Regional climatic *versus* local controls on periglacial slope deposition: A case study from west Cornwall

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Diamictic breccias, interpreted as slope deposits formed under Quaternary cold-climate conditions, are described from St Loy, west Cornwall coast. These deposits (8 m thick) overlie a granite platform that varies from strongly weathered to cleanly planated. Within the slope deposits are dated organic-rich silts that were formed under a cold-climate, boulder clusters (interpreted as a raised beach), and large bedrock slabs (interpreted as a rockfall deposit). The range of sediments and structures observed at St Loy demonstrates the interplay between regional climatic and local basinal controls on slope deposition, and the importance of the underlying granite bedrock in sediment generation/supply.

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Introduction

In contrast with much of the British Isles, south-west England was likely not glaciated during the Quaternary era (last 1.8 Ma) (Stephens, 1970; Bowen *et al.*, 1986; Scourse, 1996; Cullingford, 1998; Clark *et al.*, 2004). Although, therefore, unaffected directly by the sediment generation and erosion processes associated with glacial action, this also meant that it was unaffected by the presence of regional stratigraphic unconformities, formed during ice advance, which have the unfortunate effect of truncating the sediment record (Croot and Griffiths, 2001). South-west England is therefore of interest because its non-glacigenic Quaternary record potentially extends back farther in time than in other parts of the British Isles, and may therefore provide a more detailed record of climatic and environmental changes over (parts of) this time interval (Bates *et al.*, 2003). These sediments also have a generally high preservation potential due both to the absence of glacial erosion, and the presence of rock-bounded basins (often related to river incision, particularly in lowland areas) which provide ideal sediment depocentres (Cullingford, 1998; Croot and Griffiths, 2001; Bates *et al.*, 2003).

Quaternary-age sediments found on these coastal lowlands and in rock-bounded basins include wind-blown, beach and shallow-marine sands, beach gravels, and cold-climate (likely periglacial) slope deposits, generically termed ‘head’ (Harris, 1987, 1998; Ballantyne and Harris, 1994). In south-west England, the bedrock platforms upon which all these sediments are built likely extend back to at least the interglacial of marine oxygen isotope stage 9 at *c.* 340 kyr BP (Bowen, 1994; Scourse and Furze, 2001; Bates *et al.*, 2003). Although the overlying sediments, therefore, potentially cover a wide time span, they are also likely characterised by significant depositional hiatuses and erosional truncations. These limit the potential for entire sediment sequences to be either correlated between different locations, or to be a continuous record of climate, although parts of these sediment sequences may be useful lithostratigraphically.

Aims

This paper aims to investigate the processes of slope sediment deposition, under cold-climate (periglacial) conditions, at St Loy (west Cornwall coast). In detail, this paper (1) describes the Quaternary-age sediments exposed at St Loy; (2) considers the major processes contributing to sediment deposition at this site; and (3) evaluates the relative roles of local versus regional (climate) controls on Quaternary slope sediment activity and formation of the slope sediment record.

Description of field evidence from St Loy

At St Loy (grid reference SW 1425 0231), located 8 km west of Penzance (Figure 1), a boulder beach overlying a weathered and eroded Land’s End Granite platform is backed by cliffs (< 8 m high) mainly comprising Quaternary slope deposits (Scourse, 1987). The sediments at this site have been previously described by a number of workers, most recently by Scourse (1996) who identified a range of slope deposits, which are interbedded with organic and non-organic sandy silts. Four flat-lying sediment units are laterally continuous across this site, and are shown in Figure 2.

