over many years since the 1980s. Problems with OS Profile stem from gaps owing to labels on maps and absence of contours around anthropogenic features, and from smoothing during cartographic presentation and digitisation (Dowman *et al* 2003). However, the OS Profile DEM has a spatial resolution of 10 x 10m and vertical accuracy of *c* ±5m. Smith *et al* (2006) suggested that the OS Profile performed badly in geomorphic research identifying and delimiting the extent of drumlins.

3.4.5 None of the poorer-resolution datasets available, for example OS Panorama data, have been used in this project; Smith *et al* (2006) have reviewed the relative merits of a wider range of remotely sensed data sources. For the geomorphological mapping, the LiDAR and NextMAP products have been used, mainly the 'bare ground' version. The specifications, limitations and availability of the data sources for the three case studies are listed in Table 2.

	Spatial Resolution	**Vertical precision**	**Acquisition date**	**Cors Geirch**	**Rhosesmor**	**Ribble Valley**
Field mapping	20m	N/A	Various	Yes	Yes	Yes
Digital elevation models						
LiDAR (Environment Agency)	2m	~ 150-250mm	2003	No	No	Yes
NextMAP GB ™	5m	~ 500mm	2002	Yes	Yes	Yes
OS Profile ®	10m	~ 5000 mm	Maintained	Yes	Yes	Yes

Table 2: Data sources for geomorphic mapping and aggregate assessment

3.4.6 ***Test Case study area 1: a small esker ridge near Clitheroe***: Figure 35 a-d, shows LiDAR, NextMAP Great Britain™ and OS Profile® data for this test locality, a small (90 x 800m) ridge north of Clitheroe, in the Ribble Valley. The DEMs shown in Figure 35 are equivalently colour-scaled for altitudes between 50m and 130m OD, using a light-dark-light colour gradation to highlight morphology within the defined height range. Comparison of the three DEMs shows that they all are capable of identifying the presence of the ridge, which has a protruding altitude of 8-16m. Discerning the presence of features in remotely sensed data in no way lessens the need for field mapping, except that the process becomes more of a truthing exercise. Discerning the nature of the ridge was also the domain of the fieldworker, where a limited exposure of fluvially rounded gravel and a sandy matrix, discerned from animal burrows and plough-marks, alongside the well-drained and lush-grassed character of the land surface, contrasted with the surrounding lower, flatter, poorly drained diamict plain; this indicated that the feature was an esker. Although the breaks in slope surrounding the ridge can easily be identified in all three digital products, accuracy and precision improve incrementally with the NextMAP (Fig 35b) and LiDAR data (Fig 35c). The identification of morphometric outline was assisted by careful manipulation of the DEM to generate an appropriately coloured and height-ranged elevation surface, closely spaced contour vector data (1000mm), and slope-angle raster surfaces, all of which help to highlight and delimit the edges of geomorphic features (Fig 35d).

3.4.7 OS Profile data allowed mapping of a broad general outline for the landform (Fig 35a), exemplified by the contouring generated for this dataset. The contours are at 2.5m intervals, which is already double the claimed precision of the product, and display a 'stepped lineation' that is a function of the raster resolution (10 x 10m). Nevertheless OS Profile provides a reasonable approximation of a landform. The NextMAP and LiDAR products, at the scale of conventional geomorphic mapping (1:2500 to 1:10,000), display fewer signs of generalisation and appear to portray the morphology of the ridge-form accurately. Furthermore, comparison of the degree of capture of drainage patterns in the surrounding lowlands highlights the value of increased vertical accuracy and spatial precision in the LiDAR data, which are capable of discerning both the detail of morphological form and the character of smaller and lower relief features.

3.4.8 ***Test Case study area 2: a restricted fluvial reach in the Lower Ribble Valley***: the first case study focused upon features with a marked differential in relief, but in Lancashire aggregate extraction has targeted river gravels deposited during both deglaciation and the Holocene, and these are within 10m of the current river level. The Lower Ribble Valley is a useful setting in which to assess the value of using the different DEM data for mapping fluvial landforms, because LiDAR (Environment Agency), NextMAP and OS Profile data are all available. Historically, aggregate extraction in the Lower Ribble Valley appears to have targeted the highest two river terraces, with extensive extraction sites near Preston, and borehole survey has confirmed that the lower three terraces were primarily composed of alluvium, with very limited gravel. The respective merits of these three DEMs for characterising the fluvial geomorphology were investigated, with an assessment of the present aggregate, and a review was made of the extent to which they distinguished features that were separated by less than 10m of relief.

3.4.9 Comparison of the three DEM products (Fig 36a-c) shows an incremental improvement from OS Profile to NextMAP, to LiDAR. The LiDAR data were clearly much superior, best exemplified by the manner in which the improved spatial resolution (2 x 2m) and vertical accuracy allows the identification of palaeochannels (Fig 36c), particularly with careful manipulation of slope-angle data derived from the LiDAR data (Fig 36d). Palaeochannels are distinguishable to a lesser extent in the NextMAP data (Fig 36b), which copes well with larger features, but less so with the series of smaller scrollbar channels on the Osbaldeston Hall meander. Representation of river terrace sequence by the OS Profile data was poor (Fig 36a), which is not unexpected given that the height-range information derived from LiDAR (Fig 36f) shows that the river terraces were only separated by 5m of relief, and the claimed accuracy of the OS Profile data is only to ±5m. Mapping and identification of terrace fragments (Fig 36e) produced identical results when undertaken independently for NextMAP and LiDAR data, although it was difficult to distinguish the boundary between Terraces 3 and 4 using the NextMAP data (Fig 36b; Fig 36e).

3.4.10 In terms of identifying sand and gravel aggregate prospects, LiDAR and, to a lesser extent, NextMAP, are useful tools for rapid desk-based mapping. However, fieldwork is still essential to truth the interpretation and check the relationship between features in critical locations. The main advantage of a LiDAR-based mapping approach is spatial accuracy and altitudinal correlation of river terrace suites, because obtaining equivalent accuracy from field survey would take a greater length of time, involve using survey equipment, and would prove less cost effective. LiDAR also shows the position of palaeochannels, where aggregate reserves are often buried by thicker accumulations of soil, laminated flood silts, and organic sediment. Combining LiDAR survey and field truthing allows the rapid delimitation of the spatial extent of aggregate prospects, which can be linked with boreholes to define accurately the prospect extent and to predict likely volumes of sand and gravel.

3.4.11 ***Mapping the Geomorphology using Digital Resources***: mapping of the geomorphology was undertaken using the LiDAR and NextMAP digital elevation datasets. The information was compiled within a spatial geodatabase using the ARCGIS software suite. The mapping made use of the capability of the GIS software for stretching elevation ranges and manipulating the display to show low amplitude landforms. Slope angle rasters were compiled to identify the edges to landforms. Contour datasets were compiled from both NextMAP and LiDAR raster datasets at sub-metre intervals (0.5-0.25m) to assist this mapping process. The geomorphology geodatabase Feature Classes are detailed in Table 1 above.

3.5 FIELDWORK: MAPPING, DRILLING, SAMPLING

3.5.1 ***Surface Landform Mapping:*** despite the advantages of high-resolution DEMs for the rapid and cost-effective production of spatially and vertically accurate maps, the morphological complexity of the river–floodplain landscape often imposes severe limitations on the interpretative capability of the remote sensing approach. Interpretative problems in DEM mapping may arise, for example, in differentiating between complex palaeochannel configurations and terrace levels, or between anthropogenically and naturally formed surface morphologies. Additional problems may arise where derived 'ground surface' DEMs involve elevation errors due to tree or building coverage. Therefore, field mapping surveys represent a necessary second stage of mapping in order to 'ground truth' and improve upon the results of the DEM desk-based study.

3.5.2 Field mapping was carried out within all detailed study reaches (including Test Case study areas 1 and 2) and at other locations for which uncertainty existed in the landform interpretation arising from the DEM mapping. Hard-copy DEM-based maps of terrace boundaries and palaeochannels were plotted on a background consisting of surface elevation, contours (0.5m intervals), slope angle and OS 1:25,000 base maps. Wherever possible, terrace edge and palaeochannel maps were modified by hand in the field. However, more complex examples of newly identified landforms were mapped using a hand-held GPS, particularly where the LiDAR coverage was lacking. All alterations compiled on the field maps formed the basis for editing the glacial landform (esker, delta, moraine ridge), glacial lines features (ridge crests, erosional channels, slope breaks), river terrace and palaeochannel layers that comprise the integrated Ribble Valley geomorphology geodatabase.

3.5.3 ***Sub–surface Sedimentology and Sampling***: sub-surface sediment sequences were investigated by coring in order to gather information on river–floodplain evolution (Fig 37) or at channel bank exposures (Fig 38). Fluvial reconstructions were based primarily on established deposit/process models, for example: (1) clast–supported rounded gravels (resultant from active channel bed deposition);

(2) graded fine gravel/sand beds (resultant from high-energy overbank flood events); (3) stratified to bedded sands (reflecting braided channel/bar systems); and (4) finely laminated silts and clays (resultant from low-energy overbank flood events). Evidence from organic remains (ie root casts, mottling, leaf, wood, shells and seed remains, soil and peat horizons) was used to provide additional information on prevailing local/regional environmental conditions (ie climate, land use, hydrology, ecology) that were operating at the time of deposition.

3.5.4 In the absence of available channel bank sections, floodplain coring was carried out using a Van Walt percussion corer (100mm and 60mm bore, open barrel) capable of penetrating up to 10m below the land surface (Fig 37). Wherever possible, cores were taken from mapped palaeochannel depressions, since these provided a focus for sediment deposition, and often contain abundant flood-transported and *in situ* organic remains suitable for radiocarbon dating (*Section 3.7.18*). It was aimed to obtain sub–surface sedimentological data from a minimum of one core/bank section from each river terrace level that had been identified within each study reach.

3.5.5 Bank section and core sediments were photographed and observations made regarding sediment structure and bedding units, colour, grain size distribution, water content and cohesiveness, organic content, fossil remains and bioturbation. The resulting depth stratigraphic data were used to construct generalised vertical sequence logs, an example of which is shown in Figure 39.

3.5.6 Bulk sediment samples were taken from each major sediment unit (approximately one sample per 0.5m depth) as a basis for later physical and geochemical analyses underpinning sediment provenance studies and for identifying aggregate-potential. A few peat sequences were sampled contiguously at high-resolution (20mm thick) intervals in order to underpin future palaeobotanical reconstruction. Organic macrofossils and bulk organic material from key stratigraphic change locations (for example, the contact between channel gravels and overlying fine-grained fill; base and top of peat; switch from low-energy flood laminae to high-energy flood beds) were sampled for subsequent radiocarbon dating (*Section 3.7.18*).

3.5.7 All core/bank sections were located with an accuracy of ± 5m using a hand-held GPS system, and coordinates were transferred into a Cores profiles layer within the Ribble geodatabase. The following attribute data were attached to the layer:

- site identification code (text);
- digital photograph(s) (link to graphic image);
- stratigraphic logs (link to graphic image);
- sampling information (text);
- radiocarbon dating (text).

3.6 Outline of Approach to the Geomorphic Analysis

3.6.1 The analysis of the geomorphology focused on two aspects:

- providing an enhanced assessment of the sand and gravel deposits;

- improving understanding of the fluvial and glacial history.

3.6.2 The detailed methodology of providing an enhanced aggregate assessment is detailed in *Sections 3.3-5*. The glacial history of the Ribble and lowland Lancashire has received scant attention over the last 50 years, and so the data compiled and reviewed in this project were discussed in the context of current thinking about the deglaciation of Britain at the end of the Devensian Ice Age (*Section 2.2.3*). The analysis focused on the nature and timing of deglaciation, direct evidence for ice-marginal limits, ice-flow directions and the impacts of the differing ice-streams of the British and Irish Ice-sheet.

3.6.3 The Holocene fluvial history over the last 11,500 years reflects a complex interplay of factors including: (i) human-mediated; (ii) climate-induced; (iii) storm-driven; (iv) changes in base-level (sea-level); and (v) filtering by internal system dynamics. These combine to control the sediment yield and transmission within the catchment. This project has contributed to an enhanced understanding of the history of the fluvial development of the Ribble, and particularly with the geochronological programme (*Section 3.7*); this history has been set with respect to the key forcing factors that drive or modulate the sediment transmission of the river system.

3.6.4 Impacts of climate change on fluvial development have been assessed using available proxy evidence for changing climate within the region, particularly bog-surface wetness information, derived from the stratigraphy of the region's peat bogs (Chiverrell 2001). There are no reliable and independent archives of long-term storm frequency to assess the impact of high-magnitude events, but nevertheless the implications of storm-driven changes in the fluvial system were assessed.

3.6.5 The Ribble is in the region affected by glaciation during the Devensian, and so the basin underwent a degree of glacio-isostatic depression (Tooley 1978; Shennan *et al* 2006). The impact of the changing relative sea level during the Post-Glacial period is important as this altered the base level to which the Ribble graded, and thus would impact on cycles of incision and aggradation. The fluvial record has been compared to reconstructions of sea-level history for the region (Tooley 1978; Shennan *et al* 2006).

3.7 Geochronology: Optically Stimulated Luminescence (OSL) and Radiocarbon Dating

3.7.1 ***Introduction***: the main objective of the radiocarbon and luminescence dating programmes was to secure the chronological framework for the glacial, fluvial and hillslope geomorphology, and to provide preliminary chronological control for potential palaeoecological sites within the Ribble catchment. The most significant advance arising from this programme would be a comprehensive understanding of the late Devensian and Holocene evolution of the Ribble. The radiocarbon dating programme was subject to approval and funding from the English Heritage Radiocarbon Dating Advisory Service and the English Heritage radiocarbon dating advisors, Derek Hamilton and Peter Marshall, approved two tranches of radiocarbon dates. The assemblage of samples selected for radiocarbon dating comprised an integrated geochronological package with ten OSL samples, and addressed the core aims of the project; the OSL dating was undertaken at the OSL facility in the Department of Geography, University of Liverpool. In the case of the OSL dating, considerable difficulties were encountered during the dating programme that have proven insurmountable, and so the full experimental procedures and testing that were undertaken are detailed to advance this approach. Recommendations for the advisability of, and a methodological protocol for, OSL dating of sediments of similarly provenanced and depositional environments are also made. The rationale for field sampling, sample selection, preparation and subsequent data analysis for the radiocarbon dating is also detailed, with the radiocarbon dating results presented in context (*see Section 5.2*).

3.7.2 ***Optically Stimulated Luminescence (OSL) of fluvial deposits from the Ribble catchment - Sampling locations***: samples were collected by hammering opaque plastic tubes into the sediments on freshly cleaned outcrop faces (Fig 40) or by drilling with a percussion corer using opaque steel tubes. The tubes were recovered and immediately sealed in opaque plastic bags. Care was taken to sample only sediment layers of sufficient thickness for a homogeneous g-dose rate, and showing no signs of post-depositional changes (bioturbation, soil formation, reduction or oxidation processes). For each luminescence sample, an additional sample was taken to determine water content and radionuclide concentrations. All samples and sampling locations are listed in Table 3.

