CARBONATE CEMENTS CONSTRAIN THE BURIAL HISTORY OF THE PORTLEDGE-PEPPERCOMBE PERMIAN OUTLIER, NORTH DEVON

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Burley, S. and Cornford, C., 1998. Carbonate cements constrain the burial history of the Portledge-Peppercombe Permian outlier, North Devon. *Geoscience In South West England*, **9,** 188-202.

A sequence of carbonate cements is described for the Permo-Triassic coarse clastic fill of the Portledge-Peppercombe half-graben, North Devon. The cements comprise sparry calcites in conglomerates with high intergranular volumes (IGVs), a variety of micro-sparry pedogenic nodules and rhizoconcretions, and later dolomite-ankerite cements in conglomerates with low IGVs.

Fluid inclusions within sparry calcite have variable liquid to vapour ratios (LVR) and measured homogenisation temperatures (T_r) of between 59°C and 148°C, indicating resetting due to stretching. If the lowest T_h values record minimum trapping temperatures, then oxygen isotopes indicate these cements formed from an evolved water with a $\delta^{18}O$ composition of 0‰ to +10‰ SMOW. These sparry calcites are interpreted to be calcretes that have recrystallised at moderate subsurface temperatures. Fluid inclusions in dolomiteankerite have consistent LVRs and values that record minimum T_h values of 69°C, these being the minimum temperatures attained by the sediments. Assuming formation at these temperatures, oxygen isotope compositions indicate that the dolomites precipitated from water of $\delta^{18}0$ composition of +2‰ to +3‰ SMOW. The aqueous fluids in the calcite inclusions are of low salintiy, approximating to 0.5 wt% NaCl equivalents, but are moderately saline in the dolomite-ankerite cements as determined from depression of freezing points.

Thus early diagenetic cements and later dolomite-ankerite both yield minimum precipitation temperatures of ca 60-70°C in the red-bed fill of the Portledge-Peppercombe half-graben. These temperatures are consistent with the prediction of burial history and thermal modelling if the Mesozoic/Tertiary thicknesses measured from well and seismic data in the main Bristol Channel graben and from adjacent onshore areas are projected as the former cover for the study area. An elevated palaeo-heat flow and/or an hydrothermal flux through these Permo-Triassic redbeds as a means of attaining the predicted temperatures are considered and rejected. The thermal geo-history modelling places the timing of major uplift and erosion as an Oligo-Miocene event post-dating the Lundy intrusion.

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INTRODUCTION

The Permo-Triassic clastic sediments of the Portledge-Peppercombe outlier on the North Devon coast are described in the Geological Survey Memoir (Edmunds *et al.,* 1979) and in more detail by Gayer and Cornford (1992). Both accounts mention the presence of carbonate cements in the sequence. This paper addresses the nature and origin of these cements in their sedimentological context and uses aspects of their petrographic textures, isotope geochemistry and fluid inclusion microthermometry to constrain the post-depositional burial history of the host sediments deduced from regional stratigraphic relationships.

The exposed sections of the Permo-Triassic sediments were logged and the visible carbonate cements described. A number of cements were differentiated and a total of 10 representative samples were taken of the cement types. Sample locations and litho-stratigraphic units refer to nomenclature developed by Gayer and Cornford (1992), as shown in Figure 1. Blue coloured epoxy-impregnated polished thin sections were made of each sample for petrographic description and microphotography. Each cement type was extracted from the thin sections with a microdrill for carbon and oxygen isotopic analysis. Microthermometry of two-phase fluid inclusions was undertaken on doubly polished 80 mm thick wafers prepared without the application of heat following the method of Guscott and Burley (1993).

The burial history modelling was undertaken using Platte River's BasinMod® 1-D computer package, with the stratigraphical and mineralogical input postulated by projection of preserved sections recorded in adjacent areas. The thermal history (surface temperatures and heat flow) are in part derived from published literature and in part constrained by the new data.

SEDIMENTOLOGY

The Portledge-Peppercombe outlier is a small Permian half graben exposed on the north Devon foreshore with an inferred Permo-Triassic infill (Figure 2). The half graben is cut by a later (Oligocene?) wrench fault. The section comprises breccio-conglomerates, pebbly sandstones and argillaceous siltstones. A graphic sedimentological log of the section exposed at the Peppercombe end of the outcrop is presented in Figure 3, on which the sampled intervals are indicated. The basal sediments, comprising Units 1 and 2 of Gayer and Cornford (1992), are organised into two distinct fining-upward cycles, and are dominated by matrix-supported, coarse-grained, breccio-conglomerates and gravels with little or no internal preferred clast orientation. These sediments represent debris flow deposits which appear to be sourced from the graben margins.

Interbedded with these massive breccio-conglomerates are subordinate clast-supported conglomerates containing poorly-rounded grains that are commonly imbricated and size sorted. These sediments are the result of fluvial reworking of the debris flow surfaces during periods of increased surface-water run-off. The upper part of Unit 1 (see Figure 2) comprises interbedded siltstones and mudstones with subordinate layers of cross-bedded pebbly sandstones and breccio-conglomerates, interpreted as mud flats across which distal debris flow and sheet flood sediments accumulated.