In the western part of St Loy’s Cove (Figure 1), the surface of the granite platform is smoothly eroded with shore-normal furrows developed along bedrock joints (Figure 3). The platform surface is overlain sharply by 1 m of sub- to well-rounded local granite and exotic cobbles (< 10 cm diameter) which form a poorly sorted and massive diamicton (unit 1). The diamicton varies from clast-supported to sandy matrix-supported. Occasionally clasts are arranged into flat and discontinuous lines, and in some locations thin, sandy interbeds are present. These interbeds have a wavy geometry and pinch out laterally. Some clast-poor areas within the diamicton, often located beneath or adjacent to larger clasts, are composed of sorted, massive granules. Unit 2 is a boulder-rich facies (0.2-1.0 m thick) comprising sub- to well-rounded local granite clasts (< 1 m diameter). The unit varies in thickness laterally, depending on the concentration and size of clasts contained within it, and usually has a sharp and planar lower boundary and a more diffuse upper boundary. The clasts within the unit are usually touching, arranged in clusters, or may be supported by a matrix comprised of granules to pebbles. Some adjacent clasts are also arranged such that their upper surfaces form a flat pavement (Figure 4). Occasionally, clasts are separated by a moderately well-sorted coarse sand to granule matrix which drapes the upper surface of some clasts.

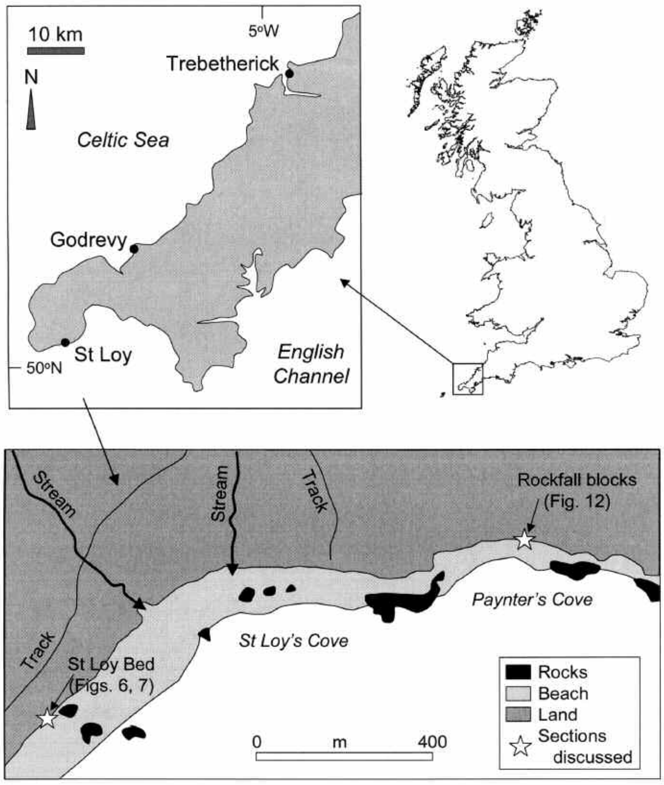

Figure 1. *Map of west Cornwall showing the location of St Loy, the sections discussed, and the location of other sites mentioned in the text.*

Unit 3 (2-3 m thick) comprises vaguely stratified granule to fine gravel beds (Figure 5). These beds (15-30 cm thick), identified on the basis of variations in matrix grain size, are laterally continuous and have undulating boundaries. Granite clasts (< 15 cm diameter) within these beds are subangular to subrounded, are usually dispersed throughout the unit, and do not touch one another. The upper boundary of this unit is transitional to the overlying unit 4 (Figure 5). Also contained within unit 3 are deformed organic-rich silts to granules that form a discontinuous bed (40-50 cm thick) located towards the base of the unit (Figures 6, 7). Within the bed, the organic-rich layers (individually 2-6 cm thick) are sometimes deformed along upward-rising shears or by similar folds with downslope-oriented fold axes (Figure 6). The organic-rich layers are also separated from one another by moderately well-sorted granules which contain isolated granite boulders (Figures 6, 7). The organic-rich bed, termed the St Loy Bed (Campbell *et al.*, 1999), is only intermittently exposed on the western side of the Cove. Pollen contained within the St Loy Bed suggests a tundra climate but it is uncertain whether this might correspond to the onset, middle or termination of a glacial period. A bulk humic alkali sample, also from this bed, yielded a radiocarbon age of 29,120 +1690/-1400 ^{14}C years BP (Scourse, 1996), placing it in oxygen isotope stage 3 (Campbell *et al.*, 1999). This date, however, is likely to be unreliable since the sediments may have been contaminated by younger carbon from cliff-face vegetation (Scourse, 1996), and cannot be considered to be *in situ* since the organic-rich layers have been clearly sheared and displaced (Figures 6, 7).