	Field code	**Laboratory code**	**Grain size for OSL (μm)**	**Details**	**Grid ref**
1	CHEW	LV213	250-300	Chew Mill (Calder). Dug out section within well-sorted flood sands 1.5-2.0m below terrace surface	SD 720 362
2	C Bank	LV214	250-300	Calder Bank Section. Flood sand layer within upper channel fill sequence	SD 721 362
3	Morton	LV215	100-300	Morton Hall Section. Well-sorted sand. Back bar within very coarse fluvial gravel terrace	SD 739 344
4	Whalley	LV216	210-300	Whalley highest terrace: well-sorted sands overlying probable laminated lacustrine muds and diamict. Sample 3-4m below surface in degraded road-cut section. Coversands?	SD 739 360
5	Brock 1	LV217	250-300	Higher Brockholes: quarry section flood-laminated sands *c* 2.5m below surface (sampled in large metal tube)	SD 585 311
6	Brock 2	LV218	250-300	Higher Brockholes: quarry section flood-laminated sands *c* 3m below surface and 0.5m above gravel (sampled in plastic tube)	SD 584 310
7	Cross 1	LV219	250-300	Cross Gill Farm: Delta section, lower sample coarse sands	SD 695 378
8	Cross 2	LV220	250-300	Cross Gill Farm: Delta section, upper sample fine sand and silts	SD 695 378
9	OSB T1	LV221	250-300	Osbaldeston Hall, Terrace, bank section, *c* 1.5m beneath terrace surface	SD 641 345
10	OSB T2 U	LV222	250-300	Osbaldeston Hall, Terrace 2, bank section, upper sample *c* 1.15m beneath terrace surface	SD 638 347
11	OSB T2 M	LV223	250-300	Osbaldeston Hall: Terrace 2, bank section, upper sample *c* 1.8m beneath	SD 638 347

	Field code	Laboratory code	Grain size for OSL (μm)	Details	Grid ref
				terrace surface	
12	OSB T2 B	LV224	250-300	Osbaldeston Hall: Terrace 2, bank section, upper sample *c* 2.3m beneath terrace surface	SD 638 347
13	Lower House	LV225	250-300	Lower House Farm: Terrace 1, sampled with Stitz corer, from sample depth 3-4m beneath terrace surface	SD 608 326

Table 3: Samples collected for optical dating

3.7.3 ***Sample preparation***: the majority of the fluvial sediments have a coarse-grained texture, and sample preparation took into account the dominant grain-size fraction of the sediment and the requirements for luminescence dating. Conventional techniques were applied to extract quartz grains in the size of 200–300µm from the sediment (Mauz *et al* 2002). The quartz sub-sample was subsequently etched in 48% hydrofluoric (HF) acid for 40 minutes to remove the outer alpha particle penetrated rim of the grains and to clean the grain surfaces. For all samples the yield of quartz after HF etching was small, indicating highlight-fractured quartz grains.

3.7.4 For luminescence measurement, the grains were sprinkled onto stainless steel discs coated with silicon oil. Aliquots of different sizes were produced: 4-5mm aliquots (~ 400 grains) and 1-2mm aliquots (~ 100 grains).

3.7.5 ***Equivalent dose (D_e) determination of quartz samples***: all measurements were conducted with an automated Risø TL/OSL DA-15 reader, equipped with a β-source (~ 6.8 Gy min^{-1}) using blue diodes (470Δ20 nm, delivering ~ 30 mW cm^{-2}) for stimulation, and an ultraviolet-transmitting optical filter for detection. All measurement protocols were based on a single aliquot regenerated dose protocol using the standard version (Murray and Wintle 2000) or modifications (*Section 3.7.14*).

3.7.6 ***Initial tests***: considerable difficulties were encountered with the set of reconnaissance samples (low OSL intensity and sensitivity, poor signal/noise ratios, weak fast component), and an extended series of test was employed.

3.7.7 ***Luminescence components***: all samples displayed slowly decaying OSL signals. This characteristic is commonly observed in feldspars but is also known from quartz when the fast OSL component is not dominant. The etching procedure employed in sample preparation should be sufficient to remove feldspar grains completely but may not impact on feldspar inclusions in the quartz grains. OSL signals recorded after extended infra-red stimulation still show the slow decay. There are two possible explanations: even after infra-red stimulation feldspar may emit a ultraviolet luminescence under blue-light stimulation; or the quartz is dominated by medium and slow components. Linearly-modulated OSL measurements (LM OSL; Bulur *et al* 2000) were employed for clarification (Fig 41). The results support the second hypothesis, but as a result of the low signal intensities the first hypothesis cannot be fully ruled out. Using a fitting procedure based on a multiple component function (Choi *et al* 2006) to the LM OSL data, sample LV213 was further analysed. The fitting results (Table 4) indicate that the fast component is almost absent. The OSL recorded in the first seconds of stimulation time seems to derive from an ultra-fast component which is rapidly passing into a medium component. This indicates that the quartz of this particular sample cannot be used for SAR-based optical dating.

Component	n	b	σ (cm)
1	2719±273	2.97±0.281	4.19^{-17}±4.78^{-18}
2	6676±284	0.500±0.039	7.05^{-18}±7.11^{-19}
3	13170±757	0.043±0.003	6.07^{-19}±5.74^{-20}
4	96904±9030	0.0050±0.0003	7.05^{-20}±6.18^{-21}
5	692569±13966	0.00068±0.00005	9.59^{-21}±9.34^{-22}

*Table 4: LM OSL components. Results from fitting a 5-component function to the LM-OSL curve of LV213 (each component is defined as: I=n*b*t/p*exp(-bt^2/2p, p=2000 s) with n: the initial concentration of trapped electrons; b: the detrapping probability; σ: the photoionisation cross section*

3.7.8 ***D_e tests:*** four samples were subjected to a standard SAR protocol to assess the equivalent dose (D_e). Thermal treatments included a pre-heat of 260°C/10 s and a cut-heat of 220°C. Four major problems were encountered: low luminescence sensitivity; poor response to the SAR procedure (ie poor recycling ratios); possible feldspar contamination; and thermal transfer.

3.7.9 Five samples were then given a pre-heat of 200°C/10 s and a cut-heat of 190°C in an attempt to avoid thermal transfer and improve recycling ratios. To aid the latter the size of the test dose was also increased.

3.7.10 All samples, except one (LV217), indicated that a feldspar OSL component still contaminated the quartz luminescence. As it was not feasible to subject the samples to further acid treatment, a SAR method for removing the feldspar component was employed (double SAR protocol involving infra-red stimulation; Banerjee *et al* 2001).

3.7.11 ***Pre-heat and dose recovery tests:*** two samples (LV215 and LV216) were selected for pre-heat tests using the double SAR protocol and including a high-temperature stimulation with blue LEDs at the end of each SAR cycle to prevent thermal transfer. Low sensitivity and poor recycling continued to be major problems.

3.7.12 In a further step, a combined pre-heat/dose recovery test was performed on LV215. The test results indicated that a dose could be recovered but with only a poor precision. Employing a reduced temperature for OSL stimulation (to increase signal to noise ratio) in a similar test on LV216 resulted in a ratio of recovered to given dose of 0.96 with a relative standard deviation of 10% for a pre-heat of 200°C/10s and cut-heat of 190°C. In the next step these parameters, namely double SAR, pre-heat of 200°C/10s and cut-heat of 190°C, were combined with an OSL stimulation at 110°C/20 s (to optimise signal extraction) followed by stimulation at room temperature for 40 seconds (to remove all signals before further steps in the procedure). The results of this test are listed in Table 5.

Sample	Aliquots accepted	Dose ratio	RSD %
LV213	3	0.93	3.5
LV217	3	0.98	5.7
LV218	5	0.97	9.8
LV219	4	1.05	10.3

Table 5: Results of dose recovery tests applied to six aliquots of each sample

3.7.13 ***Estimating the*** D_e: encouraged by the results of the dose-recovery tests shown in Table 5, two samples were selected for the application of the modified SAR protocol to 24 aliquots of each sample. Medium-sized aliquots (4mm) were used for LV217, and small (2mm) aliquots for LV218.

3.7.14 ***Adjustments to SAR***: the high-temperature stimulation was re-introduced to the SAR protocol to avoid thermal transfer and applied to three samples (LV221, LV224 and LV225) for a dose-recovery test on six aliquots per sample. Although thermal transfer was reduced to acceptable levels, the high-temperature stimulation affected the pattern of sensitivity changes and was the probable cause of the dose being overestimated for LV221 and LV225 (see Table 6). Additionally, an ultrafast component was observed in two aliquots of LV221. The dose was underestimated for LV224.

Sample	Aliquots rejected:			Aliquots accepted	D_e (Gy)
	Recycling	Thermal transfer	Low signals		
LV217	8	7	6	3	8 ± 2 (Mean)
LV218	1	3	18	1	18 ± 3

Table 6: SAR data for LV217 and LV218 from 24 aliquots of each sample

3.7.15 LV225 was the brightest of all the samples so six aliquots were subjected to a normal SAR procedure, whilst a further six were given a double SAR protocol in a dose-recovery experiment. All OSL signals were measured at a standard temperature of 125°C. All but one aliquot in the normal SAR group had to be rejected due to feldspar contamination, thermal transfer and poor recycling. The recovered dose was overestimated (ratio 1.15). All aliquots in the Double SAR group were rejected due to thermal transfer and poor recycling.

3.7.16 ***Dose rate***: the samples were measured in a low-level gamma spectrometer and the results are listed in Table 7. They yielded radionuclide activity data which are expected for a natural environment. The potassium activity was relatively low, indicating that potassium-rich rocks are not abundant in the Ribble catchment.

Sample	Aliquots accepted	Dose ratio	RSD %
LV221	2	1.12	0.9
LV224	3	0.84	5.7
LV225	4	1.10	3.3

Table 7: Results of dose-recovery tests incorporating a high-temperature stimulation at the end of each SAR cycle

3.7.17 ***Age determination***: fluvial sediments generally show skewed equivalent dose distributions as a result of heterogeneous bleaching. Statistical techniques are available to analyse such distributions (eg Galbraith *et al* 1999) but can only be successfully applied if single aliquots or small aliquots (containing small numbers of grains) are used (Lang and Mauz 2006). From the OSL test measurements on the Ribble samples it is clear that, given the very low luminescence sensitivity, the application of small aliquots is unfeasible. In addition, poor recycling and thermal transfer are major problems that could not be solved despite extensive testing and modification of SAR procedures. This renders any OSL ages obtained using the SAR method unreliable.

3.7.18 ***Radiocarbon dating - Field sampling and sample selection***: the radiocarbon dating strategy addresses a key project objective: to characterise the Late-Glacial and Post-Glacial fluvial evolution of the Ribble river system, identifying and constraining the phases of aggradation and incision, significant switches in the sediment supply and transfer regime within the catchment, and linkages between the major components of the system, eg hillslopes in the different headwater, headwater and lowland reaches, and flood basins. All samples were selected for radiocarbon dating based on the potential to yield geomorphologically useful age estimates. River and hillslope systems provided a number of different contexts for securing a history of geomorphic activity (Fig 42). These contexts are similar to the alluvial ensembles described by Lewin *et al* (2005), who focus on the radiocarbon dating of settings that secure the timing of geomorphic changes. A variety of contexts was identified and have been utilised in this research, and they characterise geomorphic changes in environments that range from upland hillslopes to alluvial floodplains.

3.7.19 ***Hillslope Contexts***: the first three contexts related directly to hillslope process and the coupling relationship with axial streams. Type I contexts are those where either a debris flow or a hillslope gully system had formed. The resultant debris cones/alluvial fans were relatively simple single-surface features and the sediments typically show the switch from axial fluvial to hillslope-derived sedimentation (Fig 42). Often a period of geomorphic stability preceded the hillslope destabilisation event and the soil or peat deposits associated with this stability are appropriate for radiocarbon dating. Type II contexts describe depositional settings also in single-surface alluvial fans, but where there was evidence for more than one phase of fan development. Basal organic materials underlying the initial phase of alluvial fan deposition are referred to as Type IIa contexts. Type IIb contexts occur where a period of geomorphic stability has occurred during alluvial fan and gully development, and allowed the formation of surfical soil or peat, which in turn has been buried by younger alluvial fan deposits (Fig 42). In Type I, IIa and IIb contexts, radiocarbon dating of the organic layers provide older-than ages for any underlying fan sediments and younger-than ages for the overlying phase of alluvial fan development. Type III contexts include those where the alluvial fan is a larger, more complex landform, with terracing reflecting more than one phase of fan development (Fig 42). In these settings organic materials can be associated with more than one alluvial fan terrace. Where organic materials occur beneath the oldest alluvial fan gravels (Type IIIa), perhaps overlying fluvial deposits, then radiocarbon dating will date the onset of hillslope gullying. If this type of context occurs in the deposits of a younger alluvial fan terrace, Type IIIb, then the radiocarbon dating will address the onset of this phase of renewed alluvial fan development. It is also possible to have Type IIb contexts within the deposits of any of the alluvial fan terraces, and these are referred to as Type IIIc.

3.7.20 These hillslope contexts are pertinent to this research, because the upland hillslopes can be crucial in terms of understanding sediment transfer and budget within a river system (Chiverrell *et al* 2006). Alluvial fan sedimentation at the tributary junctions of discrete gully systems with main valleys are settings where the geomorphic responses are more closely coupled to hillslope processes (Harvey 2002). There is considerable evidence for hillslope instability during the late Holocene (after 1000 cal BC) within the Solway Firth to Morecambe Bay area, extending from north-west England to south-west Scotland and encompassing the upland areas of the Bowland Fells, Howgill Fells, Lake District and Southern Uplands of Scotland. The episodes of increased gullying and alluvial fan often coincide or pre-date alluviation further downstream. Within river catchments they provide evidence for greater availability of sediment, and for the Ribble this is the case in the Forest of Bowland; however, relatively little is known about the other upland headwaters, particularly the Ribble in the Yorkshire Dales. Within this project the existing database of radiocarbon dates for the Bowland Fells has been utilised (Harvey and Renwick 1987; Chiverrell *et al* 2006). There was no need for further research of this nature in the Hodder headwaters, given the volume of available data; however, the Upper Ribble is another matter. Organic materials were sampled for a series of hillslope alluvial fans in the Ribble and Wharf headwaters, which offer a difficult rival opportunity for characterising headwater hillslope instability in Upper Ribblesdale and Wharfedale; as such this would be a barometer of hillslope erosion in the wider region, and of sediment flux to both river systems. Understanding the sequence of geomorphic change on the upland hillslopes for different parts of river catchments is crucial, because of the importance of anthropogenic activity, changes in farming intensity and woodland reduction on the hillslopes, which is a spatially variable and inherently local signature.

3.7.21 Using radiocarbon dating of organic deposits underlying alluvial fan gravels to constrain phases of gully incision requires consideration of two factors. The first is preservation potential, which arises because the fluvial geomorphic record typically comprises more gap than record (Lewin *et al* 2005). Alluvial fan sediments often consist of rapidly accumulated gravels lain down during storm events (Harvey 1986; Wells and Harvey 1987), and *Lewin et al* (2005) suggest that the radiocarbon-dated deposits may reflect only the most recent stages of fan formation in long-lived gully networks. This is not regarded as the case for the examples discussed in this report, because most of the gullies clearly are of Holocene age and typically the fan gravels overlie soils on axial stream gravels that signify relative stability within the fluvial system prior to fan development. Finally, in cases where there have been multiple phases of alluvial fan activity, there is geomorphic or stratigraphic evidence. The second concern is the radiocarbon dating itself, because the dating utilises different types of material (eg peat, soil, wood and charcoal). Radiocarbon assays from soils buried beneath or between alluvial or debris-flow deposits can provide information about the onset and duration of soil formation prior to subsequent burial (Matthews 1985). The approach used is often to radiocarbon-date the top and/or bottom horizons of the soil and to target humin and humic acid fractions within the soil organic matter (Harvey 1997). Humin is the least mobile fraction within palaeosols and provides older radiocarbon assays, whereas humic acids are mobile and provide younger age dates (Matthews 1993). Between them the radiocarbon assays for the humin fraction of the base of a buried soil and the humic acid from the top of a buried soil secures the duration of soil accumulation, and can provide 'older than' estimates for the underlying sediments and 'younger than' estimates for the overlying sediments. The suite of dates from the Bowland Fells (Harvey and Renwick 1987; Chiverrell *et al* 2006) conforms to this strategy. The new dates obtained for alluvial fans on the Ribble / Wharfe watershed were from hand-picked *in situ* plant macrofossils and so avoided the problems of migration of organic matter associated with soil radiocarbon dating.