The upper part of the measured section, equivalent to Unit 2 of Gayer and Cornford (1992), comprises some 15 m of cross-bedded gravels and sandstones in about 1 m thick units, that display abundant evidence of imbrication. This type of deposit is typical of coarse grained ephemeral braided rivers with gravelly side, longitudinal and transverse bars. Reworking of these pebbly bars occurred as floodwater levels waned.

THE CARBONATE CEMENTS

Three types of carbonate cement are recognised in the sediments (Table 1, Plate 1). Firstly, white, coarsely crystalline calcite spar occludes large intergranular pores between the angular clasts in the breccio-conglomerates (Plate la). In the Peppercombe section this calcite is commonly concentrated in breccio-conglomerates beneath major erosive surfaces.

Secondly, a variety of nodular and concretionary calcite cements is concentrated in the finer grained sandstones and siltstones that cap the large-scale fining-upward depositional cycles (Plate 1c-f). The majority of these concretions are small (<2 cm in diameter), and crudely spherical in shape. They increase in abundance towards the top of individual fining upward units.

Cement type description	Comments
1 Clast-supported breccio-conglomerates with white coloured sparry calcite cement	Basal sediments at Peppercombe
2 Concretionary calcite in siltstones and mudstones forming various sized cylindrical nodules, vertical calcite pipes and tubes on bedding plane surfaces	Concretions concentrated in tops of fining-upward cyles; vertical aggregates localised beneath erosional surfaces; pipes and tubes probable root structures
3 Clast-supported breccio-conglomerates with yellow ferroan dolomite-ankerite cement	Seen in both Portledge and Peppercombe sections

Table 1: Summary of the types of carbonate cements investigated.
a See Figure 3 for samples locations

More rarely, vertical, elongate carbonate accumulations are observed, often truncated by the base of overlying conglomerate beds (Plate 1c). Additionally, cylindrical and branched sub-horizontal tubes are present on pronounced bedding plane surfaces filled with concentric rings of white carbonate and chalcedony in the tube centres (Plate le). These structures are interpreted to be preserved root structures, termed rhizoconcretions.

The third type of carbonate comprises a yellow-weathering, sparry ferroan dolomite-ankerite cement that is present throughout much of the measured section in small amounts (Plate lb). This carbonate cement exhibits no apparent relationship with the sedimentology of the section.

PETROGRAPHY AND MINERALOGY OF THE CARBONATE CEMENTS

Thin sections of each of the carbonate cement types were prepared and viewed by optical microscopy. A number of distinctive textures were observed that are illustrated in Plates 2 to 4. Each carbonate cement is petrographically distinct and following description, was separated for stable isotopic analysis. Fluid inclusions are abundant in each carbonate cement generation, and these were used to determine the salinity and homogenisation temperature of precipitation. The petrography of each of the cement types is described, with fluid inclusion microthermometry and stable isotopes of carbon and oxygen being used to place limits on the conditions of formation.

Coarse, sparry calcite cements in breccio-conglomerates

These calcites form large crystals (up to several mm) that are nucleated on detrital grain surfaces (Plate 2a). Crystal size increases

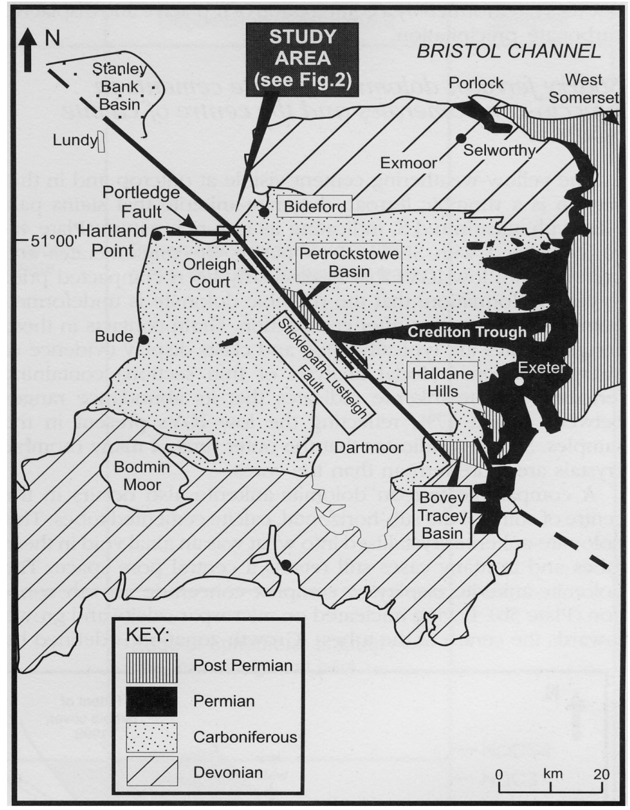

Figure The regional geological context of the Portledge and Peppercombe area.

into the centre of pores, and the crystals are typically elongated in the direction of growth, forming a coarse interlocking mosaic. Elongate crystals are commonly curved, and extinction is wavy and radiates around crystal aggregates. Carbonate staining together with energy dispersive spectrum analysis (EDS) on a scanning electron microscope (SEM) points to this cement being non-ferroan calcite.

Modal analysis of selected thin sections indicates that between 20-46% of these coarse grained samples comprises calcite cement. The variation reflects the coarse grain size of the samples and their poor sorting. Clasts are typically in point contact, and the calcite preserves high intergranular volumes (IGVs).