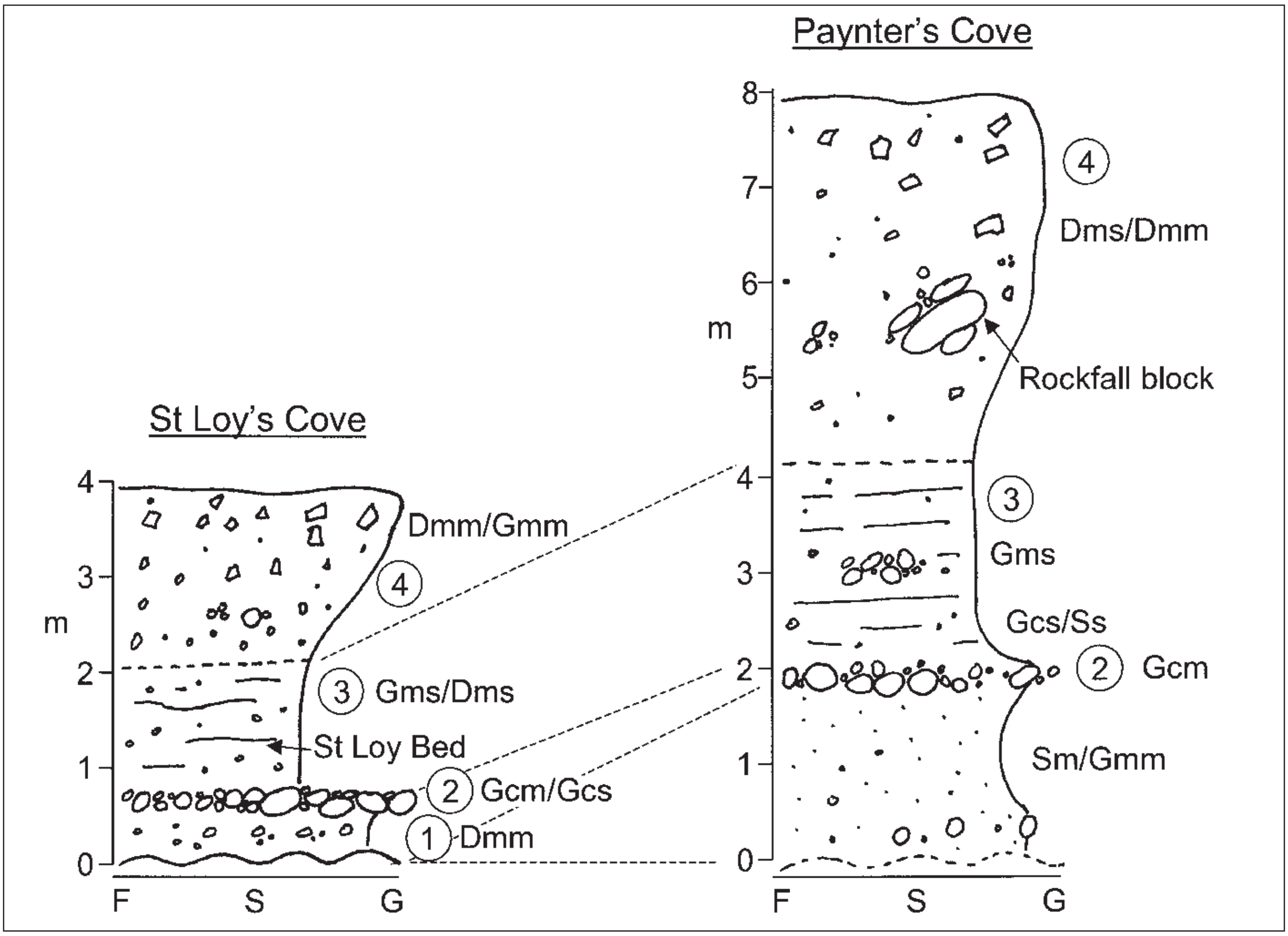

Figure 2. *Summary stratigraphic logs of sediments at St Loy's Cove and Paynter's Cove (Figure 1). Units 1-4 (circled) are discussed in the text. Lithofacies codes are given, after Eyles et al. (1983).*

