LATE PLEISTOCENE COASTAL GEOLOGY OF THE S’ILOTT REGION, ALCUUDIA, MALLORCA: A CLASSIC LOCATION FOR QUATERNARY FIELDWORK TEACHING

Steve Boreham and Julie Boreham

Abstract

This paper describes the lithology and stratigraphy of Pleistocene deposits exposed in coastal cliff sections near the small island of s’Iloot, located on the Alcudia peninsula on the southern side of Pollença Bay in northern Mallorca. The palaeosols and aeolianites from the sequence are described. These deposits potentially span some 100k years in the Late Pleistocene and record changing palaeoenvironments, distinct lithologies and well-defined stratigraphic relationships that make this location ideal for teaching Quaternary studies. Overall, this sequence records a last interglacial raised beach environment, covered by fluvial fan sediments, interbedded with palaeosols and aeolianites, recording alterations in moisture availability through MIS5, MIS4 and MIS3, with possible fluvial incision during MIS2 or the Holocene.

Introduction

SB has run field excursions to examine the Pleistocene deposits exposed in cliff sections at s’Iloot, Alcudia for more than a decade (Figure 1). These geological sections contain an interesting variety of deposits (aeolianites, fluvial gravels and red/yellow palaeosols), which can be attributed to different palaeoenvironments throughout the Late Pleistocene including the Last Interglacial (MIS5e) and MIS5d-a, 4 and 3 of the Last Glacial Period. The exposures are easily accessible, relatively safe and in many respects present an ideal teaching resource.

The classic work of Butzer and Cuerda (1962) provides reconstructions of Pleistocene palaeoenvironments that include a number of climatic cycles. Each cycle comprised a warm transgressive marine phase that laid down raised beach deposits, followed by a cooler continental phase where colluvial palaeosols and sand dunes deposits (aeolianites) were deposited. Rose et al. (1978) built on the earlier works of Cuerda, refining the model of Mallorcan Quaternary chronostratigraphy, and Ginés et al. (2012) produced a recent synthesis of Mallorcan Quaternary studies.

In 2009 Fornós et al. described some of the cliff sections on the Alcudia peninsula and provided OSL dates for key aeolianite sequences. However, the generalized coastal sections provided by Fornós et al. (2009) do not match well with more detailed descriptions of deposits around s’Iloot. This is largely due to the limited resolution possible when reporting on a long stretch of cliff section, and problems
Figure 1. (A) Map of Mallorca showing the location of the Study Area on the Alcudia peninsula. The location of Calo d’es Cans (Rose et al., 1999) is also shown. (B) Map of the study area showing elevation, drainage and the location of the Pleistocene cliff sections (I, II, III) described in the text. Note the orientation of this map with North at the bottom to aid reader to relate sections to the view of the cliffs.

caused when three-dimensional sediment architecture is projected onto a two-dimensional plane.

This paper describes the stratigraphy and three-dimensional architecture of Pleistocene deposits exposed in cliff sections between s’Illot and the sa Pedra Foguera peninsula (Figure 1), and incorporates the OSL (optically stimulated luminescence) dating of Fornós et al. (2009) to create a palaeoenvironmental history for the area.

Methods

Geological sections were described by the authors along a c.750m section of coast over multiple visits to the s’Illot cliffs between 2005 and 2018 (Figures 1 and 2). Individual sites were located with handheld GPS, and cliff heights measured using tape measures and a telescopic ranging staff. Samples of aeolianite and palaeosol were taken for laser particle size analysis and elemental analysis by ICP-OES in the Geography Science Laboratories, University of Cambridge. A thin section of the aeolianite was manufactured by JAB (Earthslides).
Geological setting