3.7.22 ***Fluvial contexts***: the geochronological strategy for fluvial settings entails obtaining radiocarbon dates for the oldest palaeochannel (highest and most remote from the current channel) for each level of river terracing. To achieve this, reaches in the Lower Ribble, Upper Ribble, Calder and Hodder were selected and were subjected to borehole investigation of a series of palaeochannels on each terrace fragment. This final group of contexts, Type IV, comes from axial stream terraces, where the deposits reflect fluvial processes. Chronological control was possible by radiocarbon dating of: organic materials within an alluvial sequence (Type IVa); peat sequences that overlie an alluvial unit (Type IVb); and soils or peat deposits between alluvial units that signify relative stability within the accretion of the alluvial sequence (Type IVc). All of the radiocarbon dating targeted the sediment fills of surface palaeochannels, with the switch from channel gravel to back channel-style organic-rich fine-grained sediments at the base of the palaeochannel fill forming the Type IVd context. These settings provided the best prospect for constraining the abandonment of the palaeochannel and perhaps the onset of incision below this river terrace level (Fig 42). Further samples were taken from the top of the palaeochannel fill, and from the uppermost horizons within the sediment that were demonstrably still affected by flood inundation (Type IVe) to provide a later constraint on terrace abandonment.

3.7.23 In terms of securing a history of geomorphic activity, each of these contexts provided a different type of information. Type IVa contexts provide an age within the accumulation of the sequence, but do not secure either the onset or duration of fluvial aggradation. They are also susceptible to the reworking of organic materials, particularly wood or charcoal remains. Type IVb contexts can provide only an older-than age for the fluvial deposits buried beneath the peat sequence. Type IVc contexts can be dated to secure the duration of a phase of stability within the aggradation of the alluvial sequence, and to provide older-than age estimates for the underlying and younger-than ages for the overlying alluvial deposits. Radiocarbon dating of Type IVd and Type IVe contexts provide some constraint on the abandonment of individual palaeochannels and provide a minimum age for the incision producing the associated river terrace. Within this approach more than one palaeochannel was targeted for significant study reaches, with the borehole programme sampling the deposits of youngest and oldest palaeochannels on each terrace fragment.

3.7.24 ***Sample Preparation and Methodology***: in total, 68 samples from 34 horizons were prepared and processed for radiocarbon dating using the Oxford Radiocarbon Accelerator Unit (OxA) at the University of Oxford and the

Scottish Universities Research and Reactor Centre (SUERC) in East Kilbride, between January and November 2006. At Oxford, the samples were processed following the procedures detailed by Bronk Ramsey and Hedges (1997), Bronk Ramsey (2001) and Bronk Ramsey *et al* (2004). At SUERC, sample preparation and measurement followed the procedures outlined by Slota *et al* (1987) and Xu *et al* (2004). The radiocarbon age determinations were all undertaken by Accelerator Mass Spectrometry at laboratories that maintain continual programmes of quality assurance and participate in international laboratory inter-comparisons (Scott 2003), which reveal no laboratory off-sets and validate the precisions quoted in the age determinations.

3.7.25 In addition to the samples that were submitted for radiocarbon dating under the auspices of this ALSF project, additional chronological control for the fluvial geomorphology and palaeoenvironmental record for the Ribble catchment was available from radiocarbon dating (Table 8) on the Ribble river terraces by Chiti (2004) and for the Hodder, in the Forest of Bowland, by Harvey *et al* (1984) and Chiverrell *et al* (2006). For the majority of horizons selected for the new dating, the English Heritage strategy of dating two handpicked plant macrofossils for each horizon has been adhered to. The exceptions were a relatively small number of samples in the first batch submitted for dating, and, in the second batch, only handpicked plant macrofossils were admissible. The samples comprise a mixture of wood, plant remains (leaves, stems and twigs), seeds and occasional charcoal, with identification to the best possible taxonomy undertaken by Elizabeth Huckerby (OA North), Richard Chiverrell (Liverpool) and experts at Kew Gardens. In the case of wood, samples that comprised 'heartwood' were excluded from the analyses. A complete list of the radiocarbon-dated locations, horizons, and materials dated is given in Table 8.

Sample code (LV)	**U (Bq kg^{-1})**	**Th (Bq kg^{-1})**	**K (Bq kg^{-1})**
215	23.80±0.79	32.63±0.76	265±7
216	28.33±0.86	30.28±0.74	261±7
218	25.32±0.79	35.43±0.86	354±9

Table 8: Radioactivity concentrations measured in some samples

3.7.26 ***Analysis of the results and calibration***: the entire suite of radiocarbon results are presented as conventional ages in Table 9 in accordance with the international standard, the Trondheim convention (Stuiver and Kra 1986). Within later sections the dates are presented in context with the geomorphology and palaeoenvironmental interpretation, where the dates have been calibrated, which relates the radiocarbon measurements to calendar ages. All dates are calibrated using the OxCal software (v 4.0: https://c14.arch.ox.ac.uk/oxcal/OxCalPlot.html: Bronk Ramsey 1995; 1998; 2001) and the calibration curve of Reimer *et al* (2004). The probability distribution and calibration of an individual radiocarbon date is shown in Figure 43a.

Area	Location and nature of radiocarbon-dated sites	Dated materials	^{14}CYears BP	Calibrated Years
Bowland Fells	Langden Valley (Harvey and Renwick 1987; Miller 1991)			
	Langden Castle Fan - soil buried beneath fan gravel	*Betula* remains	980±70 (WIS-1611)	cal AD 898-1214
	Fiendsdale Fan - organic soil underlying fan gravel	*Betula* timber	1970±70 (WIS-1612)	166 cal BC-cal AD 213
	Little Hareden Fan - organic clay overlying fan gravel	*In situ Betula*	2000±70 (WIS-1615)	201 cal BC-cal AD 137
	Little Hareden Fan - soil buried beneath fan gravel	*In situ Betula*	1020±70 (WIS-1616)	cal AD 879-1206
	Lower Langden - base of organic fill in a gully	Wood remains	1780±70 (WIS-1628)	cal AD 84-403
	Main river terrace - base of overlying peat	*Betula* remains	4680±80 (WIS-1614)	3646-3125 cal BC
	Upper Langden Fan - top of soil buried beneath fan gravel	Humic fraction	1450±50 (SRR-3340)	cal AD 443-668
	-	Humin fraction	1650±60 (SRR-3340)	cal AD 255-540
	base of soil buried beneath fan gravel	Humic fraction	3390±60 (SRR-3341)	1878-1528 cal BC
		Humin fraction	3970±70 (SRR-3341)	2839-2210 cal BC
	Dunsop Valley (Harvey and Renwick 1987)			
	Whittendale Fan - beneath fan gravels	Wood remains	1200±70 (WIS-1627)	cal AD 675-975
	Hodder Valley (Harvey and Renwick 1987) - base of channel fill on the low river terrace	Wood remains	4320±80 (WIS-1613)	3331-2679 cal BC
Higher Brockholes	Suite of radiocarbon dates obtained by Bernardo Chiti (2004) East of the M6, Ribble Terrace 2			
	Main palaeochannel loop: C1 Basal sand	Organic clay	8043±59 (AA-49826)	7172-6709 cal BC
	Main palaeochannel loop: C1 Basal flood silt/clay	Plant remains in silt/clay	7591±60 (AA-49827)	6593-6271 cal BC
	Main palaeochannel loop: C1 Top of basal silt/clay (A)	Plant remains in silt/clay	6068±59 (AA-49829)	5208-4836 cal BC
	Main palaeochannel loop: C1 Top of basal silt/clay (B)	Plant remains in silt/clay	8361±66 (AA-49828)	7572-7193 cal BC
	Main palaeochannel loop: C1 Base of peat (A)	Peat	5104±54 (AA-49830)	4037-3773 cal BC
	Main palaeochannel loop: C1 Base of peat (B)	Peat	5046±55 (AA-49831)	3960-3711 cal BC
	Main palaeochannel loop: C1 Top of peat	Peat	4067±51 (AA-49832)	2864-2473 cal BC
	Main palaeochannel loop: C1 Alluvium above peat	Organic layer in alluvium	4228±58 (AA-49833)	3002-2621 cal BC
	1st scroll-bar palaeochannel: C2 mid-palaeochannel fill	Peaty layer	9163±40 (AA-48975)	8531-8286 cal BC
	2nd scroll-bar palaeochannel: C4 base-palaeochannel fill	Leaf-rich peat	7819±58 (AA-48973)	6982-6481 cal BC

Area	Location and nature of radiocarbon-dated sites	Dated materials	^{14}CYears BP	Calibrated Years
	2nd scroll-bar palaeochannel: C4 mid-palaeochannel fill	Leaf-rich peat	6149±70 (AA-48974)	5299-4912 cal BC
	2nd scroll-bar palaeochannel: C4 mid-palaeochannel fill	Leaf + wood detritus	6522±53 (AA-48972)	5878-5673 cal BC
	Sunderland Hall Plant detritus towards base of alluvium	Organic layer in alluvium	6885±44 (AA-48976)	5878-5673 cal BC
Lower Brockholes	West of the M6, Ribble Terrace 2 (Gearey and Tetlow 2006)			
	Main palaeochannel loop northern edge (T6 Pit 4) Top peat	wood	4430±40 (BETA-213393)	3331-2922 cal BC
	Main palaeochannel loop northern edge (T6 Pit 4) Base peat	R peat (humic)	4070±60 (BETA-213394)	2867-2473 cal BC
	Main palaeochannel loop closest to river (T3 Pit 3) Top peat	R peat (humic)	2500±50 (BETA-213392)	791-416 cal BC
	Main palaeochannel loop closest to river (ETP1) Base peat	R wood (humic)	5330±70 (BETA-213391)	4331-3994 cal BC

Table 9: Previously published radiocarbon dating from the Bowland Fells (Harvey and Renwick 1987; Miller 1991; Chiverrell et al 2006) and from the Lower Ribble (after Chiti 2004; Gearey and Tetlow 2006)

3.7.27 Where two handpicked plant macrofossils for each horizon were dated, statistical comparison between the pairs of dates was undertaken to assess the significance of any differences. This has been achieved using functions within the OxCal software (v 4.0: https://c14.arch.ox.ac.uk/oxcal/OxCalPlot.html: Bronk Ramsey 1995; 1998; 2001), and in particular incorporated the ability to test whether the calibrated probability distributions for two or more dates could be combined. This process produces an agreement index, underpinned by a Chi-square comparison of the probability distributions, and assesses whether the dates can be combined dependent on threshold levels (Fig 43b). The thresholds levels are expressed as an Agreement Index. This process highlights when pairs of dates obtained for each horizon have proven statistically identical and increases the confidence chronology developed for the dated horizon. Given that all the contexts dated in this research are from fluvial settings, with a tendency towards regular reworking of materials, then discrepancies between pairs of dates are important. Figures 43b, 43c and 43e show example comparisons from the lower Calder, where the Agreement Index was acceptable and unacceptable. For the degree of agreement to be sufficient, values greater than 60% are needed, as is the case for the three dates in Figure 43b, where the overall agreement index is 128.4%; for the other example (Fig 43c) the agreement is poor, at close to 0%.

3.7.28 The details of the radiocarbon results, statistical analyses and environmental interpretation and discussion are presented in context with the geomorphology and sedimentology in *Section 5*. Throughout this report, radiocarbon dates are expressed as reported as calibrated years BC/AD (cal years BC/AD) to two standard deviations, with the end points rounded outwards to 10 years, because the error term for all the age determinations is greater than 25 years (Mook 1986).

3.8 CHARACTERISING THE NATURAL LANDSCAPE AS A HERITAGE ASSET

3.8.1 The physical environment forms an important natural archive of past climatic and environmental change, and the geodiversity and biodiversity of this environment are both under threat from a multitude of sources: climate change; resource consumption; and land surface transformation (Ellis *et al* 2007). Geoconservation of our landscape heritage is an increasingly important component of the successful stewardship of the natural environment. The physical environment is currently protected under a number of statutory and non-statutory schemes, the main statutory scheme being the SSSI (Sites of Special Scientific Interest) scheme administered across the UK by Natural England (2007), Scottish National Heritage (SNH) and Countryside Council for Wales (CCW). The non-statutory conservation and management of sites is facilitated through the Regionally Important Geological/ Geomorphological Sites (RIGS 2007) scheme devised by the former Nature Conservancy Council (NCC). The scheme is locally initiated through interest groups and supported by the Association of United Kingdom RIGS Groups (UKRIGS 2007), a national organisation formed in 1999, with the encouragement and support of the then English Nature, Countryside Council for Wales, Scottish Natural Heritage and the Royal Society for Nature Conservation (RSNC). UKRIGS represents the RIGS movement and the large number of independent RIGS groups across the UK. The Lancashire RIGS Group (2007) is a focus for activity within much of the Ribble ALSF region, with the West Yorkshire RIGS Group contributing to RIGS notification in the headwater reaches of the Ribble.

3.8.2 The process of identifying what constitutes important scientific geological or geomorphological sites has been facilitated by the *Geological Conservation Review* (GCR), coordinated by the Joint Nature Conservation Committee (JNCC). The GCR selection process is underpinned by the highest scientific standards to identify systematically important sites that would reflect the range and diversity of Great Britain's Earth heritage (Ellis *et al* 2007) and each GCR site must satisfy the legal requirements for notification as a Site of Special Scientific Interest by reason of its geology or geomorphology, which must be of international importance. International importance is conferred for a variety of reasons: to capture sites that show time interval or boundary stratotypes, are the type localities for biozones (defined by fossil content); and chronozones type localities for particular rock types, mineral or fossil species; historically important localities where rock or time units were first described, characterised, or linked to advances in geological theory; and where geological or geomorphological phenomena, concepts or theory were first recognised and described. Sites can also be listed because they have unique, rare or special features, with the intention that the highlights of British geology and geomorphology are conserved, and to ensure representative coverage of the essential features of Britain's Earth heritage.

3.8.3 Within the current SSSI and RIGS sites listed for the Ribble ALSF study area, the number that reflect the fluvial and glacial geomorphology is somewhat limited (Fig 44). This is largely a function of the relative absence of research into the lowland fluvial geomorphology of north-west England and the glacial history of Lancashire. The only fluvial geomorphology sites listed in GCR reviews that cover north-west England are in Cumbria (Langstrathdale, Wasdale, fan deltas at Buttermere and Crummock Water, Carlingill, Langdale and Bowderdale Valleys in the Howgill Fells), and the River Dane, near Swettenham, Cheshire. Langden Brook (Bowland Fells) is the only representative from the Ribble drainage basin. With the exception of upland rivers in the Bowland and Howgill Fells, there has been relatively little research of the Quaternary development of the river systems of north-west England, particularly when contrasted with the extent of research in north-east England (Macklin *et al* 2005).

3.8.4 Given that academic research appears to be one of the precursors to designation and listing of sites for geological and geomorphological reasons, it is perhaps not surprising that there are few sites currently listed within the Ribble ALSF region. Sites can be nominated for RIGS status through the site assessment process of the local RIGS groups and UKRIGS (2007). Sites can become SSSIs for geological and geomorphological criteria through the *Geological Conservation Review* series, and the GCR of 'Fluvial geomorphology' has been identified for possible revision (Ellis *et al* 2007). The research undertaken during the Ribble ALSF Project has assessed in some detailed the fluvial and glacial evolution of the Ribble, and, as a part of that work programme, the heritage value of the physical environment has been advanced. Sites that have contributed significantly to understanding the physical landscape, and the Quaternary and Holocene geomorphic history, are clearly now candidates for RIGS status and perhaps GCR nomination. Any sites that meet these criteria and are comparable in merit to existing RIGS/GCR sites will be identified in the recommendations (*Section 10*).