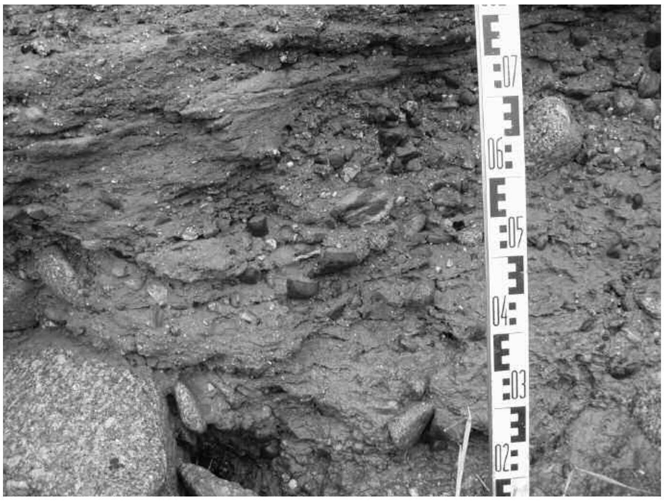

Figure 3. *Photograph showing Unit 1 at St Loy's Cove. Staff for scale.*

Figure 4. *Photograph showing the boulder layer (Unit 2) at St Loy's Cove. Staff for scale is 2 m long.*

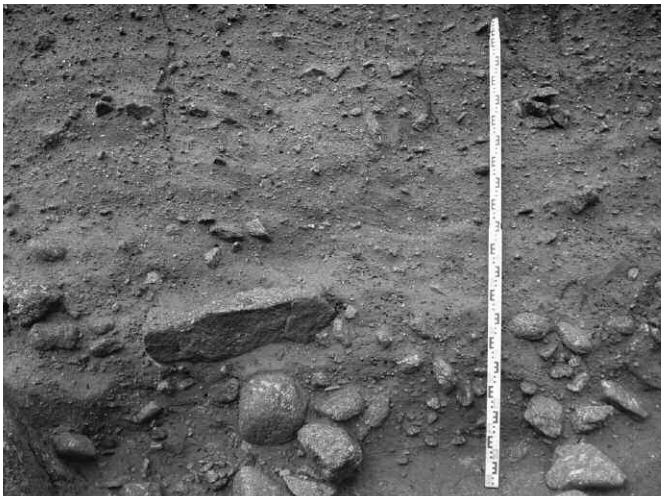

Figure 5. *Slope sediment units 3 and 4 at St Loy's Cove (upper part of the photograph). Staff for scale is 2 m long.*

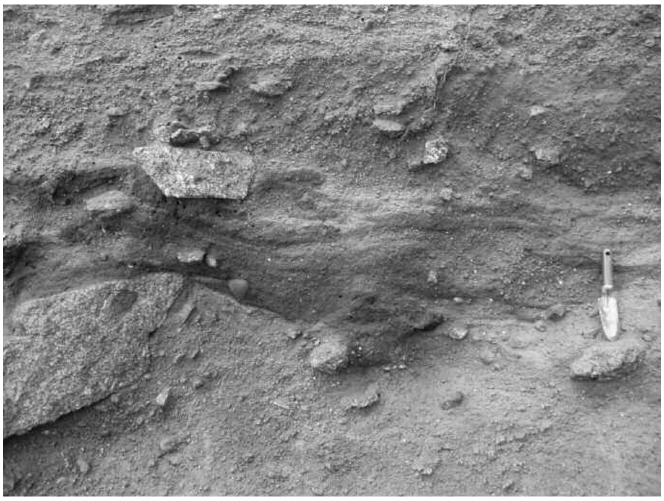

Figure 6. *Photograph of the St Loy Bed (part of Unit 3, located to the left of the trowel which is 28 cm long).*