Concretionary calcites in fine grained sandstones and siltstones

These small, irregular calcite nodules, that are concentrated in the finer lithologies at the tops of fining upward sequences, are composed of micritic, non-ferroan calcite. In thin section they exhibit a variety of complex fabrics, that include concentric laminations expressed by variation in crystal size, peloidal aggreagates, micro-tubules of sparry non-ferroan calcite and microfractures that cross-cut laminations and micro-tubules (Plate 3a). The microspar ranges from 10 mm in crystal size to 50 mm, with the finer crystals being darker in colour, probably as a result of replacive growth of an argillaceous matrix. Microtubules are of various sizes, ranging from ca. 1 mm to 50 mm, with the larger ones typically seen in transverse section and the samller ones in variable orientation, including longitudinal sections. Additionally, there are areas of highly microporous, xenotopic euhedral calcite within the nodules. The elongate sub-horizontal calcite concretions in argillaceous siltstones and mudstones comprise microsparry non-ferroan calcite comparable to that of the small calcite concretions.

In most cases the matrix cannot be optically resolved, but occasional areas of silt and mudstone are preserved, and floating grains of quartz are present, all confirming that these microsparry nodules have formed by a combination of replacive and displacive carbonate precipitation.

Sparry ferroan dolomite-ankerite cements in breccio-conglomerates and the centre of calcite nodules

The yellow-weathering cement visible at outcrop and in thin section is a rhombic ferroan dolomite-ankerite that stains pale blue with alizarin red S, indicating its iron-rich nature (Plate 4a-b), confirmed with SEM-EDS. It occurs in conglomerates and breccias with low IGVs that have clearly been compacted prior to cement formation: that the rhombic dolomite is undeformed points to precipitation after compaction. Grain contacts in these conglomerates are typically long, and clasts display evidence of interpenetration. Modal analysis of thin sections containing ferroan dolomite-ankerite indicates that its abundance ranges between 8 and 17%, reflecting the low IGVs present in the samples. Staining indicates that the outer rims of many rhombic crystals are more ferroan than the cores.

A comparable ferroan dolomite-ankerite also occurs in the centre of some of the sub-horizontal, calcite cemented tubes. This dolomite-ankerite crystallised into what was an axial void in these tubes and in many cases still retains a central pore space. The dolomite-ankerite displays a complex concentric growth zonation (Plate 3b), having nucleated on microspar calcite and grown towards the centre of the tubes. Growth zonation is defined by

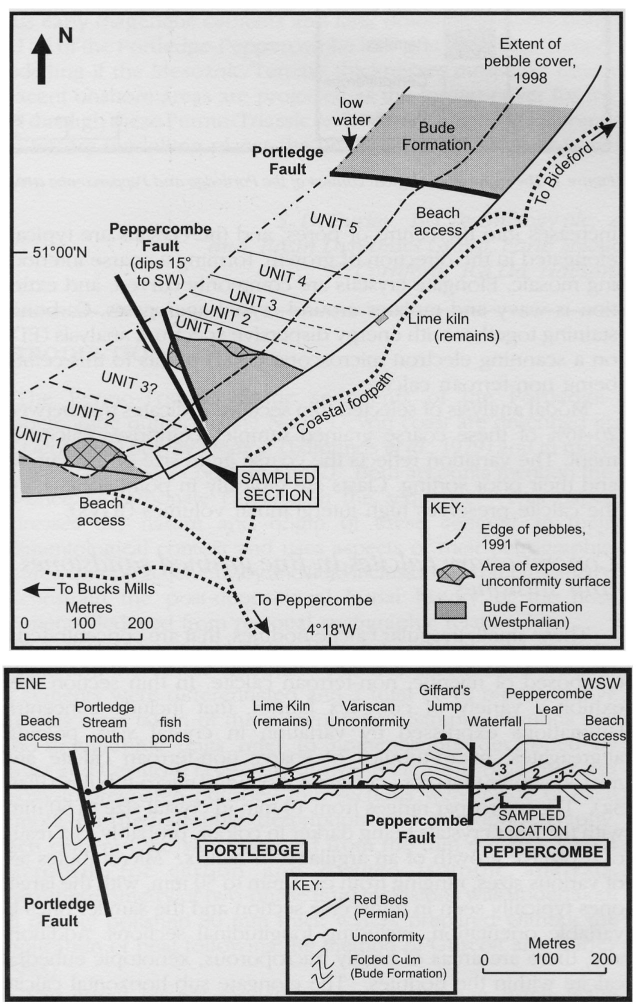

Figure 2. Map of the foreshore between Portledge and Peppercombe showing the outcrop of the Permo-Triassic sequence and a sketch cross-section through the two half graben basins (based on Gayer and Cornford, 1992).