3.9 CHARACTERISING THE ARCHAEOLOGICAL RESOURCE

3.9.1 ***The Archaeological Database:*** the preliminary archaeological database was constructed in Microsoft Access 97 to hold the archaeological events and monuments data for the project. Events are defined as an episode of archaeological activity, such as an excavation or a survey, and the monuments are the archaeological sites that are revealed by the event. Single events, such as a survey, can result in the creation of large numbers of monuments or if they are unsuccessful, may create no monuments. Monuments by the same token may have been informed by multiple events, and in some instances, if derived from historic mapping (for example), may have no corresponding events.

3.9.2 The structure of the database was designed to obey the latest MIDAS standards (English Heritage 2000), and to incorporate standard word lists (Inscription: http://www.fish-forum.info/inscript.htm) and thesauri (http://thesaurus.english-heritage.org.uk/thesaurus.asp?thes_no=1) to ensure computability with the widest range of existing datasets. The structure incorporates the generally accepted division between archaeological events and monuments, with the additional inclusion of palaeoenvironmental event information where appropriate. Monuments were taken to include all statutory designations (ie Listed Buildings and Scheduled Monuments).

3.9.3 Initially, events and monuments were entered into the database and displayed on the GIS as point data only, then as more detailed information became available for particular events these were displayed in the GIS as boundary polygons, which were linked to the appropriate record within the database by a Lancashire HER Primary Record Number (PRN).

3.9.4 ***Previous Research and Investigations:*** during the data-gathering phase of the project, datasets were provided by Lancashire County Council and national sources. These included data on events and monuments, generally in digital form (either as data tables or as shape files), and mapping data (generally in the form of georeferenced raster images), for incorporation into the project GIS.

3.9.5 Datasets provided by Lancashire County Council comprised:

- Historic Environment Records;
- Roman roads;
- Portable Antiquities Scheme;
- Listed Buildings;
- Registered Parks and Gardens;
- North West Wetlands Survey.

National Sources comprised:

- National Monuments Records;
- Archaeological Investigations Project.

3.9.6 Records from each dataset were defined as events or monuments in the GIS, although these were not always mutually exclusive. For example, a building survey would be assigned an event record for the survey, and a monument record for the building itself. As part of the data entry process, external references were added, indicating the source dataset for each record. In some cases records were duplicated between datasets, in which case they were assigned an external reference for each source, rather than duplicating the entire record. Additionally, a grey literature search was undertaken, particularly from the archives of OA North.

3.9.7 The datasets were not entirely error-free, and data cleansing was a significant part of the data entry process. Common errors included inaccurate location information, duplication of records within individual datasets, omissions in fields, and spelling or grammatical errors. It was also necessary to change descriptive terms to ensure consistency and compliance with current standards. In general, this meant changing event types to match the ALGAO event-type list (http://www.fish-forum.info/i_alget.htm), changing periods to match the RCHME period list (http://www.fish-forum.info/i_apl.htm), and the monument type to match the broad class and type listed in the RCHME thesaurus (http://thesaurus.english-heritage.org.uk/thesaurus.asp?thes_no=1). Where alterations were made, this was noted in the project notes for return with the primary datasets. To ensure compliance with MIDAS standards (English Heritage

2000), additional fields were completed that were not generally included in the primary datasets, such as National Grid Reference Precision.

3.9.8 ***Mapping****:* the following sources of mapping were acquired for the project:

- current Ordnance Survey MasterMap (digital vector);
- current Ordnance Survey Landline (digital vector);
- current Ordnance Survey 1:10,000 (digital raster);
- current Ordnance Survey 1:25,000 (digital raster);
- current Ordnance Survey 1:50,000 (digital raster);
- Ordnance Survey First Edition 6 inch (digital raster);
- Ordnance Survey Second and Third Edition 6 inch (hardcopy);
- Ordnance Survey First Edition 25 inch (digital raster);
- NextMAP 5m contour data;
- Saxton (1577);
- Yates (1786);
- Speed (1610);
- Tithe Maps.

3.9.9 Digital vector mapping is, by nature, georeferenced and could be displayed in the GIS immediately, along with the contour data. The current Ordnance Survey digital raster mapping was supplied georeferenced and was incorporated as an image catalogue within the GIS. The Ordnance Survey first edition 1:10,560 (6” to 1 mile) mapping was obtained digitally, georeferenced and incorporated together as an image catalogue within the GIS. The Ordnance Survey Second-and Third-Edition 1:10,560 (6” to 1 mile) mapping were scanned by the Lancashire County Council Environment Directorate from hardcopy base maps. The resultant scans were then trimmed, georeferenced and also incorporated as an image catalogue.

3.9.10 The more detailed 1:2500 (25 inch to 1 mile) maps for Lancashire were made available in PDF format by the Digital Archives Association in Warrington. The number of map tiles required to give coverage of the study area would have made the trimming and georeferencing of the image files very time-consuming. As a result they were consulted as appropriate rather than being incorporated into the GIS. The other historic maps were utilised in the same way.

3.9.11 ***Air Photographs and LiDAR***: at the project outset, HER data showing the locations of available oblique aerial photography was provided by Lancashire County Council and incorporated into the project GIS. The photographic archive used included 115 oblique photographs scanned from the Lancashire Record Office, in addition to runs from the National Monuments Record and Holdings of historic RAF coverage. The entire Lancashire area was subject to vertical aerial survey in 2000 and Lancashire County Council loaned this to the project. Additionally, a small amount of extra flying was undertaken by Jamie Quartermaine of OA North, which examined the potential aggregate extraction area opposite Brockholes Quarry, and the village of Rathmell in North Yorkshire.

The aim of this exercise was to provide a comparator for an equivalent block of LiDAR data and hence this technique was not systematically applied across the study area.

3.9.12 The locations of the oblique photographs were displayed in the GIS and the images consulted, along with modern mapping, historic mapping and vertical air photographic mapping. Features seen on the air photographs were then noted and cross-referenced against all other known archaeological monuments, and only when it was confirmed that there was no duplication were they added as new sites in the database. The problem with mapping features from oblique aerial photography is resolving the oblique distortion, and in this case this was helped by direct comparison with equivalent LiDAR data.

3.9.13 ***LiDAR:*** LiDAR data was supplied under licence for the duration of the project by the Environment Agency, although full coverage of the study area was not available (Fig 45 Available LiDAR Coverage). The coverage that was available was integrated into the GIS as georeferenced raster images created from basic ASCII files. These rasters are capable of producing very precise surface models that can be examined in a variety of ways within the GIS. For the purpose of this project two methods were most commonly used: hillshades and slope models.

3.9.14 ***Hillshades***: the hillshade function calculates the illumination values for each cell in a raster representing a surface, given a hypothetical light source in a specified position. It does this by setting a position for the light source and calculating the illumination values of each cell in relation to neighbouring cells. It can greatly enhance the visualisation of a surface for analysis or graphical display by highlighting subtle changes in the topographic surface.

3.9.15 From the perspective of searching for archaeological monuments, the hillshade function simulates the effect of low-level aerial photography, in that the angle and azimuth of the sun can be selected to allow one to view the landscape as if from an aircraft. In this way landscape features stand out in the same way as they would under oblique photographic conditions.

3.9.16 Once a hillshade layer had been created in the GIS, it was overlaid onto the current vertical colour aerial photographic mapping to enhance the landscape, and this was systematically examined in transects across the study area. Any unknown features that could not be explained by the known archaeological monuments were recorded as new monuments and digitised as polygons, or points, as appropriate within the GIS.

3.9.17 ***Slope Models*****:** these were created using the height values attached to the LiDAR data. The slope model identifies the steepest downhill slope for a location on a surface. For raster surfaces, this is the maximum rate of change in elevation between a cell and each of its nearest neighbours. The lower the slope value, the flatter is the terrain; the higher the slope value, the steeper the terrain. Although full coverage of NextMAP 5m contour data was available, the LiDAR data were used where available for constructing slope models for the identification of archaeological monuments as it provided considerably improved resolution (Fig 4b Example of Slope model, Village of Waddington).

3.9.18 Both slope and hillshade were manipulated in ArcScene, which allows a three-dimensional view of the data, and allowed the landscape to be examined from virtually any angle and with different orientation of light sources. Again, the landscape was systematically examined and any new monuments recorded on the GIS (*Section 3.2*).

3.9.19 ***Secondary Sources***: a selection of secondary sources was consulted, both relating to the study area and the wider landscape:

- *Historic Landscape Characterisation* (HLC) Project (Ede and Darlington 2002);
- *Ribble Valley Catchment Archaeological Rapid Identification Survey* (LUAU 1997b);
- Documentary Survey of 1890s map (Lancashire HER 2006);
- Grey Literature from the archives of OA North/LUAU;
- Conservation Areas/SSSIs;
- Designated Ancient Woodland;
- Countryside Character Areas;
- Ribble Catchment Flood Management Plan (Environment Agency 2005).

3.9.20 The Conservation Area/SSSI/Countryside Character/Ancient Woodland datasets did not provide evidence for events and monuments, but rather for more general information about the study area, or about land designations. These were added to the GIS without any form of data cleansing and were added as external references to monuments as appropriate.

3.9.21 The main focus of this research was to enhance the information held on existing events and monuments, and to identify any that had not been addressed in the main datasets. However, this research also provided a wealth of historical background information for the project, and in addition uncovered several elements, other than archaeological remains, that were pertinent to the study area.

3.9.22 The second stage was to examine the landscape surrounding the Ribble Valley to provide a broad-based understanding of the modern character of the study area. The most useful sources for this were the Water Framework Directive (Environment Directive 2007) and the works undertaken by English Nature and the Countryside Agency (English Nature 1999a; 1999b; 1999c; Countryside Commission 1998). These provided an understanding of the modern landscape types, a brief outline of historical influences on the region, and the location of particular designated areas such as Sites of Special Scientific interest (SSSI) or Designated Ancient Woodland. The Countryside Agency has created a map of character areas (Fig 3) that divide the landscape into 'packets' of similar character (Countryside Commission 1998 (*Section 2.1*)). The descriptions also relate how that character has developed and how it is changing; as such they provide a context against which the archaeological development of the study area can be assessed.

3.9.23 The Record Office and relevant libraries of Lancashire and North Yorkshire were visited and local history sections searched. The scope of the material was initially wider than the study area in order to determine whether the area matched patterns observable in other parts of the north-west England, or whether it was unique. The approach taken for the secondary source information was to create a period-by-period description of the known archaeological and historical information from the North West, but focusing on the Ribble Valley.

3.9.24 Several recent publications were consulted at both a regional and site-specific level, including English Heritage's *Earthwork Survey of Sawley Abbey* (Hunt 2005), which provides a detailed survey of the earthworks and concise history of the site. The *Lancaster Imprints* publication of the excavations at Ribchester (Buxton and Howard-Davis 2000) and the English Heritage *English Landscapes* volume for the North West (Winchester 2006) were also consulted, as was the *North West England Archaeological Research Framework, Archaeological Resource Assessment* (Brennand 2006).

3.9.25 ***Field Survey and Ground-Truthing***: a rapid programme of ground-truthing was undertaken during the course of the project, utilising OA North's *Level 1 Identification Survey Methodology* (OA North 2002), which covers walkover survey by visual assessment. This level of survey represents the minimum standard of record for field investigation, and is aimed at the discovery of previously unrecorded archaeological monuments. Its objective is rapidly to record the existence, location, and extent of any monument using four elements: reconnaissance; mapping; description; and photography, and includes comments on character and condition. Monuments already identified within the study area by the NMR and HER were checked and recorded at the same level of consistency as newly discovered features.

3.9.26 This survey generated core information for entry into the project database and GIS. Each area was walked in transects at an interval between 20m and 50m, depending on local topography and ground cover. A primary part of the exercise was to ground-truth the information gathered by the remote sensing techniques, notably LiDAR, aerial photographic and cartographic data.

3.9.27 ***Creating an Enhanced Monument and Event Dataset***: the data sources listed as the *Archaeological Resource* were compiled within the GIS as either monuments or event data where appropriate. This data represented a merging of the cleansed point data for monuments, events, Listed Buildings and the Portable Antiquities Scheme findspots, with point data from the North West Wetlands Survey (Middleton *et al* 1995), the *Ribble Valley Catchment Archaeological Rapid Identification Survey* (LUAU 1997b) and the Lancashire County Council Survey of the 1890 Ordnance Survey Map (Lancashire HER 2006) This was used in conjunction with the other linear or area-based features, namely Roman roads; Historic Landscape Characterisation; and Historic Parks and Gardens (English Heritage 2007). This allowed both an initial assessment the distribution of known archaeology within the study area, and the creation of the enhanced database for the GIS analysis.

3.9.28 This data did not have a field allocated for the National Monuments Broad Class (English Heritage 2000) entry. As such, all monument data were assigned the correct Broad Class. Table 10 contains the NMR broad class list for all known archaeology prior to, and after, the addition of new sites recorded by the ALSF project.

NMR broad class List	Count
Agriculture and Subsistence	107
Civil	2
Commemorative	1
Commercial	35
Defence	29
Domestic	133
Education	21
Findspot	55
Gardens Parks and Urban Spaces	38
Health and Welfare	5
Industrial	161
Maritime	22
Monument	16
Recreational	9
Religious Ritual and Funerary	68
Transport	93
Unassigned	18
Water Supply and Drainage	93

Table 10: NMR broad class types found in the Lower Ribble Valley study area

3.9.29 ***Mapping**:* examination of the OS first edition mapping revealed eight new sites (Table 11) that were depicted on the maps but had not been incorporated into the HER for the study area. In addition, two earthworks were identified by comparing the LiDAR coverage with the first edition OS mapping.

Count	NMR Class	Monument Type
1	Agriculture and Subsistence	Barn
1	Industrial	Gravel bank
1	Monument <Form>	Earthwork
1	Recreational	Racecourse
1	Transport	Footpath
1	Unassigned	Reclaimed Land
2	Water Supply and Drainage	Palaeochannel

Table 11: New sites identified from OS first edition mapping

3.9.30 ***Aerial Photography***: a surprisingly small number of new sites was found using the aerial photographs alone; in total, five sites were identified in this way (Table 12). An additional eight were identified by comparison of aerial photography to LiDAR data (Table 13).

Count	NMR broad class	Monument Type
3	Monument	Earthwork
1	Unassigned	Cropmark
1	Water Supply and Drainage	Palaeochannel

Table 12: New sites identified from aerial photographs

Source	Count	NMR broad class	Monument Type
2000 VAP/LiDAR Slope	1	Agriculture and Subsistence	Ridge and Furrow
2000 VAP/LiDAR Slope	5	Monument	Earthwork
2000 VAP/LiDAR Slope	1	Water Supply and Drainage	Palaeochannel
LiDAR Slope/HER PRN3292 / / N1281 AP	1	Monument	Earthwork

Table 13: New sites identified from combinations of aerial photography and LiDAR

3.9.31 ***LiDAR**:* LiDAR was found to be an invaluable asset, which identified a total of 162 sites from examination of slope or hillshade models (Table 14).

Count	NMR broad class	Monument Type
2	Agriculture and Subsistence	Field system
27	Agriculture and Subsistence	Ridge and Furrow
1	Industrial	Mill Race
1	Industrial	Sluice
1	Monument	Bank
91	Monument	Earthwork
8	Monument	Field boundary
9	Monument	Linear Feature
1	Transport	Road
1	Unassigned	Site of (no longer extant)
3	Unassigned	Unknown
1	Water Supply and Drainage	Drain
12	Water Supply and Drainage	Palaeochannel
4	Water Supply and Drainage	Pond

Table 14: New sites identified by LiDAR

3.9.32 ***Grey Literature Search**: The Ribble Valley Catchment Archaeological Rapid Identification Survey* (LUAU 1997b) had been provided as a Shape file containing point data for each site visited during the survey. This was compared to the HER monument data for the study area and it was found that 149 of the sites recorded during the Ribble Catchment Survey were located in the Ribble Valley study area.