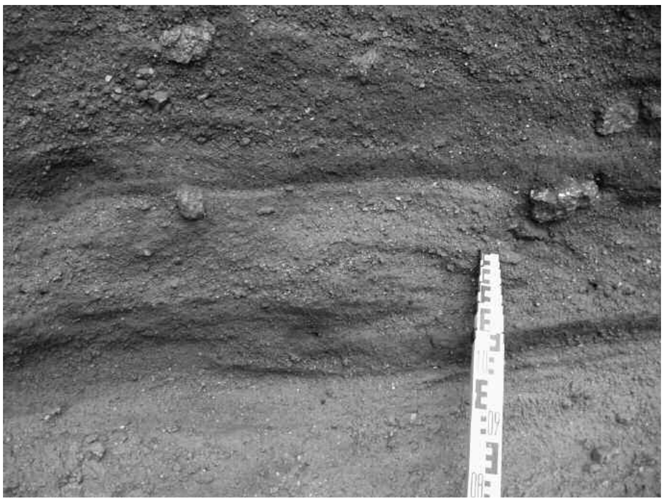

Figure 7. *Deformed and overfolded organic-rich sediments of the St Loy Bed (left of the staff top) within Unit 3 in St Loy's Cove.*

Figure 8. *Photograph of angular, weathered granite clasts within massive and poorly sorted slope deposits (Unit 4) at St Loy's Cove. Trowel for scale is 28 cm long.*

Unit 4 is a diamictic breccia that varies in thickness (2-4 m thick) but is laterally continuous across the exposure. The breccia is massive to occasionally planar stratified and contains subangular to angular local granite clasts (6-45 cm diameter). Clasts are dispersed throughout the unit, sometimes clustering particularly at bed boundaries, and commonly show downslope-dipping clast *a-b* planes (Figures 8, 9).

In the adjacent Paynter's Cove (Figure 1), the same broad pattern of four sedimentary units is observed (Figure 2). Here, the granite bedrock surface is highly weathered across the exposure and is separated by a transitional facies boundary from the overlying massive to poorly-stratified granule bed (0.3-1.0 m thick) (Figure 10). These sediments are very dissimilar to unit 1 observed at St Loy's Cove, and so the granule bed is classified as part of the granite platform. Also within the granule bed, isolated and well-rounded granite clasts are sometimes present. Vertically-aligned structures within the granule bed, which are also developed in the underlying granite platform, become progressively fractured upwards and are deformed in a downslope direction (Figure 10). The uppermost boundary of the granule bed is sharp and planar and overlain by concentrations of well-rounded granite boulders (25-40 cm diameter) that are laterally variable across the exposure. These boulders (comprising unit 2) are generally touching one another, may be imbricated and form larger clusters, and usually have a granule to pebble and matrix. Unit 3 (2 m thick) comprises planar stratified gravel and diamicton beds that are generally laterally extensive across the exposure; individual beds (10-20 cm thick) are identified on the basis of variations in matrix grain size, which varies from silt to granules (Figures 10, 11). Discontinuous silt wisps (< 2 cm thick, 4 m long) are present throughout the unit. Also present, particularly within the upper part of the unit, are lens-shaped clast clusters (0.3-0.5 m thick, 2 m wide) comprising stacked, touching boulders (10-30 cm diameter) that are clast-supported and may be imbricated (Figure 10). The upper boundary of unit 3 is planar and transitional. Unit 4 (2-4 m thick) is laterally continuous across the exposure and comprises a coarse and massive diamictic breccia composed of angular local granite clasts supported in a granule matrix (Figure 11). Also present at one location within this unit are imbricate-stacked (and in places chaotic), subangular local granite slabs (< 8 m in observed width and 2 m high) (Figure 12). These slabs are incorporated within, and overlain by, the surrounding diamictic breccia.