Sample	Petrography	$\delta^{13}C$	$\delta^{18}O$
NDCS 1.1	Core of coarse blocky spar	-6.96	-1.71
NDCS 1.2	Edge of coarse blocky spar	-6.18	-0.46
NDCS 2.1	Coarse blocky spar	-5.77	-2.53
NDCS 3.1	Core of coarse blocky spar	-6.48	-2.12
NDCS 3.2	Edge of coarse blocky spar	-5.09	-1.77
NDCS 4.1	Coarse blocky spar	-7.8	-2.07
NDCS 4.2	Coarse blocky spar	-8.08	-1.9
NDCS 5.1	Coarse dolomite-ankerite cement	-8.1	-5.5
NDC 6.1	Calcrete spar	-5.9	0.8
NDC 6.2	Nodular calcrete microspar	-5.23	-0.65
NDC 7.1	Nodular calcrete microspar	-5.64	0.6
NDC 7.2	Calcrete spar	-6.48	-2.53
NDC 8.1	Nodular calcrete microspar	-5.36	1.16
NDC 8.2	Calcrete spar	-5.47	0.78
NDC 9.1	Zoned dolomite-ankerite cement	-13.07	-4.83
NDC 9.2	Outer zoned dolomite-ankerite cement	-5.97	-4.05
NDC 9.3	Inner calcite	-7.53	-6.8
NDC 9.4	Outer calcite	-7.41	-7.12

Table 2. Averages of carbon and oxygen stable isotope values (‰ PDB)

extreme variations in the abundance of fluid inclusions. Mostly this dolomite-ankerite forms an overgrowth to the microsparry calcite but locally it becomes replacive. Selected areas of are replaced by chalcedonic silica.

CONSTRAINING THE CONDITIONS OF CARBONATE CEMENTATION

Sparry calcite cements

Fluid inclusions are common in the sparry calcites. They are scattered throughout the coarse crystals, but display no relationship to the growth zones or crystal boundaries. Many form ghost outlines of former crystals. All the fluid inclusions are two phase, being liquid-rich aqueous inclusions that do not fluoresce under UV-excitation. The inclusions, of variable sizes (2 - 20 mm), are roughly rectangular in shape, although small rounded and highly irregular inclusions also occur. Liquid to vapour ratios are very variable, with approximate ratios ranging from 90:10 to 60:40. Some very large inclusions have decrepitated during wafer preparation. T_h for 40 inclusions measured from a single sample gave values of 59 - 148°C (Figure 4a). The smallest inclusions gave the lowest T_h values. The inclusions typically froze at -51°C, with first melting occurring at around -30°C, and final melting in the range -0.8 to -0.5°C. This indicates metastability in a dilute $MgCl_2$- rich fluid.

Stable isotope analysis results for sparry calcite cements and concretionary calcites are listed in Table 2 and plotted in Figure 5. The sparry calcite cements have $\delta^{13}C$ values of -5.9 to -8.1 ‰ PDB, and $\delta^{18}0$ values around -2 ‰ PDB. The concretionary calcite cements have similar carbon values (range -5.2 to -6.5 ‰ PDB), but heavier oxygen values (+0.6 to 1.5 ‰ PDB).

Sparry, ferroan dolomite-ankerite cements

Fluid inclusions are also common in the rhombic dolomiteankerite cements, occurring as regular, rectangular, two phase, small (2-5 µm) aqueous inclusions orientated along growth zones (Plate 4c-d). Comparable inclusions occur in the coarsely crystalline dolomite-ankerite cements in the centre of the cylindrical tubes (Plate 3b-d). None of these inclusions fluoresce under UV excitation. The inclusions are typically small, and LVRs are consistently estimated as about 90:10. Measurement of T_h values on 32 inclusions from sample NDC9 gave values of 70-76°C (Figure 4b). Freezing data were difficult to obtain because of the small size of fluid inclusions, but freezing took place at temperatures >65°C, and final melting was in the region of -12°C, indicating the presence of a moderately saline brine.