The Alcudia peninsula southeast of s’Illot is underlain by Jurassic and Cretaceous limestones, which rise from the coast to form the peak of Talaia Alcudia (c. 446 m a.s.l.) (Figure 1). The northwest facing slopes are drained by seasonal streams or ‘torrents’, which rise from springs at c. 150 masl. The low coastal cliffs are largely comprised of Pleistocene deposits including medium-coarse partly bioclastic sands, interpreted as aeolianites, and matrix-supported gravels, interpreted as fluvial fan gravels. The aeolianites often form inclined dunes, sometimes interbedded with talus, palaeosols and fluvial gravels, ramped against fossil cliff-lines cut into the bedrock by high Pleistocene sea levels (Butzer and Cuerda 1962). Fluvial gravels often form fans where torrents exit confined valleys and empty on to the coastal plain (cf. Rose et al., 1999). Fornós et al. (2009) identified two such gravel fans, the s’Illot Fan Formation and the sa Punta Llarga Fan Formation in this study area. In stratigraphic order the main Pleistocene sedimentary units identified in this study are:

4) Upper Gravel – matrix-supported sand and gravel occupying a channel-form
3) Middle Gravel – matrix-supported sand and gravel occupying channel-forms
2) Aeolianite – carbonate cemented medium-coarse partly bioclastic sands, sometimes incorporating palaeosols and gravel beds.
1) Lower Gravel – horizontally bedded matrix-supported gravels with palaeosols and an often clast-supported basal cobble bed.

Description of geological sections

The coastal cliffs exposing Pleistocene deposits have been divided into three separate sections;

I - to the northeast of the Torrent de s’Aladernar (Figure 2A,B, 3(I))
II - s’Illot (Figure 2C, 3(II))
III – to the southwest through sa Punta Llarga towards sa Pedra Foguera (Figure 2D, 3(III))

Section I (Figure 2A,B, 3(I)) starts to the northeast in a rocky cove where the Pleistocene deposits are ramped up against a buried cliff line cut in to Jurassic limestone. Logs A-C show steeply inclined angular clast-supported talus from the cliff grading into the Lower Gravel, which is overlain by aeolianite. Within the Lower Gravel are two prominent red palaeosol beds comprising pea grit (a term for ~10mm clasts) and coarser gravel in a matrix of red silt. The very basal part of the palaeosol at logs B and C also contains often clast-supported cobbles within a sand matrix.

The aeolianite has inclined beds of angular talus both within it and above it. The basal part of the section between logs C-H is partly obscured by fallen blocks. It appears that the Lower Gravel here is mostly horizontally bedded, although this could be a function of the alignment of the section and the apparent dip of the
Figure 2. (A) Photograph of Section I Log B (c.7m high) showing aeolianite with interbedded talus and red palaeosols, (B) Photograph of Section I Log G showing the yellow palaeosol (c.20cm thick) within the lower gravel unit, (C) Photograph of S’illot island looking north (Section II Logs L-Q) showing aeolianite capped by middle gravel, (D) Photograph of Section III Log T (c.5m high) showing aeolianite overlying the lower gravel and red palaeosols.

beds. Angular talus beneath aeolianite was encountered in logs D-F, and this can also be seen at log E in a section normal to the fossil cliff, where a bed of talus within the aeolianite is evident. At log H it appears that the red upper palaeosol has bifurcated, and above this are at least two thin yellow palaeosols. The aeolianite is progressively cut out by the Middle Gravel of the s’illot Fan Formation, which fills a channel-form at Log J, where it is partly obscured and possibly slumped. At log K a second channel-form filled by Upper Gravel (gravel, sand and silt) cuts out the Middle Gravel, and the entire sequence is cut through by the incised channel of the Torrent de s’Aladernar. The red upper palaeosols at log J progressively thin to the southwest and are absent at log K. The very basal part of the palaeosol at log J also contains mostly clast-supported cobbles within a sand matrix.

Section II (Figure 2C, 3(II)) shows the Pleistocene stratigraphy of s’illot as viewed from the northern seaward side of the island (logs L-Q). The basal
horizontally bedded matrix-supported Lower Gravel contains a red palaeosol towards the top. The overlying aeolianite contains intercalated horizontally bedded clast-supported gravel and two thin red palaeosols comprising pea grit in a matrix of red silt. The aeolianite is overlain by the horizontally bedded clast-supported Middle Gravel, which caps s’Illot island.