Interpretation of field evidence

The four sedimentary units exposed at St Loy illustrate some of the slope processes taking place under cold-climate conditions (e.g. Matsuoka, 2001) and in a coastal setting. The granite bedrock surface, which varies from cleanly incised (St Loy's Cove) to highly weathered (Paynter's Cove), suggests that deep weathering, possibly to a depth of several metres, took place *in situ* across a granite surface that may have been subaerially exposed. The deformed, vertically-aligned structures developed within the granular weathering product (Figure 10) suggest drag-folding downslope by gravity-driven slope processes (Brooks, 2003). The rounded granite clasts observed within the granule bed at Paynter's Cove are interpreted as corestones formed by the *in situ* weathering of surrounding granite (e.g. Beauvais *et al.*, 2003). The absence of the granule bed at St Loy's Cove suggests that this weathering product was removed by marine, fluvial, or other processes associated with the emplacement of Unit 1.

Unit 1 could have a number of genetic interpretations, but its position on top of a clean and incised granite platform may suggest marine erosion of the weathered granules followed by slumping of unstable marine cliffs on to the platform. The presence of rounded clasts of diverse lithology may support an alternative model, in which fluvially-derived material from inland was reworked by slope processes on to the platform (Figure 3). Either way, sediments within the embayment at Paynter's Cove were protected from erosion, possibly by the presence of bedrock headlands (Figure 1).

Unit 2, present at both locations and comprising planar concentrations of granite boulders, is interpreted broadly as a raised beach (Scourse, 1996). This is evidenced by the size, shape and disposition of these boulders and their arrangement in a laterally-extensive, flat-lying unit that thins eastward. This spatial pattern is consistent with the marine-erosion interpretation of the granite platform, discussed earlier. The presence of imbricated clasts, and clasts with aligned upper surfaces (Figure 4), may also support an alternative model in which boulders are organised within the intertidal zone by shore-moving sea ice floes (e.g. Dionne, 1981, 1996). Through this transport mechanism, boulders can be arranged in clusters (Dionne, 1981), stacked through ice floe rafting processes, or organised in the intertidal zone as pavements with flat upper surfaces (McCabe and Haynes, 1996).

The gravels and diamictic breccias of units 3 and 4 are interpreted broadly as cold-climate (periglacial) slope deposits (e.g. Scourse, 1987; van Steijn *et al.*, 1995; Blikra and Nemec, 1998; Matsuoka, 2001), and are therefore considered together. Here, variations in bed thickness and matrix grain size are related to the depth of the active layer under periglacial conditions, weathering of minerogenic materials within surficial sediments (including soils), and sediment supply from upslope. All these factors are in turn related closely to regional climate (air and ground temperature, aridity/humidity) which controls vegetation and soil development, and the susceptibility of slopes to creep and mass movement (Matsuoka, 2001). Variations in clast size in units 3 and 4 are related to both sediment supply from upslope (controlled by weathering and frost-shattering of bedrock blocks from exposed cliffs and tors), and *in situ* weathering of clasts following their emplacement within the sediments (discussed below). The composition and arrangement of beds within units 3 and 4 suggest downslope movement of sediments under gravity (Harris, 1987; Scourse, 1987; Blikra and Nemec, 1998). Vertical and lateral variations in clast/matrix size suggest that slope sediment fluxes varied markedly over time and space, thus that the slope deposits were emplaced neither continuously nor by uniformly-acting processes (Scourse, 1987; Blikra and Nemec, 1998).