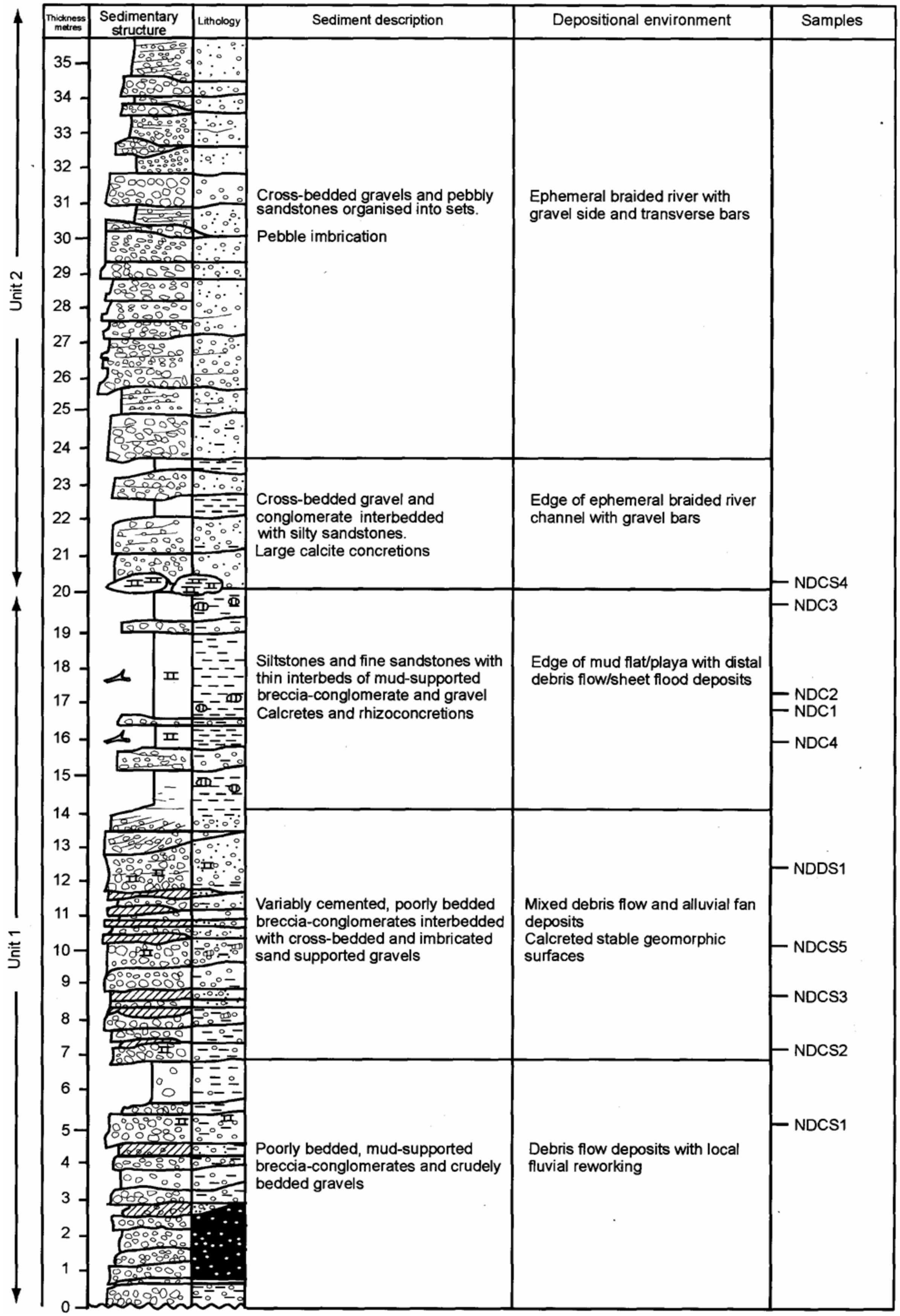

Figure 3. Sedimentological log through units 1 and 2 (of Gayer and Cornford, 1992) at Peppercombe showing sample locations, depoistional units and interpreted environments of deposition.

Plate 1. Outcrop photographs of carbonate cements (a) white sparry calcite cement in breccio-conglomerate (b) compacted breccio-conglomerate with ferroan-dolomite/ankerite cement (c) vertical, elongated calcite concencretion (d) small spherical calcite concretions on a bedding plane (e) large calcite concretion and (f) elongate, horizontal rhizocretion on a bedding plane surface. Pencil is 12cm long; hammer head 18cm.