Section III (see Figure 2D, 3(III)) starts at the incised channel of the Torrent des’Aladernar. Horizontally bedded clast-supported Lower Gravels containing a lower red sand unit and red palaeosols comprising pea grit in a matrix of red silt are present at logs R-V. The very basal part of the palaeosol at logs T-V also contains cobbles within a sand matrix. The palaeosols are progressively cut-out by the overlying aeolianite, which at log U has been OSL dated to 43±5 ka BP and interpreted as of MIS 3-to-MIS4 age (Fornós et al., 2009). Several shallow channels filled with matrix-supported gravel are present within the aeolianite (logs V-X). At log Y the aeolianite has been OSL dated to 46±5 ka BP and again interpreted as Middle Weichselian (MIS 3/4) (Fornós et al., 2009). Between logs Y and AD the aeolianite is incised by a large channel-form filled by matrix-supported Middle Gravel of the sa Punta Llarga Fan Formation, which forms the promontory of sa Punta Llarga. The Middle Gravel here also contains some pockets of red sand and a little angular clast-supported talus. To the southwest, aeolianite is exposed in a rocky cove and is ramped-up against a buried cliff line cut in to Jurassic limestone (logs AD-AJ). A red palaeosol comprising pea grit in a matrix of red silt is present within the aeolianite. At log AH the palaeosol is represented by a small channel containing red-stained angular clast-supported talus. At log AD the aeolianite beneath the palaeosol has been OSL dated to 97±2 ka BP and interpreted as of MIS 5b age (Fornós et al., 2009).

**Palaeosol investigations**

Red palaeosols (terra rossa soils), sometimes called red rendzinas or chromic luvisols, are usually formed through the weathering of limestone bedrock in Mediterranean climates with cool wet winters and hot dry summers, and are rich in ferric iron oxide (haematite). Yellow (cinnamon) palaeosols (ferric luvisols), are formed through weathering of limestone in more arid conditions, and are rich in hydrated ferric iron hydroxide (limonite) and calcium carbonate (Boero and Schwertmann, 1989). Both are ‘zonal soils’ (Allen, 2001) whose distribution reflects climate rather than topographic position or other local factors.

Samples of the red and yellow palaeosols at log H (section I Figure 2B, 3(l)) were investigated using laser particle size analysis. Both beds showed a fine-skewed distribution with a modest amount (<10%) of fine-medium (250-500µm) sand. The yellow palaeosol samples showed a clear peak in the 4-8µm (fine-medium silt) fraction, whilst the red palaeosol samples were finer grade with a peak in the
Figure 3. Geological section (I) of the cliffs northeast of Torrent de s’Aladernar s’Illot, Alcudia peninsula, Mallorca and (II) of s’Illot, Alcudia peninsula, Mallorca and (III) of the cliffs southwest of Torrent de s’Aladernar, s’Illot, Alcudia peninsula, Mallorca.
range 2-4μm (very fine silt) (Figure 4). Neither bed had appreciable amounts of sub-micron clay.

Samples from the red and yellow palaeosols were subjected to elemental analysis by ICP-OES. The two palaeosols were comparable across a wide range of elements, but the red palaeosol showed elevated iron (c.3%), aluminium (c.2%), magnesium (c.1%) and potassium (c.1%), whilst the yellow palaeosol contained elevated calcium (>20%) levels. This is entirely compatible with their interpretation as red chromic and yellow ferric luvisols.

**Aeolianite investigations**

A thin section of an aeolianite sample taken from log H was manufactured by JAB (Earthslides). Figure 5 shows a photomicrograph of the thin section in plain light. A large proportion of the sand-sized clasts are composed of reworked Mesozoic limestone, with some biogenic material and a few quartz grains (Calvet et al., 1980). Laser particle size analysis of the aeolianite suggests that most of the clasts are 300-800μm (medium sand), with a tail of silt in the 10-100μm range (Figure 4). This is confirmed by the micromorphology, which shows 2-5 mm thick laminations of medium-coarse sand interbedded with lightly cemented bands of finer sand and a little silt. These have been interpreted as a type of pin-stripe lamination formed by migrating wind ripples (Fryberger and Schenk, 1988) that are often overprinted by coarser-scale rhythmic banding (2-5 cm). Fornós et al. (2012) suggested that the degree of cementation is related to seasonal changes in Mediterranean humid and dry periods. The aeolianites also show cross-bedding formed by large climbing dunes (Clemmensen et al., 1997, Clemmensen et al., 2001). The aeolianite at log H appears to represent sand ramp or cliff front dunes (Fornós et al., 2012).