The presence of the organic-rich St Loy Bed within Unit 3 is useful because it can be considered as a planar marker horizon, the deformation of which provides insight into contemporary slope processes. Although the original number, thickness and disposition of the original beds is unknown, the observed shearing (Figure 6) is likely associated with vertical duplication of stratigraphy (thus bed thickening), and lateral shortening. These parameters could not be estimated given the restricted exposure of the St Loy Beds. The vertical rise of the shears, and their continuity, may also suggest the extent to which sediments within the slope were moving *en masse* (through mass movement) as compared with sediment movement by pervasive, active-layer creep. The overfolds observed within the St Loy Bed (Figure 7), which show displacement of some 25-cm in 2D section, suggest that shortening (and sediment thickening) is a significant process. The presence of undeformed (planar) organic-rich beds (e.g. in Figure 7) also suggests that there were considerable temporal variations in land surface stability and thus slope sediment fluxes (van Steijn *et al.*, 1995).

The large, bedrock slabs found within unit 4 at Paynter's Cove (Figure 12), and located south-west of a prominent rock cliff which overlooks the cove, are interpreted as syndepositional rockfall or rockslide blocks that have been incorporated within the sediments from above (Scourse, 1987). This interpretation suggests that upper parts of the bedrock slope were sediment-free and existed as weathered, tor-like features, and that slope deposits mantling the bedrock were confined to valley positions. The disposition of the bedrock slabs suggests that they slid passively downslope over a relatively short time period, which may be associated with periods of enhanced freeze-thaw and/or increased precipitation (Blikra and Nemec, 1998).

Controls on slope sediment deposition

Slope deposits and sediment stratigraphy at St Loy reflect the interplay between regional/hemispheric scale climate (determining phases of land surface instability and the susceptibility of sediments to move downslope) and local scale controls on sediment flux, including sediment generation/supply and accommodation space.

Regional/hemispheric-scale records, such as the Greenland ice cores, reveal the dynamics and magnitude of Quaternary climate changes (Bond *et al*., 1993), in particular the rapid (millennial-scale and shorter) climate changes (including changes in continental aridity and windiness) associated with Dansgaard-Oeschger cycles (Dansgaard *et al*., 1993). These cycles are also manifested in the terrestrial environments of amphi-Atlantic landmasses such as Europe (Björck *et al*., 1998;

Figure 9. *The sediment succession at St Loy's Cove showing diamictic breccias (units 3 and 4) overlying boulders of Unit 2. Staff for scale is 1 m long.*

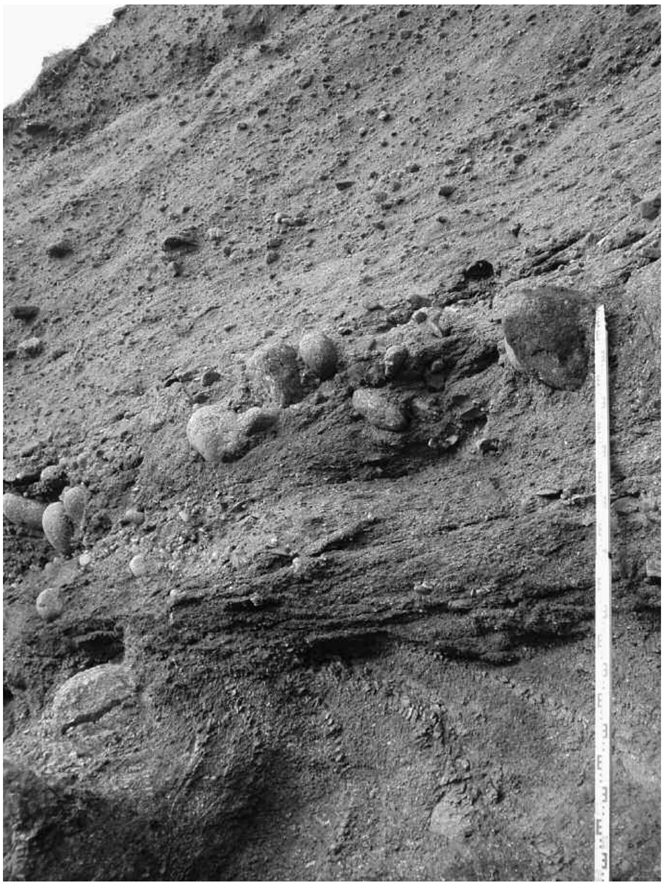

Figure 10. *The sediment succession at Paynter's Cove showing deformed bedrock (lowermost part of the photograph) overlain by granules and a discontinuous boulder layer (Unit 2), and stratified slope deposits (unit 3, top of photograph). Staff for scale is 2 m long.*