3.9.33 Seventy-seven sites were recorded as monuments on the county HER and these were visited as part of the survey. These needed to have a corresponding reference added to each to mark this survey event. The remaining 72 sites recorded by the survey had not been allocated a PRN number nor added to the HER records. These were allocated a number from the set of PRN numbers issued to the Ribble ALSF project by Lancashire County Council Archaeological Service. Again, each of these required a corresponding event reference to this survey.

3.9.34 The total additions made to the HER dataset for the Ribble Valley are summarised in Table 15.

NMR broad class List	Initial	Enhanced Count
Agriculture and Subsistence	107	145
Civil	2	2
Commemorative	1	1
Commercial	35	35
Defence	29	37
Domestic	133	133
Education	21	21
Findspot	55	79
Gardens Parks and Urban Spaces	38	39
Health nd Welfare	5	7
Industrial	161	167
Maritime	22	24
Monument <by Form>	16	158
Recreational	9	10
Religious Ritual and Funerary	68	76
Transport	93	99
Unassigned	18	84
Water Supply and Drainage	93	120
Total	**906**	**1237**

Table 15: Additions made to the HER dataset for the Lower Ribble Valley

3.10 CHARACTERISING THE PALAEOBOTANY OF THE LOWER RIBBLE VALLEY

3.10.1 ***Previous work in the general environs and study area*:** previous palaeoenvironmental work within the study area is restricted to the thesis by Bernardo Chiti (2004) from the Lower Ribble Valley, and a recent environmental assessment from Lower Brockholes, near Preston (Gearey and Tetlow 2006). Chiti's research concentrated on the evolution of the lower course and estuary of the River Ribble rather than the palaeoecology *per se*, although a pollen diagram through the organic fill of a palaeochannel at Brockholes provides a record of vegetational change from the middle and later Mesolithic to the early Neolithic periods.

3.10.2 A brief pollen assessment of samples from two test pits from another organic deposit at Brockholes (Gearey and Tetlow 2006), the top of which was dated to 3331-2922 cal BC (4430±40 BP; Beta-213393), suggests a generally wooded environment, with oak, hazel and alder in all three of the samples assessed from the first test pit, although the environment was more open in the middle sample. A single pollen sample from a further test pit suggests a less open environment, with alder locally dominant. The Coleoptera were assessed from a number of different transects and test pits from the site. This provides a picture of a local environment with indications of boggy backswamp and damp meadows and with some temporary or more permanent aquatic areas.

3.10.3 The only other palaeobotanical research within the study area of the Lower Ribble Valley is that from the Roman fort at Ribchester (Buxton *et al* 2000, 21-3; Huntley and Hillam 2000, 349-59) and, except for a brief pollen study of the pre-rampart soils (Innes 2000), this is closely associated with the fort itself rather than the regional picture. The pollen evidence from two consecutive buried soils records the vegetation at the site before the Roman occupation. The lower buried soil records a local alder carr beside the river before a period of major agriculture activity. The lower part of the overlying buried soil records a second episode of intensive cultivation before the construction of the earliest rampart at Ribchester.

3.10.4 Regionally, the picture is more comprehensive and there is an extensive body of palaeoecological research from the lowlands to the south-west and north-west of the most westerly section of the Lower Ribble study area. Research in the upland areas of the eastern part of the study area is more limited, with published and unpublished work from the Bowland Fells (LUAU 1997a) to the north and Anglezarke (Howard-Davis 1996) to the south.

3.10.5 Pollen diagrams from the lowland mosses of south-west Lancashire (Middleton *et al* forthcoming), north Lancashire (Middleton *et al* 1995), north Merseyside (Cowell and Innes 1994), and north Greater Manchester (Hall *et al* 1995), although in some instances related to changing sea level, do give some indications of the regional vegetation from the Late Devensian (Late-Glacial) and the Holocene (Post-Glacial). Pollen recorded in the peat from the central areas of the large raised mires is thought to record changes in the regional landscape rather than more local changes identified from the margins of raised mires (Turner 1975) or from small basins (Jacobson and Bradshaw 1981). Therefore the pollen studies from the Fylde area of Lancashire (Oldfield and Statham 1965; Barnes 1975; Tooley 1978; Middleton *et al* 1995; Wells *et al* 1997) represent regional changes to the vegetation, as do those from south-west Lancashire and Merseyside (Tooley 1978; Cowell and Innes 1994; Middleton *et al* forthcoming) and Red Moss, Greater Manchester (Hibbert *et al* 1971; Hall *et al* 1995).

3.10.6 Regionally frequent, extensive and widespread charcoal horizons are recorded in the mire stratigraphy and pollen diagrams for the Mesolithic period. This suggests both *in situ* and regional burning of the woodland. It is not possible to prove conclusively the causes of this burning, whether it was the result of natural events, such as lightening strikes, or of anthropogenic activity. However, Rackham (1986, 71-2) states that British trees, except for pine, burn like 'wet asbestos' and it is therefore unlikely that British wild wood would have burnt naturally.

3.10.7 In south-west Lancashire and the Fylde, the pollen record is influenced not only by climate and anthropogenic activity but also by changing sea levels, with many palaeoecological sequences interrupted by marine deposits (Tooley 1978; Middleton *et al* forthcoming). This extensive body of palaeoecological research records that towards the end of the last glaciation there was a temporary amelioration of the climate before a return to colder conditions.

3.10.8 From the early Neolithic period onwards, anthropogenic activity is recorded with more certainty in the pollen diagrams from the region, for example at Fenton Cottage, in the Fylde (Middleton *et al* 1995; Wells *et al* 1997), and at sites in south-west Lancashire (Middleton *et al* forthcoming). These diagrams record that episodes of regeneration and short-term clearance alternated throughout the Neolithic and Bronze Age, before secondary woodland regenerated in the Iron Age. This Iron Age regeneration coincides with the identification of proxy climatic indicators in the peat stratigraphy, which suggest possible climatic deterioration.

3.10.9 The same body of published and unpublished research also records the regional vegetation from the late Iron Age to the present day. The evidence for anthropogenic activity is considerable for the remainder of the Holocene, although there are some episodes of woodland regeneration in the early part of the post-Roman period.

3.10.10 There are fewer pollen studies from the upland areas bordering the Lower Ribble Valley. In the north there is the research of Mackay and Tallis (1994) from Fairsnape Fell, as well as the tightly targeted work from the Bowland Fells undertaken as part of the *Upland Peat Project* (OA North in prep) and to the south pollen studies are confined to Anglezarke (Bain 1991; Howard-Davis 1996; OA North in prep). The chronological length of the pollen record is limited by the date of peat inception, the earliest peat forming in the Mesolithic period (OA North in prep) on the higher fells in the Forest of Bowland at 5711-5563 cal BC (6720±35 BP; SUERC-4505), gradually spreading downslope in the Neolithic and Bronze Age, with peat at Site 3 in the Forest of Bowland starting to accumulate in the Iron Age, at 732-379 cal BC (2365±40 BP; SUERC-4507; *ibid*). The pollen studies from Fairsnape Fell, to the north-east of Preston, are the nearest to the study area. Mackay and Tallis (1994) recorded changes in the vegetation from 350-2 cal BC (2105±40 BP; SRR-4507) to the present day.

3.10.11 ***Methods of prospection and analytical techniques: description of sampling work***: in the first instance the LiDAR and mapping data for the study area were examined to identify possible palaeoecological sites that could record the Holocene vegetational history. In the case of the Lower Ribble Valley no potential mire sites were noted; however, in the Yorkshire study area two possible sites were identified, one directly within the study area and one a little outside it. These were the SSSI of Long Preston Deeps (SD 81315 58296), near Goosmire Lathe (Hall Moss on the first edition OS maps), and Cocket Moss (centred SD 78557 61766). A brief visit was made to both sites and limited numbers of exploratory cores were taken with a 30mm-bore Eijkelkamp gouge auger, to record the possible depth of the peat and potential for palaeoecological analysis.

3.10.12 In the Lower Ribble Valley, the OA North environmental archaeologist visited four sites with the team from University of Liverpool (*Section 3.5.2*). The first site, an exposed section on the Calder near Whalley, was sampled and wood was retrieved for dating and identification. The other three sites were cored using a Van Walt percussion corer through the fluvial deposits, which included buried peat deposits. Samples were retrieved in the field for dating, pollen and plant macrofossil analysis.

3.10.13 A pollen assessment of samples from Flashers Moss, Cocket Moss and Long Preston Deeps was also undertaken (*Section 5.3.1*). All samples were prepared for pollen analysis using a standard chemical procedure (method B of Berglund and Ralska- Jasiewiczowa 1986), using HCl, NaOH, sieving, HF, and Erdtman's acetolysis, to remove carbonates, humic acids, particles >170 microns, silicates, and cellulose, respectively. The samples were then stained with safranin, dehydrated in tertiary butyl alcohol, and the residues mounted in 2000 cs silicone oil. Slides were examined at a magnification of 400x (1000x for critical examination) by equally spaced traverses across at least two slides to reduce the possible effects of differential dispersal on the slide (Brooks and Thomas 1967). The aim was to obtain a pollen count of at least 100 land pollen and spores for each level counted. *Lycopodium* tablets (Stockmarr 1971) were added to a known volume of sediment at the beginning of the preparation so that pollen concentrations could be calculated. Pollen identification was made using the keys of Moore *et al* (1991), Faegri and Iversen (1989), and a small modern pollen reference collection. Anderson (1979) was followed for identification of cereal-type grains. Indeterminable grains were also recorded as an indication of the state of the pollen preservation. Plant nomenclature follows Stace (1997).

3.11 ASSESSING THE MINERAL POTENTIAL AND GEOMORPHIC RISK

3.11.1 ***History of mineral extraction:*** the focus of the Ribble ALSF Project is upon land-based sand and gravel aggregates, for which previous and current extraction has targeted glacial, fluvioglacial and fluvial deposits. To assess the history of mineral extraction and future mineral planning, and to produce an inventory of current, past and future extraction of sand and gravel, information has been compiled from various sources. Since its formation in 1835, the British Geological Survey (BGS) has collected information about working mines and quarries, mainly because they provide the best sites to understand the local geology. These data have been compiled in the *Directory of Mines and Quarries* (DMQ) (Cameron 2005), which has been published at approximately two yearly intervals. The data were derived from a database called BritPits, and includes both active and inactive surface quarries and underground mines, and usefully the holdings include the name of active mines and quarries, their geographic location, address, operator, mineral planning authority, geology, mineral commodities produced and end-uses. BGS believes that BritPits is one of the most comprehensive and up-to-date sources available, and it is a useful source for identifying the history of sand and gravel extraction within a region.

3.11.2 The LCC Waste and Minerals Policy Group documentation is an important resource. Of particular importance are the *Lancashire Minerals and Waste Local Plan* (LCC 2006), and its successor, the *Joint Minerals and Waste Development Framework*, which is currently being prepared by Lancashire County Council, Blackburn with Darwen Borough Council, and Blackpool Borough Council. This, and the existing *Minerals and Waste Local Plan* (LCC 2006), set out the strategy for future minerals and waste development, and include mineral extraction, protection of mineral resources and the restoration of minerals extraction sites. To facilitate a greater understanding of the sand and gravel reserves in Lancashire, LCC has commissioned several sand and gravel studies (see *Section 3.3*). The Entec UK Ltd (2005) and the Geoplan Ltd (2006) reports provide the most detailed information on mineral quality and are particularly pertinent to the study of the aggregate resources of the Ribble catchment area. Both studies were constrained in that they focused on predetermined study areas, with only a limited brief to look at new areas, and only those for which there was extant geological data.

3.11.3 Another important knowledge base are the reports (1999-2006) of the Regional Aggregate Working Party (RAWP 1999-2006) for north-west England. The Regional Aggregate Working Parties (RAWPs) provide technical advice in relation to the supply of and demand for construction aggregates (including sand, gravel and crushed rock) to the Regional Assemblies/Regional Planning Bodies and to the Secretary of State for Communities and Local Government (DCLG), previously (before 2005/6) to the First Secretary of State for the Office of the Deputy Prime Minister.

3.11.4 All these sources were examined and analysed to compile a database of sand and gravel mineral extraction activity within the study area. These data were used to compile a spatial geodatabase of current and past extraction sites, including both solid rock and sand and gravel aggregate quarries.

3.11.5 ***Current minerals planning, survey and knowledge:*** the main resources to inform minerals planning are:

- Drift geology maps and digital databases of the BGS, particularly the five 1:50,000 sheets covering: Garstang (BGS 1990); Settle (BGS 1991); Rochdale (BGS 1974); Preston (BGS 1982); and Clitheroe (BGS 1975). The Preston sheet is currently under revision, and the present study is contributing to that process (AJ Humpage and RG Crofts (BGS) *pers comm*);
- The Department of the Environment-commissioned report, *Sand and Gravel Resources of Lancashire*, by Allot and Lomax, which reported in 1990;
- The report, *Sand and Gravel Study Stage 1*, commissioned in November 2003 by Lancashire County Council from Entec UK Ltd (2005) in partnership with the British Geological Survey (BGS), http://www.lancashire.gov.uk/environment/lmwlp/;
- The report, *Sand and Gravel Study Stage 2*, commissioned in June 2005 by Lancashire County Council from Geoplan Ltd (2006), http://www.lancashire.gov.uk/environment/lmwlp/.

3.11.6 Each of these data resources has been analysed to assess the extent to which they have identified sand and gravel prospects within the study area. The exception to this is the Geoplan Ltd report (2006), which emerged towards the end of this project, but nevertheless the findings and implications of that report have been incorporated into the later sections (*Section 7*).

3.11.7 Boreholes clearly provide the ready means of confirming the nature of areas identified as having potential for sand and gravel extraction. The BGS hold copies of all deposited borehole records at their national headquarters, with summary data, including borehole number, location and depth available from the BGS website. A list of potentially useful boreholes was collated (*Section 3.3.4*) and these were then compiled by examination and interpretation at the BGS archive at Keyworth. Additional boreholes were accessed from consultancy reports developed for past and planned mineral extractions at lower and higher Brockholes (Gearey and Tetlow 2006). This data compilation exercise was undertaken for all areas identified as having potential aggregate prospects from existing map and digital sources, and then repeated after the interrogation of the new geomorphological and Quaternary geological mapping was undertaken in the course of this study. This two phase approach has proven necessary because the process of cataloguing borehole records demonstrated that, like the comparison of new geomorphic boundary data with BGS drift boundaries, BGS maps and the minerals plans based on the BGS mapping, especially older ones, are often inaccurate in their identification of the type of glacial sediment and depiction of boundary locations between them. This arises because the traditional basis of geological mapping, the identification of lithology at the surface, is inappropriate when mapping areas of thick glacial deposits because of their inherent variability and rapid vertical and lateral transition between lithological units in glacial sediments. As a consequence of this, many boreholes identified as being located in areas of non-aggregate mineral, such as till, show significant thicknesses of potential mineral hidden by thin surface tills. More modern maps, not available for much of the Ribble area, are based on the identification of sediment-landform assemblages, which provide a more accurate depiction of likely sediment type. As a consequence of these problems, a significant number of boreholes, originally rejected as occurring in areas of non-mineral, will have to be brought back into the assessment process.

3.11.8 All borehole locations were identified and the coordinates transferred into a Boreholes layer within the integrated Ribble geodatabase. The following attribute data was attached to the layer:

- borehole identification code (text);
- borehole classification according to their usefulness;
- maximum depth;
- geomorphology associated with the borehole location;
- description of the sedimentology.

3.11.9 ***Producing an enhanced mineral assessment***: to identify and characterize the mineral aggregates for the Ribble ALSF study area, it was necessary to identify a set of search criteria that define the type of mineral aggregate that is sought. It should be emphasised that the search criteria applied within the target areas may vary depending upon local circumstances. It must also be emphasized that an assessment of the criteria requires intervention by extraction, test pit or borehole; without these types of data, confidence in any assessment is reduced. Further, gleaning this type of information from the BGS borehole archive is often difficult, owing to the variable quality of the recording.