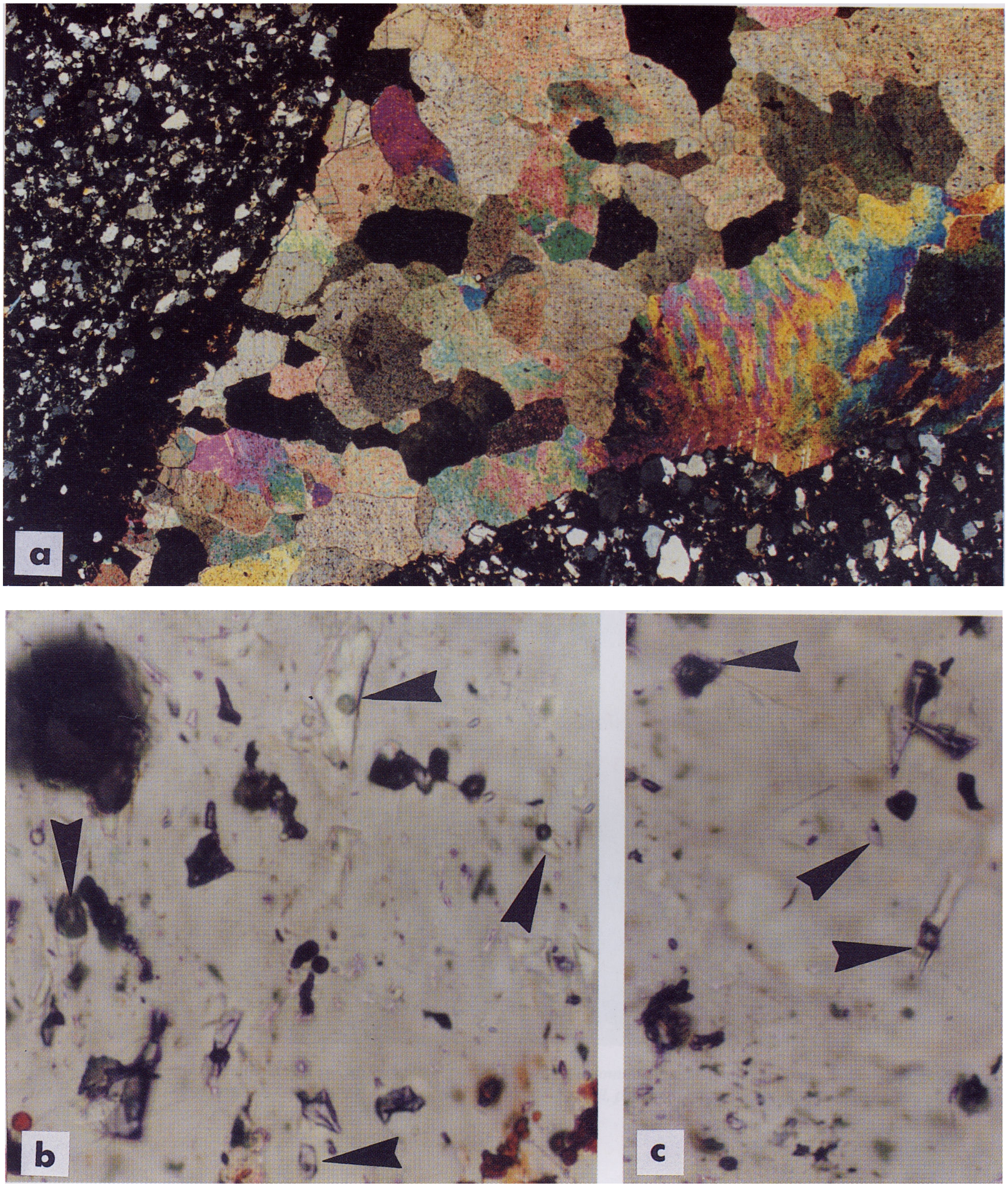

Plate 2. Photomicrographs of sparry calcite cement (a) crossed polars view of coarsely crystalline calcite mosaic. Note radial crystal growth and cloudy, inclusion-rich crystals (b) and (c) details of two phase aqueous inclusions. Note variable LVRs; inclusions exhibiting range of LVRs arrowed.

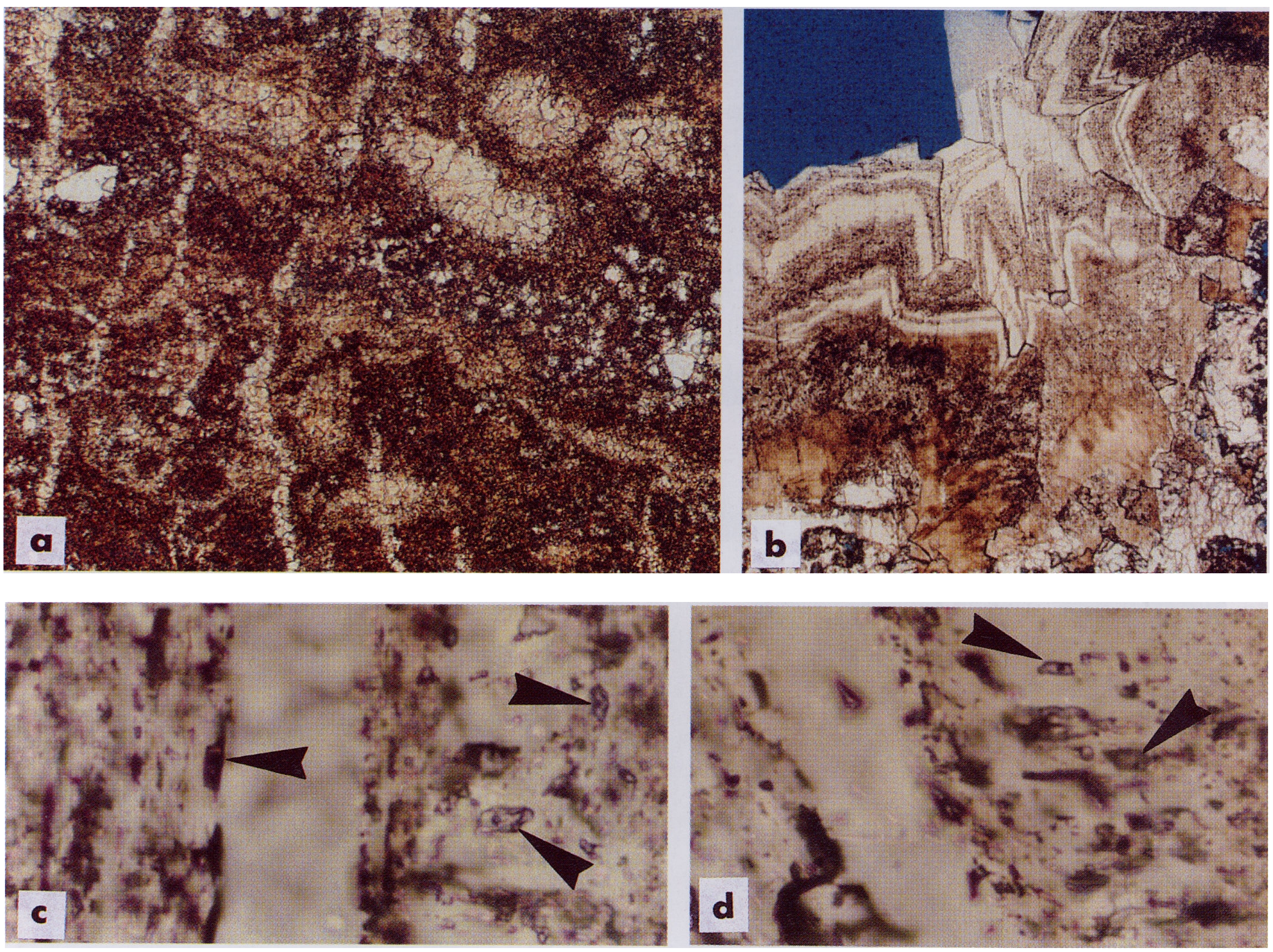

Plate 3. Photomicrographs of micritic calcite and dolomite-ankerite pore fills. (a) plane polarised view of microspar in rhizoconcretion. Note laminations, microtubules and sparry fills to tubules. (b) Coarse dolomite/ankerite crystals within the centre of rhizocretion. Note crystal growth zones defined by abundant fluid inclusions. (c) and (d) details of primary, two phase aqueous inclusions aligned along growth zones. Note constant LVRs. Representative inclusions arrowed.