Figure 11. *Photgraph of planar stratified slope deposits (Unit 3, centre of photograph) at Paynter's Cove, overlain by more massive slope deposits (Unit 4, top of photograph). Trowel for scale (centre right) is 28 cm long.*

Figure 12. *Imbricate bedrock slabs at Paynter's Cove, contained within slope deposits (unit 4) and interpreted as rockfall blocks. The long axis of the largest slab is 5 m long.*

Knight, 2003). Here, climate changes are recorded in slope and river deposits, and sediments and biota in lakes and peatlands, as changes in mean land/air temperature, seasonality, and aridity/humidity (Tzedakis *et al*., 1997). Although Greenland climate records can help identify time periods in which slopes are likely to have been most active (Blikra and Nemec, 1998), a simple climate forcing-response mechanism implies unlimited sediment availability and lowland accommodation space (Ballantyne, 2002). However, some recent studies show that, even when dated, slope and other periglacial deposits cannot be matched clearly to Greenland climate changes (e.g. Murton *et al*., 2003). It is likely that most slope deposits accumulated over relatively short time-spans rather than over entire glacials (Murton *et al*., 2003; Curry and Morris, 2004). Other time lags may also be involved (Matsuoka, 2001). For example, sediment cover on upper hillslopes may be thickest at the beginning of glacial periods due to interglacial weathering and stabilisation by vegetation. Conversely, slope sediment fluxes may be greatest towards the middle of glacial periods, but will be eventually limited by sediment supply rate from upslope (Brooks, 2003). Finally, basinal controls (size, shape, slope angle) will control detailed processes of sediment deposition and three-dimensional sediment unit geometry. Therefore there is a potentially complex interplay between climatic, geologic and slope processes on different scales, particularly on coastal lowlands.

In the formation of the slope sediment record at St Loy, other geologic factors are also important. The high rate of granular weathering of granite bedrock, under both warm and cold climates (Guglielmin *et al*., 2005), is critical in the generation of the granule- and sand-sized materials that characterise the matrix population at St Loy (e.g. Figure 5). The presence, density and alignment of bedrock structures such as joints and dikes (e.g. as in Figure 10) also help determine weathering rates and the size and location of resulting corestones, as well as releasing blocks from exposed bedrock summits prior to their transport downslope. The clasts exposed in section at St Loy may also have been weathered following their deposition, therefore that clast parameters such as roundness may, to some extent, be a post-depositional artefact. This is potentially significant because post-depositional weathering of a sediment unit will increase its observed matrix proportion, which may have implications for geotechnical modelling, interpreted depositional processes and so forth. In addition, structures diagnostic of cold-climate conditions, such as periglacial involutions, are poorly developed in granitic breccias (Scourse, 1987). This contrasts with locations elsewhere in west Cornwall which are underlain by slates, such as Godrevy and Trebetherick (Figure 1), where involutions are very well developed (Scourse, 1996).

Concluding remarks

The Quaternary slope sediment record at St Loy illustrates the interplay between local- and regional-scale controls on sediment accumulation, including the roles of climate change and sediment generation/supply (cf. Blikra and Nemec, 1998; Ballantyne, 2002). It also demonstrates the complex nature of slope sedimentation processes and issues of sediment reworking (Matsuoka, 2001), post-depositional weathering of granitic breccias, and the capacity of these breccias to develop climatically-significant structures such as periglacial involutions. The local importance of the granite bedrock, in determining the characteristics of the overlying slope deposits at St Loy, may be a hindrance to regional correlation with slope sediments at adjacent sites that show a stronger climatic imprint. Regional climate interpretations could therefore be compromised if climatic signals are imprinted unequally on slope sediments derived from different bedrock types.

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