**Timing of formation**

The Lower Gravel unit represents the oldest deposits encountered in this study. It occurs stratigraphically below the oldest aeolianite (see Section III) dated to 97±12 ka (see Table 1). The basal cobbles within the Lower Gravel seen in Sections I and III appear to represent raised beach deposits c.1.5m asl and most likely relate to the marine transgression in the latter part of MIS 5e (122-117 ka); the Y2 marine cycle [Eutyrhenian] of Butzer (1975). Raised beach deposits from the earlier part of the last interglacial MIS 5e (128-138 ka), the Y1 marine cycle of Butzer (1975), generally occur at a greater elevation (>9 m.a.s.l.) and are not seen in this study (Vicens et al., 2012, Fornós et al., 2012). For the most part the Lower Gravels appear to be fluvial in origin, but incorporate talus from the buried cliff line and several palaeosols representing an increasingly continental phase within MIS 5d/c (117-100 ka).

There is clearly an erosional phase that occurred after the deposition of the Lower Gravels, but before the deposition of the First Aeolianite at 97±12 ka MIS 5b/c).
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**Table 1.** Chronostratigraphy proposed for the s’Illot Pleistocene deposits
This is most likely due to fluvial incision driven by lowered sea levels. Raised beach deposits from the MIS 5a marine transgression (~ 80 ka) (the Y3 marine cycle [Neotyrrhenian] proposed by Butzer 1975) are not seen in the sections. MIS 5a may be represented by the palaeosol within the aeolianite (sections II and III). MIS 4 is represented by renewed aeolianite formation terminating soon after the start of MIS 3 (43-46 ka). The Middle Gravel is everywhere incised into the aeolianite and must be younger than ~40 ka. The Upper Gravel incised into the Middle Gravel must be younger still and may also date from MIS 3 or MIS2 as is the case at Calo d'es Cans further east along the coast (Rose et al., 1999). It seems plausible that the incised channel-form occupied by the Torrent de s'Aladernar and Holocene fluvial deposits may have been cut in MIS2, or the Holocene, when vegetation cover inhibited the sediment supply to the local streams.

![Figure 4. Laser Particle Size Distribution Plots for the Aeolianite, Red Palaeosol and Yellow Palaeosol.](image)

![Figure 5. Photomicrograph of a thin section of aeolianite in plain light from log H from Geological Section I.](image)

**Conclusions**

Taken together, the sequence from s'Illot represents a fragmented record potentially spanning some 100k years in the Late Pleistocene. The changing palaeoenvironments recorded in the deposits (raised beach, talus, fluvial fan, sand dunes and land surface) are striking, and the distinct lithologies and well-defined stratigraphic relationships make this location ideal for teaching and student projects. Investigations into the nature of the palaeosols and aeolianite conformed with previously published descriptions and interpretations. The s'Illot Fan Formation is clearly the product of Pleistocene fluvial activity from the Torrent de s'Aladernar, but the sa Punta Llargu Fan Formation originates from an un-named torrent that exits onto the coastal plain through a narrow gorge just to the west of the s'Illot cafe. Presumably several of these seasonal streams and the nearby Torrent de ses Fontanelles once joined to form a fluvial system in Pollença Bay at times of low sea level.
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References


Steve Boreham

Department of Geography, University of Cambridge
Downing Place, Cambridge, CB2 3EN
United Kingdom

Julie Boreham

Department of Geography, University of Cambridge
Downing Place, Cambridge, CB2 3EN
United Kingdom