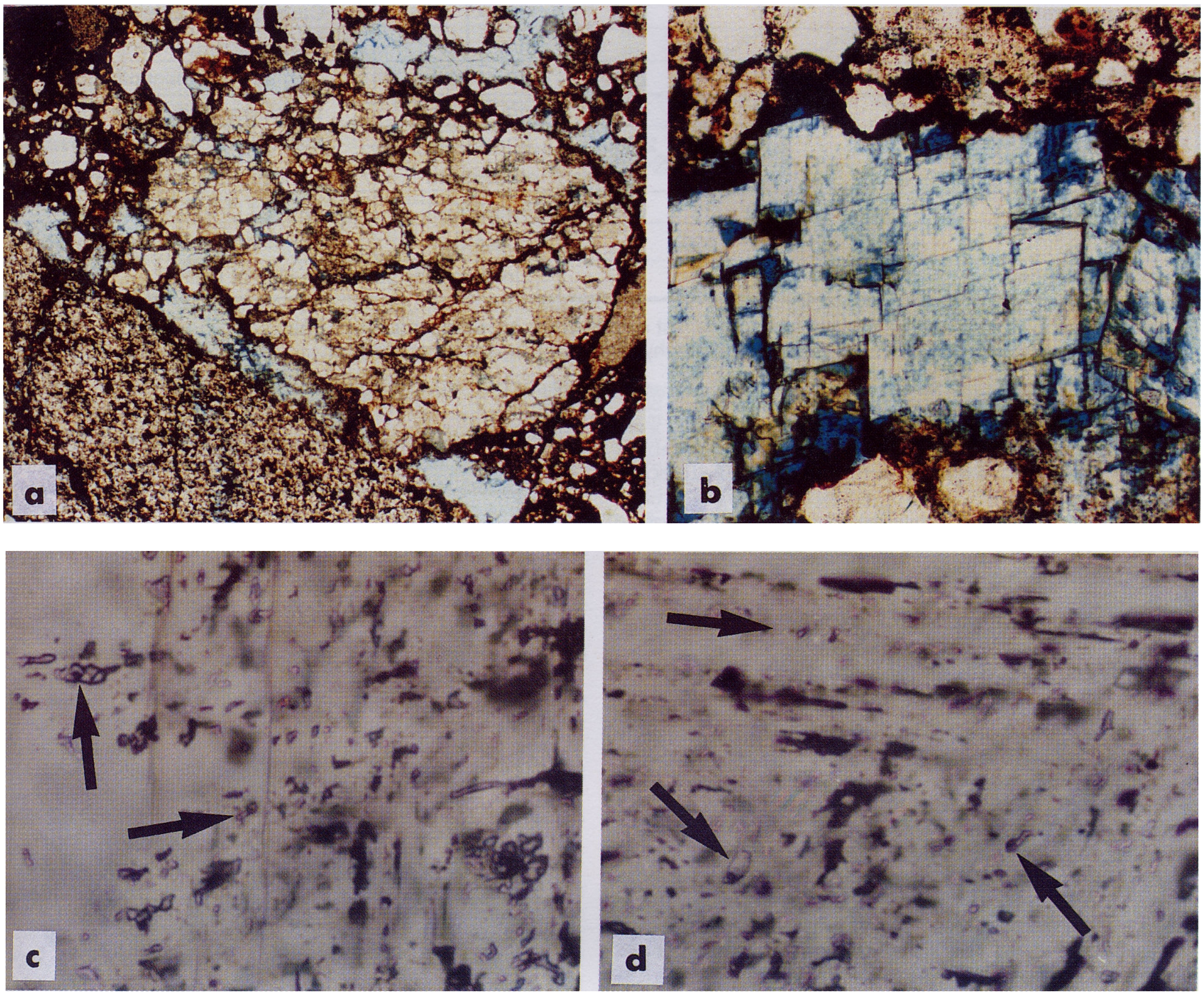

Plate 4. Photomicrographs of dolomite-ankerite cement (a) plane polarised view of dolomite/ankerite enclosing large clasts in a compacted sediment (b) detail of rhombic dolomite/ankerite showing crystal form. (c) and (d) details of small, primary two phase aqueous inclusions aligned along growth zones. Note constant LVRs. Representative inclusions arrowed.