3.11.10 ***Lithology****:* examination of the mineral plans for Lancashire suggests that there is a need to identify new sand and gravel reserves and so there is no targeted preference for particular aggregate products. However, there is an additional focus on identifying high-grade sand in both the recent LCC commissioned sand and gravel studies.

3.11.11 ***Proportion of Fines****:* in order to minimise processing, potential resources need to be relatively free of silt and clay. In their regional mineral assessment reports the BGS has traditionally used a maximum proportion of 40% fines (<0.0624mm) to differentiate between mineral and non-mineral. Consultation with the industry, however, suggests that this figure is too high and a figure of 15% is more appropriate.

3.11.12 ***Minimum thickness:*** the BGS uses an average minimum thickness of 1m to define an economically viable mineral resource. This is felt to be much too low and consultation with the industry suggests an average minimum thickness of 3m is more appropriate.

3.11.13 ***Minimum ratio of overburden:*** 'overburden' is defined as the ratio of non-mineral overlying mineral in any potential resource. This ratio is important as higher ratios increase the cost of extraction. The BGS uses a ratio of not more than 3:1 but consultation with the industry suggests that a ratio of 1:1 is more appropriate.

3.11.14 ***Waste:*** 'waste' is defined as the ratio of mineral to non-mineral within any potential resource. This is important because many types of glacial deposit, especially those deposited in ice-marginal environments, contain rapidly varying, often discontinuous, sequences of sediment, that are usually diamict or laminated or massive mud, and which serve to contaminate the potential mineral and increase the cost of extraction. Consultation with the industry suggests that a minimum ratio of waste to mineral of 1:1, or 50% of a potential resource volume is acceptable.

3.11.15 ***Minimum quantity:*** consultation with the industry suggests that the minimum quantity of extractable mineral in any potential resource likely to be used for regional scale supply should not be less than half a million tonnes. The Geoplan (2006) survey utilised a cut-off figure of one million tonnes, but recognised that it may be economic to extract quantities under that threshold.

3.11.16 ***Depth:*** in the industry the normal maximum depth of extraction, below which technical difficulties and hence costs increase, is 20m. Potential resources located below this depth have therefore been excluded.

3.11.17 ***Working conditions:*** in general, resources located above the water table are significantly cheaper to extract than those below the water table. Extraction below the water table may also cause significant environmental problems due to contamination of ground-water, alteration of the ground-water circulation system, leakage of water used in processing into river systems and disposal of water saturated with mud washed from the mineral removed. In the Lower Ribble Valley, notably the Brockholes sand and gravel site, extraction has been close to, or at, the water table and so this is not a barrier to extraction (Chiverrell pers comm).

3.11.18 ***Deleterious materials****:* deleterious materials are naturally occurring rocks, sediments or minerals such as coal, shell beds, peat and alkali-silica reactive minerals that reduce the quality of mineral aggregate or make them unsuitable for use by reducing their load-bearing or shear strength or causing chemical reaction when mixed with cement in concrete production. This information may be difficult to gauge from the available data.

3.11.19 ***Methods for identifying potential resource areas***: traditional approaches to the identification of workable sand and gravel (soft aggregate) reserves in the UK have varied from standard geological drift mapping, with borehole support, to more deductive use of sediment and landform relationships discerned through programmes of geomorphological mapping (Crimes *et al* 1992; 1994). This project has applied a sediment/landform approach and the integrated geomorphic and lithofacies models to identify and predict the distribution, quantity and quality of sand and gravel deposits (after Chiverrell *et al* forthcoming). A series of sand and gravel surveys in Wales and Lancashire has underpinned this approach; consequently, its focus spans a variety of former glacial and fluvial depositional environments. Within these areas, geomorphological mapping has demonstrated that considerable potential reserves of sand and gravel were deposited during and immediately after the retreat of the ice sheets of the last glaciation (Crimes *et al* 1992; 1994). Within these areas, economically extractable sand and gravel deposits are associated with certain sediment/landform assemblages, particularly sandur, pro-glacial alluvial and sub-aqueous fans, deltas, kames, eskers, and river terraces. Understanding the spatial sedimentological relationships and geometries within the landform types allows construction of palaeogeographical models for different depositional settings. This sediment-landform assemblage approach provides a methodology for predicting the distribution, character and quality of sand and gravel reserves.

3.11.20 Technological and methodological developments in recent years, particularly the development of high-quality digital elevation models (DEMs) (*Sections 3.4.3*-5), provide considerable scope for improving the quality and accuracy of mineral aggregate spatial databases. Integrating the information available within a highly resolved DEM, with detailed field mapping and more accurately described field truthing, can improve our understanding of the relationships between landforms and allow the production of refined spatially accurate sediment-landform models. These palaeoenvironmental models provide a framework for assessment, mapping and quantification of sand and gravel reserves.

3.11.21 Investigations of how both glacial and fluvial systems behave in terms of transport and deposition of debris have resulted in the generation of models of landform-sediment relationships, which can be used to identify potential mineral aggregate resources. The basis of these models is the recognition that particular types of landform are associated with particular types of sediment, because the landform reflects the depositional process that created it. This leads to the concept of the sediment-landform assemblage, which is defined as an area in which relatively homogeneous geomorphological, stratigraphic and lithological characteristics occur. The identification of sediment-landform assemblages therefore provides a first approximation for potential mineral resources. Four major sediment-landform assemblage zones can be recognised within the British Isles that often provide deposits utilised as reserves of sand and gravel by the aggregate industry.

3.11.22 ***Sub-glacial assemblage zone***: this includes all the landforms and sediments generated by the erosion, transportation and deposition of debris at the base of a glacier and can be divided into two sub-assemblages.

3.11.23 A sub-glacial erosional assemblage, normally associated with upland glaciation, is dominated by erosion over deposition and is characterised by the extensive occurrence of glacial erosional landforms at a wide range of scales from large cirque basins to small ice-moulded rock landforms (Johnson 1985). This assemblage covers most mountainous areas of Britain, which are, as a consequence, relatively free of glacial deposits. Where glacial deposits occur they are predominantly composed of diamict deposited in thin, irregular, often impersistent sheets. Sand and gravel occasionally occurs within diamict as a response to deposition by subglacial streams but this is often thin and discontinuous. Consequently, this assemblage has very limited aggregate potential and what occurs is frequently of low volume, is very coarse, and difficult to identify.

3.11.24 A sub-glacial depositional assemblage, in contrast, is normally associated with lowland glaciation in which eroded materials are transported through the ice and frequently redeposited further down the flow direction (Crimes *et al* 1992). This process often leads to very thick accumulations of subglacial diamict and the generation of a characteristic set of ice-moulded depositional landforms, including drumlins. Although some small areas of sand and gravel occur in isolated esker systems formed in tunnels at the base of the ice, the predominance of diamict ranks the aggregate potential of this assemblage as very low. Within the sub-glacial assemblage zone, three depositional landform types can be identified.

- *Diamict plains* are areas of relatively low amplitude, subdued topography underlain almost entirely by diamict. Where the diamict is very thick the surface is often flat and featureless and often poorly drained. These deposits are highly variable, often partly consolidated, unsorted, with high quantities of fines; consequently, their aggregate potential is negligible.
- *Drumlins* are elongated, smooth ridges on a scale of up to 1km in length, 50m high and a few hundreds of metres wide. They occur in fields, commonly with what is called a 'basket of eggs' topography. They display a common orientation running parallel with the former ice-flow direction, and are formed under fast-flowing, thick ice during episodes of major subglacial flooding, the drumlin form being a type of bedform. They are almost wholly composed of diamict except where the rapid advance of ice has moulded previously deposited well-sorted sand and gravel into drumlins, but for the most part their aggregate potential is negligible.
- *Eskers* are long, narrow, sharp-crested, often sinuous ridges up to 20m in height and are composed of sand and gravel. They represent the former position of subglacial tunnels draining the base of the ice and preserved as a 'cast' of the tunnel form, complete with its sedimentary fill. This provides good aggregate potential as the ridge form is easily exploited, but often, reflecting the high velocity of flow in subglacial tunnels, the sediment is very coarse.

3.11.25 ***Ice-marginal assemblage zone:*** this includes all the landforms and sediments deposited at the margin of a glacier. By definition, the velocity of a glacier reduces to zero at the snout and all the debris contained within and beneath it is, as a consequence, rapidly released, often in very significant volume in what is termed an ice-contact environment. Because of the rapidity of snout positional changes, wide varieties of depositional environments are generated, including ice-front alluvial fans, ice-marginal sandur and temporary lake basins. Much of the associated deposition takes place over ice which, on melt, collapses, causing complex ice-disintegration topography to be created. At the same time moraine ridges are generated, either by accumulation of debris at the margin or by bulldozing movement of the ice. Together these processes create a very distinctive suite of landforms associated with complex sequences of diamict, gravel, sand and mud. Consequently, they form potentially good sources of aggregate; they are easily identified but often difficult to extract due to their inherent coarse grain and complex inter-digitation with diamict and mud.

3.11.26 Ice-front alluvial fans accumulate at the immediate ice-margin, often on the ice itself, from meltwater stream exit tunnels. They are characteristically steep and very coarse-grained, reflecting the high velocity of flow in the feeding tunnels, and are often intercalated with sheets of diamict formed by slumping from the immediate ice-margin. Their aggregate potential is consequently low, due to the high proportion of waste and cobble and boulder content. Marginal sandur form when meltwater draining the ice-margin is obstructed by older moraine in the immediate pro-glacial area and flow is directed parallel to the ice-margin rather than directly away from it in relatively narrow, flat-floored troughs. Deposition within them is invariably coarse and often mixed with diamict formed from slumping off the adjacent ice-margin. Consequently, their mineral potential is moderate, owing to the volume of unusable coarse gravel and waste.

- *Kame terraces* are areas of mounded topography that occur in irregular bands or linear sets of isolated mounds. They form at the edges of glaciers which abut against steep rock slopes either along the flanks of valley glaciers or the edge of lowland ice-sheets. Meltwater sedimentation is channelled between the ice-margin and the rock slope and deposition takes place in a linear trough on or against the ice. In some cases the trough grades down-ice into marginal sandur. When the ice beneath the trough melts out, the sediment above collapses to form irregular 'kame mounds' and water-filled basins (kettleholes). When the ice-margin retreats, the inner margin of the trough of sediment accumulation collapses to form an irregular terrace edge. Mineral potential is relatively low because of the generally coarse nature of the trough fill and abundance of diamict.

- *Moraines* are linear or arcuate ridges up to 50-60m high formed at the margin of glaciers. They often occur as successive parallel ridges where each ridge represents either a temporary stillstand during retreat or a subsequent re-advance limit. The term 'moraine' is used in the literature to describe both a landform and a deposit; to avoid confusion the term is used here to identify a landform only. In the absence of exposure it is often difficult to classify moraines correctly on geomorphological criteria alone, as their form is often similar. A number of different moraine types can be distinguished, based primarily on their internal structure and composition, and only partly on their form.

- *Ablation moraines:* these form at the margin of the glacier by supra-glacial debris sliding off the surface of the ice-margin, or melted-out from within the ice itself and accumulating as a wedge of sediment against the snout. They are almost invariably composed of diamict and their aggregate value is minimal.

- *Push moraines:* these form by the bulldozing of debris lying in the immediate pro-glacial zone by the forward movement of the glacier during re-advance or minor snout oscillation. They are commonly highly deformed internally and their lithological composition depends upon the type of sediment incorporated from the pro-glacial zone. If this includes sand and gravel then the aggregate potential of the push moraine ridge may be high; if it includes diamict it will be low.

- *Kame moraines* are similar to kame terraces but are usually larger and more complex. They form at the snout of a stagnating glacier by the accumulation of both diamict and outwash on top of buried ice. As the ice melts a complex area of ice-disintegration topography is generated, consisting of small-scale ridges, mounds and basins, often in wide linear belts. The mineral potential is variable and depends upon the sediment of which they are composed.

3.11.27 ***Pro-glacial assemblage zone:*** this includes landforms and sediments deposited beyond the margin of a glacier. At the snout all the water derived from melt of the glacier is discharged from exit tunnels into very large melt water streams that carry exceptionally high loads of sediment. In many pro-glacial environments large lake systems develop, dammed by ice margins or moraines, or impounded in over-deepened rock basins. These act as major sediment sinks as meltwater streams immediately drop their sediment load on entry into a lacustrine system as either deltas or sub-aqueous fans. Consequently, these settings have high, good-quality aggregate potential. Within the pro-glacial assemblage zone, two depositional landform types can be identified.

- *Sandur* act as major pro-glacial sediment sinks and are formed by the lateral and vertical accretion of sediment deposited by meltwater stream systems emerging from a glacier and fanning outwards into the pro-glacial area. Reflecting the decline in stream power they decrease in surface gradient downstream and progressively deposit finer-grained sediment, and are size sorted. The upper deposits are coarse gravels, the central deposits are finer gravel and sand, and the lower deposits are fine sands and silt. As a potential mineral resource they contain clean, well-sorted gravels, sands and silts, in ordered succession, and often very thick.

- *Deltas* form when sandur stream systems enter lake basins or the sea and, due to a reduction in velocity on entering the water, the sediment is rapidly deposited. Most deltas show a three-fold internal structure. Topsets are deposited across the delta surface by progradation of the sandur system and are composed of gravel; fore-sets are deposited by avalanche down the delta slope immediately beyond the water-line and are usually composed of sand; bottom sets are deposited across the floor of the lake by suspension from the fine-grained sediment in the input water and are usually composed of silt and clay. Sub-aqueous fan systems are similar to deltas in form except they lack the topset component, and more accurately should be within the ice-marginal assemblage zone, given the need for direct ice-contact with the waterbody. There is a degree of overlap between sandur, delta and sub-aqueous fans, because if the sub-aqueous fan grows to break the water surface, delta-style sedimentation occurs, and in turn with delta progradation or ice retreat, sandur develop. Delta and sub-aqueous fan sediments are frequently dissected by fluvial action to form a series of incised terraces during and after drainage of the pro-glacial lakes, or as sea level falls in response to eustatic and isostatic factors. The topset and fore-set components of delta sediments represent significant, well-sorted aggregate resources, but the bottomset are usually too fine for use.

3.11.28 ***Non-glacial fluvial assemblage zone:*** sediment and depositional landforms lain down under non-glacial conditions have also proven valuable aggregate resources.

- *River terraces and valley alluvium*: following ice retreat, fluvial processes became dominant and stream systems attempted to adjust their courses through the cover of glacial deposits. As the sea level was low in the early Holocene, the glacial deposits were rapidly dissected by down-cutting streams and much sediment was removed, leading to the deposition of river terraces further downstream. As much of the finer sediment was washed out into the sea these terraces were formed of relatively clean, well-sorted sand and gravel, forming good potential mineral resources. However, many of these river terraces are only a few metres above modern river level and are difficult to work, as excavation extends below the watertable.
- *Alluvial fans:* following glaciation, many tributary valleys were left ‘hanging’ as a consequence of glacial over-deepening of the main valley. During the Late-Glacial and early Holocene, much of the debris lying on valley slopes was flushed out to form substantial alluvial fans, even for relatively small tributaries. These can provide an aggregate resource, especially in isolated areas, but can be contaminated by fines lain down by debris flows.

3.11.29 ***Identification and assessment of individual Resource Blocks:*** from the geomorphological maps generated for the Ribble, a filtering process was used to identify potential Resource Blocks. The first level of filtering was by the type of geomorphological feature. Thus, features identified as sandur, marginal sandur, ice-front alluvial fans, deltas, kames, kame terraces, eskers and river terraces were all included as, reflecting their depositional environments, they are likely to contain potential mineral. Features identified as diamict plains, drumlins, lake floors, push-moraines and ablation-moraines were excluded as they are unlikely to contain potential mineral. Within the river terraces, a further filtering was undertaken to exclude all except river terraces 1 and 2, because the lower river terrace of the Ribble, terraces 3 to 5, comprise fine-grained alluvium. The second level of filtering was done on the basis of pre-existing borehole information and section detail reported in the literature. Thus, if a pre-existing borehole provided confirmatory information of quality aggregate it was included, otherwise unpromising prospects were excluded. Each resource block identified normally equates to an individual geomorphological feature, though in some cases several adjacent features of similar type are combined together.

3.11.30 ***Calculation of mineral volumes for prospects***: one of the principal aims of geomorphology-based sand and gravel assessments is the accurate gauging of the volume of a deposit. Detailed accurate borehole information (provided by BGS) characterises and describes the composition of the prospect, and without this information there is a great deal of uncertainty associated with sand and gravel assessments. It is in the volumetric assessment of landform geometry that DEMs and GIS come into their own, because the software allows the rapid calculation of the volumetric fill for a landform or shape, compared with another surface, typically the base of the deposit. Recent practice in volumetric estimation of aggregate reserves has been two-fold (Crimes *et al* 1994); the first has been to apply an estimated averaged deposit thickness to the resource block area to calculate volume, and the second, more complicated approach, involved producing isopachytes of equal mineral thickness and relating this to the area between two isopachytes. The second approach takes account of variations in surface elevation and mineral thickness, and is analogous to the GIS approach using OS Profile data, but has less precision and accuracy. Using a DEM-based approach represents a clear methodological improvement; however, it must be stressed that volumetric estimate of aggregate within resources blocks must take account of other areas of uncertainty, including product to waste ratios and overburden thickness, which need to be taken into consideration.

3.11.31 ***Clitheroe Esker Ridge:*** on the esker ridge near Clitheroe, this test example used a uniformly flat estimate of the probable base of the deposit (68m OD). The estimated volume of deposit within the esker form highlighted in *Section 3.4.6* (Fig 35), using the same outline shape mapped from the LiDAR data, are 4,777,560m^3, 4,840,490m^3 and 4,522,620m^3 respectively for the LiDAR, NextMAP and OS Profile DEMs. Comparison of the volumetric assessments undertaken using outlines defined independently from the different DEM products provided very similar results. These values, although broadly comparable, show that the OS Profile prediction is lower than the other two, which is a function of the generalisations involved in the production of the OS Profile data.

3.11.32 ***Example of fluvial terraces:*** examples of the primary aggregate prospects of Terrace T1 near Hothersall Hall and Terrace T2 near Osbaldeston Hall (Fig 36; *Section 3.4.9*) provide an indicator of the volume calculation. The aggregate resource associated with these terraces in the Lower Ribble Valley is typically *c* 4m and 2.5m in thickness respectively for Terraces T1 and T2, which indicate that the two prospects may contain *c* 1.6 and 0.9 million tonnes of sand and gravel. As the industry works by weight of aggregate, all volumes have been converted from cubic metres, derived from area times thickness calculations, into metric tonnes using a value of 1.6 tonnes per cubic metre as the average *in-situ* bulk density. In some consolidated deposits this figure may be higher (up to 2.0 tonnes per cubic metre) but is unlikely to be much lower. Tonnages quoted are therefore minimum estimates, within the limitation of the volumetric calculation. The quantities of mineral associated with the Late-Glacial and early Holocene river terraces of the Ribble Valley are significantly lower relative to the prospect area than glacigenic landforms, including the nearby (10km) small esker ridge form near Clitheroe (*Section 3.4.6*), which has projected volumes three times greater than these river terraces (*c* 4.8 million tonnes).

3.11.33 ***Reliability of volume and quality estimates***: Resource Blocks have been classed into categories of reliability to reflect the sources of information available about each block and the method used for estimating volume and quality. These categories generally equate to the method of assessing resource-block volume and quality used, but also take into account uncertainties in landform identification, variations in the thickness of overburden, and waste.

- *High:* this is used where borehole information is available and is consistent in terms of thickness, broad grain-size and thickness of overburden. Some reliance may be placed on these estimates in the immediate vicinity of borehole locations but should not be extrapolated to adjacent areas as glacial and fluvial deposits can vary considerably over short distances.

- *Medium:* this is used where there is no borehole information, but some sample information is available from either exposed section. These estimates have a moderate margin of error but should be used with caution. A detailed drilling and sample testing programme should be undertaken before exploitation of blocks classed as of medium reliability is considered. In the case of the older river terraces of the Ribble Valley, confidence may increase because the landform suite demonstrably comprises sand and gravel throughout the Lower Ribble.
- *Low:* this is used where no borehole, sample or exposure information is available. Volume and grain-size distribution estimates are based on comparison with other blocks of similar geomorphological character and the general geological conditions in the area. Nevertheless, any estimates have a wide margin of error and should therefore be used with very considerable caution. A detailed drilling and sample testing programme should be undertaken before exploitation is considered, on blocks classed as of low reliability.

3.11.34 ***Environmental constraints***: Resource Blocks have been classified according to the degree to which they are constrained by highway access, proximity to market, environmental designations and planning zonation. It should be noted that the significance of the latter factors can vary due to changes in planning policy or commercial conditions. Similarly, environmental constraints are rarely absolute and policy towards them often changes in the light of changed economic conditions.

3.11.35 Consequently, an assessment of any particular resource block as of high commercial potential should not be taken as a recommendation. It has been assumed that, with the exception of National Parks, SACs, SPAs and RAMSAR sites, all other environmental designations or planning constraints do not, necessarily, preclude the possibility of mineral extraction. The method of assessment used applies a ranking that takes into account the potential value of the prospect and offsets it against likely restrictions.

3.11.36 ***CAESAR and the available data resources:*** CAESAR (Cellular Automaton Evolutionary Slope and River model) is a dynamic geomorphological model that simulates the movement of water and sediment and the development of landforms in river catchments and on floodplains (Coulthard *et al* 2000). The model is based on a regular grid of cells within a digital elevation model (DEM) that is a representation of the landscape. A catchment hydrological model drives the downstream movement of both water and sediment from slopes to tributary streams and to the main river channel. Each cell stores key geomorphological data: elevation; slope; water and sediment discharge; grain-size distribution; and these are updated over small time steps (ie seconds to minutes) across the entire catchment (Fig 47). This type of dynamic modelling approach will facilitate assessment of likelihood of future geomorphic change under various climate scenarios and assessment of the predicted risks for the geoarchaeological heritage. A variety of data sources was compiled to contribute to the CAESAR modelling, and these were the production of high-quality DEM, river discharge data to validate the model outputs, contemporary precipitation data to drive the model, and future climate change projections to provide scenarios for future precipitation.

3.11.37 The Ribble Valley is well represented in the *National River Flow Archive* (Centre for Flow and Hydrology 2007), with the responsibility for the 13 gauging stations within the Ribble basin lying with the Environment Agency (Fig 48). In terms of characterising flow within the main channel and major tributaries, the following stations are important: the Samlesbury station represents flow in the main Ribble system; the Blue Bridge station does the same for the Darwen; Whalley Weir station for the Calder; Hodder Place station for the Hodder; and Henthorn station for the Upper Ribble. Daily discharge data are readily available for Samlesbury from the *National River Flow Archive* (Fig 49). Precipitation data are available for several meteorological stations across the Ribble catchment, with the longest hourly record available from Preston. There appears to be a strong relationship (Fig 49) between daily discharge at Preston and rainfall at the top (Stainforth) and bottom (Preston) of the catchment. Comparisons of the annual rainfall totals shows an increase of 200-350mm between the lowland Ribble and the Pennines headwaters; consequently, rainfall data from Preston, which are the most complete and provide hourly time-step data, are appropriate for characterising both the precipitation pattern and discharge response of the Ribble.

3.11.38 ***Modelling initial conditions and testable scenarios:*** modelling of this type is extremely time intensive and consumes considerable amounts of computing power. The modelling used a digital elevation model derived from LiDAR, NextMAP and OS Profile datasets, amalgamated in that preferred order to produce a new 10 x 10m DEM for the entire catchment. To streamline the modelling process, the DEM was subdivided into four sub-catchment areas: the Hodder; Upper Ribble; Calder; and the Ribble downstream of the Ribble, Hodder and Calder confluences. The river gauging stations in the Ribble catchment are opportunely situated to validate the modelled discharges for these sub-catchment areas. The DEMs were rescaled to 50 x 50m spatial resolution, because this reduction in resolution significantly improved model run-times and minimised negative impacts on the model output. The model had to be run for the three headwater reaches: Hodder; Upper Ribble; and Calder. The hourly discharges from these rivers were recorded throughout the modelling period and the hourly discharges were then totalled for the three rivers to provide a discharge into the top of the Lower Ribble downstream of the Ribble, Hodder and Calder confluences. CAESAR was then run again, in what is termed a reach mode, using a better resolution DEM, 10 x 10m spatial resolution, for the entire period using the modelled discharges.

3.11.39 Historical and future climate modelled data were compiled from the UK Climate Impacts programme (UKCIP 2002). These data were used to identify the average climate for the catchment, and to produce average monthly rainfall and annual rainfall totals for the catchment. The aim of this analysis was to use daily Preston rainfall data to drive the dynamic geomorphic model; consequently, this Preston rainfall series has been factored to reflect catchment average rainfall totals. A future precipitation rainfall series for Preston was created based on the most likely extreme changes evident in the UKCIP scenarios for future precipitation. For example, UKCIP model predictions of increased rainfall for August in 2080, under their high emissions scenario, are shown in Figure 50. These monthly rainfall totals were used to manipulate the Preston long-term hourly rainfall data and generate a Current and a Future catchment average precipitation series, which was used to drive the CAESAR modelling. Because the model runs were carried out for three different sub-catchments, individual precipitation series were generated for each of the headwater reaches.

3.11.40 The Environment Agency has modelled the impact of climate change on the 1% fluvial event as an increase in river flow of *c* 10-20% (Environment Agency, *Draft Plan* 2006). It is now widely accepted that the UK's climate is changing over time and the reasons are thought to be the build-up of greenhouse gases (eg carbon dioxide and methane) in the Earth's atmosphere. What this means for changes in future flood risk is not well understood; however, recent research by the UK Climate Impacts Programme (UKCIP 2002), indicated that winter rainfall intensities (and therefore flood flows) might increase by as much as 20% by 2050.

3.11.41 The UKCIP (2002) scenarios show that various sub-catchments of the Ribble basin are in an area with increased winter precipitation (increase of up to 25%) and decreases in summer precipitation (decrease of up to 35%) for both low and high emissions runs (Fig 51). The UKCIP data also suggest that the number of 'intense' rainfall days may increase in winter and decrease in summer. The Environment Agency suggest that this may result in an increase in winter river flow and therefore flooding in the catchment, particularly in areas vulnerable to main river flooding. Areas susceptible to flash flooding from intense rainfall events (for example Darwen and Trawden), plus areas susceptible to flooding from culverts, may see an increase in flooding during the winter and a decrease in flooding during the summer.

3.11.42 The CAESAR modelling undertaken for this project assessed the geomorphic response of the catchment to 1) contemporary and 2) increased precipitation. Both these model runs lasted for a simulated time period of 20 years and provided indications of the potential for geomorphic change under two different sets of climatic conditions. These climate scenarios are end members of the range of UKCIP climate predictions.

3.11.43 ***Identification of potential for geomorphic change:*** the processes of erosion and deposition simulated by CAESAR result in changes to the elevation of geomorphologically active DEM grid cells. The most important output data produced by the model is a raster GRID of cumulative elevation changes modelled within a given catchment or reach over a given time period. While the amount of land-surface change, exemplified by surface lowering by erosion, surface raising by deposition, or no change in elevation, will vary spatially, for the purposes of the present project the landscape has been classified into areas with the greatest potential for change either by erosion or deposition. Variations in the degree of change have not been considered. Within ArcGIS, the following steps were undertaken to transform the CAESAR-derived elevation difference GRID into a feature class suitable for integration within the Ribble geodatabase:

1) zone the GRID into three classes that represent the nature of change, and these were 'erosion', 'no change', 'deposition';
2) convert the classified GRID into a three-band (RGB) TIFF image;
3) convert the TIFF image into a polygon shape file with areas for each of the colour classes.

3.12 ENHANCING AN UNDERSTANDING OF THE ARCHAEOLOGICAL RESOURCE

3.12.1 ***General Methodology***: several key techniques were used to enhance the HLC and to model the archaeological potential. They include the conversion of vector data to raster, and the use of the Kolmogorov-Smirnov (KS) test.

3.12.2 ***Raster Conversion***: this process involves creating a grid across the study area, with the value of each cell representing the value of a given variable at that point. For example, in converting an elevation model into a raster, each cell would contain the average elevation at that point.

3.12.3 When converting vector data to raster, several parameters must be taken into account. The first is the cell size of the resulting raster. A smaller cell size is more detailed but results in a larger overall file size, and when converting point data to raster, a large cell size may also result in several closely grouped points being merged into the same cell. Originally a 5m cell size was used, but this proved unworkable, as each task took a considerable amount of time to complete, and the resulting cell sizes were unmanageable. During the second phase of analysis, a 10m cell size was used, being a good trade off between file size and loss of detail.

3.12.4 The second parameter is the extent of the raster. In general, the raster is a square delineated by the extent of the shape file being converted, but it can be 'masked', using a second dataset to block out areas that are not required. In this case, the polygon, representing the outline of the study area, was used as the analysis mask. This has the advantage of further reducing the file size of the raster and producing a more visually attractive image.

3.12.5 ***KS test:*** the Kolmogorov-Smirnov (KS) Goodness-of-Fit test (Kvamme 1990) was used to compare statistically the location of the monuments of each period to particular background variables, such as environmental parameters or HLC classification. This is a one sample statistical test that compares a sample (in this case the location of monuments) against a background standard (the whole study area).

3.12.6 To run this test, a combination raster must be created, that contains values for every combination of the constituent rasters. Normally this is a continuous environmental parameter such as elevation or slope, and a discrete set of points such as the location of archaeological monuments. The ArcMap raster calculator 'Combine' function was used to create this raster, and the data table behind it was then exported into Excel, where the calculations for the KS test could be run. Table 16 shows the count of cells and their corresponding presence or absence (PA) of Roman monuments at defined elevation intervals. Table 17 shows an example of the exported data table in Excel used for KS calculations.

Elevation (m)	Roman PA	Count
0	0	7697
25	0	276919
25	1	12
50	0	222416
50	1	56
75	0	496124
75	1	15
100	0	259236
100	1	4
125	0	100367
125	1	1
150	0	35803
175	0	12488
200	0	5776
225	0	3148
250	0	813

Table 16: Attribute table for raster combining Roman presence or absence map, and elevation

3.12.7 To run the KS test, the columns were set out as in Table 17. The frequency (F) is defined as the count for a given elevation value, divided by the total count (in bold italics). The cumulative frequency (CF) is the sum of the frequencies working down the elevation values, in other words the CF for 50m is the sum of F(0), F(25), and F(50). The difference (Diff) between the CF for Roman Presence and the Total CF was then calculated, and the absolute value (Abs Diff) taken. Finally, the maximum of Abs Diff (DMAX) is found. This is then compared to a critical value (d), which is a measure of the sample size and confidence interval (σ). The confidence interval is gained from generally agreed tables, and for the social sciences a value of 95% is normally used, for which σ = 1.36, leading to the formula: d=1.36/√(total size of sample). If DMAX –d is positive, then there is a statistical correlation between the sample and the background standard, in this case the hypothesis that the location of Roman monuments within the study area is influenced by elevation.

3.12.8 ***Enhancement of the HLC - basic preparation***: at the start of the project the completed HLC for Lancashire was made available to the project (Ede and Darlington 2002). This consisted of two datasets, the first containing every individual land parcel as a single polygon, and with the detailed individual landscape types assigned, and the second with broad landscape types assigned but with all the parcels of a particular type merged into one record (Fig 52). As analysis required individual polygons for each land parcel, but with the HLC broad type, the ArcMap Append Tool was used to add this information to the required dataset.

Elevation (m)	Count Roman Presence	Roman F	Roman CF	Count Roman absence	Total Count	Total F	Total CF	Diff	Abs Diff
0	0	0	0	7697	7697	0.005417	0.005417	-0.00542	0.005417
25	12	0.136364	0.136364	276919	276931	0.194902	0.200319	-0.06396	0.063955
50	56	0.636364	0.772727	222416	222472	0.156574	0.356893	0.415835	0.415835
75	15	0.170455	0.943182	496124	496139	0.349178	0.706071	0.237111	0.237111
100	4	0.045455	0.988636	259236	259240	0.182451	0.888522	0.100114	0.100114
125	1	0.011364	1	100367	100368	0.070638	0.95916	0.04084	0.04084
150	0	0	1	35803	35803	0.025198	0.984358	0.015642	0.015642
175	0	0	1	12488	12488	0.008789	0.993147	0.006853	0.006853
200	0	0	1	5776	5776	0.004065	0.997212	0.002788	0.002788
225	0	0	1	3148	3148	0.002216	0.999428	0.000572	0.000572
250	0	0	1	813	813	0.000572	1	0	0
	88				***1420875***				
								DMAX	0.415835
								d	0.144976
								DMAX -d	0.270858
								CORRELATION	

Table 17: Example of KS test calculations on Roman monuments and elevation

3.12.9 The county-wide HLC dataset was 'clipped' in ArcGIS to the boundary of the Lower Ribble Valley study area. In some cases this broke previously single polygons into two or more pieces, which then had to be re-merged. Further analysis indicated that there were areas, known as 'slithers', where adjacent polygons overlapped. These are normally created during the initial process of digitising polygons on screen. It was important to remove these, as they would have a choice of two possible HLC classifications. This created a selection of 322 polygons divided into 16 broad types (Table 18).

HLC broad type	Count
Ancient and Post-medieval Ornamental	3
Ancient and Post-medieval Settlement	11
Ancient and Post-medieval Wood	49
Ancient Enclosure	91
Modern Communications	3
Modern Enclosure	20
Modern Industry	16
Modern Ornamental	2
Modern Recreation	11
Modern Settlement	32
Modern Woodland	7
Post-medieval Enclosure	71
Reverted Moorland	1
Saltmarsh	2
Sand and Mudflats	2
Water	1
Total	322

Table 18: Numbers of individual polygons in the Lower Ribble Valley study area by HLC broad type

3.12.10 Once the reduced dataset had been cleaned, a copy was made in which the original HLC attribute data could be removed. New fields were then added to the attribute table, into which additional data could be added. The new fields were:

- overall count of monument records within each polygon;
- count of prehistoric, Roman and medieval monument records within each polygon;
- overall density of monument records within each polygon;
- density of prehistoric, Roman and medieval monument records within each polygon;
- value statement regarding level of ground disturbance;
- numerical value regarding level of disturbance;
- count of known events;
- measurement of potential for prehistoric, Roman and medieval archaeology;
- measurement of overall archaeological potential;
- current threat (Deposition or Erosion or N/A, see *Section 3.13.15*);
- future threat (Deposition or Erosion or N/A, see *Section 3.13.15*);
- suitability for aggregate extraction.

3.12.11 Using the Intersection tool in ArcGIS it was possible to calculate many of the attributes within each HLC polygon, and this was also used to assign the HLC polygon number to each monument and event located within it.

3.12.12 Data on aggregate extraction suitability, along with calculations of threat and erosion from fluvial change, were supplied by Richard Chiverrell as a separate polygon geodatabase feature class. These data were overlain on the HLC polygons, and the intersection tool in ArcGIS used to assign the geomorphological attributes to the HLC data.

3.12.13 The queries required to aggregate the event and monument data relating to each HLC polygon could not be constructed easily within ArcGIS as only a reduced subset of SQL (structured query language) is available. Consequently, the enhanced HLC polygon shape file needed to be converted to a geodatabase feature class. This procedure allows the data tables for shape files to be manipulated and queried within a more fully-featured database environment, in this case Microsoft Access 97.

3.12.14 Once the HLC, event, monument and geomorphological data had been amalgamated into a geodatabase, it was possible to aggregate the data together to produce a gazetteer of data relating to each polygon (Fig 52). The free-text synthesis and interpretation were then filled in manually.

3.12.15 The gazetteer was output as a Microsoft Access report, which was saved as a .pdf file, with a separate page for each polygon's entry. In ArcGIS a hyperlink field was added to the HLC geodatabase feature class, which linked to the appropriate page of the .pdf for each polygon. By clicking on a polygon in

ArcGIS using the hyperlink tool, the .pdf gazetteer then opened at the correct page for that polygon (Fig 53).

3.12.16 ***Enhancement of HLC - Lynher Valley Model***: the first attempt at enhancing the HLC records followed the methodology used by the Lynher Valley Project developed by Cornwall County Council (Cornwall Archaeology Unit 2002). The Lynher model calculates the relative significance of archaeological site occurrence within HLC classes. The archaeological monuments were divided into NMR broad classes, and the HLC, by its HLC broad types. The significance was calculated by taking each HLC broad type and calculating the percentage of the total study area that it occupies. Secondly, the number of sites of each NMR Broad Type that fall within a given HLC area are calculated as a percentage of their total number within the study area. The relative significance is the NMR representative percentage divided by the HLC representative percentage. 'A figure of 1 would be expected by chance; results greater than 1 indicate a tendency to fall within the predicted HLC types; results of 2 indicate twice as likely as chance, 8 indicates eight times more likely than chance, etc' (Cornwall Archaeological Unit 2002, 100).

3.12.17 The combination of the datasets was carried out using the Raster Calculator within ArcMap. The results of all the calculations performed were combined in an Excel table that allows checks to be made against each HLC Entry Level for both the KS test and the relative frequency. These results were weighted in terms of 'High', 'Medium' and 'Low' archaeological potential.

3.12.18 Firstly, all HLC Broad types were combined with each individual monument class for all the records in the database, producing 11 calculation maps, which were then tested against the 'goodness of fit' model. All HLC Broad types were then combined with each individual monument class for all the records in the database, producing 11 calculation maps, which were then tested for relative significance and distribution.

3.12.19 All new monument records created by this project were broken down by their type and combined with each individual HLC type, producing 14 calculation maps, which were then tested for relative significance and distribution.

3.12.20 It became apparent that there was little correlation between the datasets, so it would not be possible to use this approach to create maps of archaeological potential. Consequently, this approach was abandoned in favour of exploring environmental parameters for monument location, but HLC data were also examined to establish whether there was any statistical bias between the location of monuments of different periods and different HLC types.

3.13 MODELLING ARCHAEOLOGICAL POTENTIAL

3.13.1 ***Analysis of the Lacunae***: before modelling areas of potential for hitherto undiscovered archaeology, it was necessary to analyse the distribution of the known archaeology. It was postulated that, in general, the location of known monuments would match the location of events, and conversely that areas where no archaeological monuments had been discovered represented an absence of events rather than monuments. Areas subject to development would contain below-ground disturbance, but also of archaeological assessment, and would therefore contain more known monuments but would have a low potential for the discovery of new sites. Furthermore, land uses that caused a large amount of below-ground disturbance, such as landscaping or quarrying, would also represent areas of low potential for undisturbed archaeology.

3.13.2 To provide a broad-scale assessment of disturbance across the study area, the HLC land classification was examined, and each category was assigned a score from 1 to 3 on the level of below-ground disturbance likely to have been caused by a particular historic land use. To establish whether or not there was a correlation between the location of known monuments and the level disturbance caused by a particular land use, the KS test was again used (*Section 3.12.5*).

3.13.3 To analyse whether the location of monuments was biased towards the location of events, the ArcGIS ‘Select by Location’ tool was used, which allowed the identification of the number of monuments that occurred within set distances from events (*Section 6.4.19*).

3.13.4 ***Modelling Potential***: one method of predicting the location of hitherto unknown monuments is to analyse the environmental variables (ie slope, elevation, and distance to water) responsible for the location of known sites, and look for areas with the same variables elsewhere in the study area (*Section 6.6*). To search for this correlation the KS test was used. The initial approach was to assume that monuments of a given NMR broad class would have similar locational requirements, regardless of their period. In other words prehistoric, Roman and medieval settlements would be situated in roughly similar locations. As too few monuments would give spurious results, those classes with less than 2% of the total number of monuments were not included. Similarly, the ‘unassigned’ and ‘monument <by form>’ classes were not included.

3.13.5 The second approach was to reduce the extent of the analysis to the size of the terraces, and to run the KS test in more detail on this smaller area. However, issues with the differential coverage of the datasets were encountered and it could not be continued (*see Section 6.6.9*).

3.13.6 Thirdly, the location of monuments of a given period was analysed. This procedure produced more meaningful results (*Section 6.6.12*). The environmental variables thought to have a bearing on the location of the monuments were:

- *Elevation*: this was calculated by deriving a TIN (Triangular Integrated Network) from the Landform Profile data supplied as part of the project. This dataset is not as detailed or high resolution as the LiDAR data but offers complete coverage of the study area. The study area consists of a valley and floodplain, with 88% of the area below 100m above sea level;

- *Slope*: this is defined as the maximum rate of change of elevation. It is calculated in different ways depending on if the surface is a TIN (Triangular Integrated Network) or a raster. For a TIN the slope is calculated across each triangle in the network. For a raster it is the difference between a cell and its eight neighbours. It can be calculated in degrees or percent, with higher values representing steeper slopes. Some 91% of the study area has a slope of less than 10σ from the horizontal;

- *Distance from Water*: watercourses within the study area were derived in two ways. The first was by selecting all the features from the Ordnance Survey MasterMap data that were classified as water features. This layer comprised all water features, including modern ponds and reservoirs, so these elements were removed manually. The second was to use the palaeochannel dataset that was created by the University of Liverpool during their analysis. The MasterMap water features were originally polygons, but were converted to polylines to match the geometry of the palaeochannel dataset. These two datasets were then merged, and the ArcGIS Multiple Ring Buffer Tool was used to create buffers around the features at 250m increments, up to a distance of 1000m; this maximum distance allowed coverage of the entire study area. Initially, an attempt was made to buffer the features at 100m increments, but the resulting dataset was too large to manipulate. During the initial analysis, the palaeochannel dataset was not available, and as such the original KS tests against NMR broad class were run against the MasterMap water features alone. Also, the original buffer sizes used were 100m, 200m, 500m and 1000m, but it was felt during the later stages of the analysis that equal sized buffers were required;
- *Distance from Roman Roads*: this variable was used for the Roman and medieval datasets. A shape file of the location of the Roman Roads within the study area was provided by Lancashire HER for the project. The multiple ring buffer tool was used to create buffers at 250m increments, to a maximum of 2000m, and this covered most of the study area. Thirty-four of the Roman monuments were references to the roads, so it was necessary to remove those before running the KS test.

3.13.7 For each of the four variables, the original shapefile was converted into a raster. The original rasters contained values accurate to the metre of elevation or degree of slope. It was necessary to group these values into bands in order to run the KS test. The ArcGIS 'Reclassify' function was used to achieve this. The elevation raster was reclassified in 25m increments, the slope raster in 10° increments, and the distance buffers in their 250m increments.

3.13.8 The monuments for each period were then selected from the database and the resulting dataset also converted to a raster. The 'Condition' (con) function in ArcGIS Raster Calculator was used to assign the value 0 to all cells with no monuments in, and 1 to all cells containing a monument, in other words a presence-absence (PA) map.

3.13.9 For each of the variables, in conjunction with the monument Presence or Absence map, the Raster Calculator 'Combine' function was used to create a new raster that contained a record for each combination of variable and monument.

3.13.10 For each period the variables where correlation occurred, and the values of the variables, were ranked according to the number of monuments that occurred at that value. It was necessary to maintain consistent ranking across each period and variable, in order to provide unbiased weightings. The elevation raster was then reclassified using the rank as the new value for the cells (Table 19).

Elevation (m)	Count Roman	Rank
0	0	1
25	12	3
50	56	3
75	15	3
100	4	2
125	1	2
150	0	1
175	0	1
200	0	1
225	0	1
250	0	1

Table 19: Ranking for elevation raster reclassified according to the number of Roman sites at each level

3.13.11 The density of known features was also thought to have a bearing on the potential for further archaeological monuments within an area, as it is an indicator of increased levels of human activity in a locality. The ArcGIS Spatial Analysis Kernel Density function was used to create a density map for the monuments of each period, calculating the density of points in the neighbourhood of any given point, using radii of 100m, 250m and 500m. The resulting map highlighted fuzzy ‘hotspots’, or clusters of sites, rather than focusing on individual locations. The particular radii were chosen as they represented a compromise between too narrow (highlighting individual sites) or too broad (highlighting only the extreme concentrations of sites such as Ribchester). The density rasters for each period were then reclassified into three bands of high, medium and low density.

3.13.12 To create the aggregated maps of potential for each period, the rasters representing variables for which the KS test indicated correlation and the Kernel Density rasters were added together. The resulting combination raster had cell values that were the sum of the values of the cells in the constituent rasters. These values could again be grouped into three bands, representing low, medium and high potential, with the highest totals representing the highest potential. Finally, the maps of potential for each period were added together to create a combination raster of overall potential for archaeology.

3.13.13 It was then possible to continue the HLC enhancement process by establishing the potential for archaeology of each period within each individual HLC polygon. Four further fields were added to the HLC dataset, representing the potential for each period and overall, and the ArcMap spatial query tools were used to select out the polygons that intersected the zones of potential. Since the potential maps had been created using other datasets alongside the HLC, the boundaries between the different zones in the potential maps did not always match those of the HLC; occasionally a polygon would contain more than one level of potential. It was decided to err on the side of caution and assign the highest level of potential in those cases.

3.13.14 ***Analysis in combination with the geomorphic mapping:*** the geomorphic data supplied by the University of Liverpool was used in three ways: firstly, to continue the HLC enhancement process by highlighting the present and future threat and potential for aggregate extraction within an individual polygon; secondly, by analysing the threat to known, existing archaeological monuments;

and thirdly, in conjunction with the maps of potential, to highlight areas at greatest threat from fluvial change and aggregate extraction. The two threat datasets contained two values: deposition and erosion (*Section 8*). The aggregates dataset contained a value for overall suitability for extraction, based on a set of criteria (*Section 7.2.6-7*), with low values equating to high suitability for extraction and vice versa. This dataset was grouped into three equal bands, representing high, medium and low suitability, for the purposes of updating the HLC.

3.13.15 The procedure for updating the HLC dataset was the same as that described in *Section 3.2.16*. A further three fields were added to the HLC attribute table to represent the two threat levels and the aggregate extraction potential. During the procedure of updating the threat fields, in the case where an HLC polygon intersected with areas of deposition and erosion, it was assigned a value 'deposition/erosion'. HLC polygons that did not intersect with the threat mapping at all were assigned a value 'N/A'. When updating the aggregate suitability field, if a polygon intersected with more than one band, it was assigned the highest level of potential suitability. Again, if a polygon did not intersect with the suitability mapping it was assigned a value of 'N/A'. To analyse the threat to existing archaeology, the known monuments of each period that fell within polygons with a threat of aggregate extraction suitability were highlighted using ArcMap's Spatial Query tools.

3.13.16 The geomorphic datasets were converted into rasters, using deposition or erosion for the threat mapping values and extraction suitability for the aggregate mapping, with a cell-size of 10m. For each geomorphic dataset and each map of archaeological potential by period, the Combine function in ArcMap's Raster Calculator tool was used to add the two rasters together. The resulting dataset had individual values for each combination of potential and threat from the constituent rasters.