Interval[4]	Top age	Thicknesses[1]		Lithology[2]	Comments ....
	(my)	Min (m)	Max (m)		
Quaternary	0	25		'Head'	Peri-glacial deposits
Lost Neogene	1.6	-150	-800	n/a	Period of major uplift
Lost Paleogene	25	(-50)[3]	300	20sst/40slt/	Movement on Sticklepath fault &
				20sh	Lundy 'granite' intrusion
Lost Upper Cretaceous	65	50	400	Chalk	Campanian at Orleigh Court
Small break	85	n/a		n/a	Possible hiatus event
Lost Lower Cretaceous	100	-50	250	50sst/50sh	Thin but persistent off-shore
Late Cimmerian uplift	140	-50	-600	n/a	Subsidiary uplift event
Lost Jurassic	145	2,000	2,600	20sst/80sh	Mainly Liassic - as W. Somerset
Lost Triassic	208	200	650	40sst/60sh	Condensed as W. Somerset
Lost Permian	145	200	900	50sst/50slt	As west Credition Trough
Permian	160	130		60sst40slt	Preserved in Portledge section
Variscan Orogeny	286	—		Unconformity surface; 5-8km of uplift[5]	

[1] negative numbers indicate uplift; [2] Lithotypes as %, sst = sandstone, slt = siltstone, sh = shale;
[3] if outside the Paleogene basin; [4] preserved stratigraphy in **bold;** [5] Cornford et al., 1987

Table 3. Reconstructed post-Variscan stratigraphy of the Portledge-Peppercombe area

Only 3 samples of the dolomite-ankerite cements were available for stable isotope analysis. Results are listed in Table 2 The coarse dolomite-ankerite cement from the compacted breccio-conglomerates gave a $\delta^{13}C$ value of -8.1‰ PDB and a $\delta^{18}O$ value of -5.5‰ PDB, whilst the dolomite-ankerite from the centre of the tube structures gave $\delta^{13}C$ values of -6 to -13‰ PDB and $\delta^{18}O$ values of -4.8 to 4‰ PDB (see Figure 5).

DIAGENETIC SEQUENCE AND ORIGIN OF TILE CARBONATE CEMENTS

The calcite and dolomite-ankerite cements have markedly different distributions and characteristics. The sparry calcite cements in the coarse sediments appear to be related to depositional processes, being associated with breaks in the sequence, and probably reflect the development of stable geomorphic surfaces. Their concentration in the lower part of the section (Unit 1 of Gayer and Cornford, 1992) suggests a drier environment than the more channelled upper unit, with petrographic observations indicating that the non-ferroan sparry calcite cements are early precipitates. The high IGVs and open grain framework are indicative of early diagenesis prior to significant compaction. The sparry calcite cements are interpreted to be groundwater calcretes, common in Present Day arid alluvial basins (Arakel, 1986; Wright and Tucker, 1991).

Micro-sparry calcites together with their fabrics are typical of incipient pedogenic calcretes, which form at stable geomorphic surfaces on vegetated alluvial fans (Klappa, 1983). The irregular and elongate nodules with peloidal micritic fabrics are typical of rhizocretions (organo-sedimentary structures produced by roots), with the microtubules representing either small rootlets or root hairs. The peloidal aggregates may represent poorly calcified cell groups. The variation in microspar grain size and complex fabrics are common in rhizoconcretions because different roots frequently occupy the same cavity over time. That the roots are largely horizontal points to a shallow water table (as opposed to long vertical roots striving to reach deep water source). In contrast, soil profiles of a different type have been described from the Triassic Otter Sandstones (Purvis and Wright, 1991) and Permian coarse clastics (Cattell, 1997) of South Devon.

It is thus paradoxical that these syn-sedimentary cements contain fluid inclusions with both liquid and gas-phases indicative of temperatures in excess of 50°C. This is confirmed by the minimum T_h of 59°C, at variance with the petrographic evidence for shallow burial

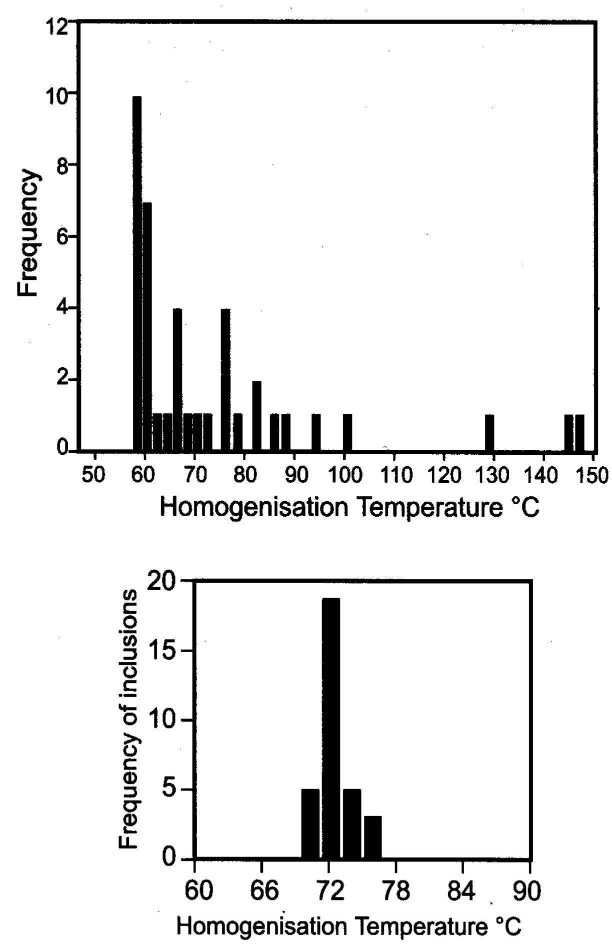

Figure 4. Histograms of homogenisation temperatures in (a, upper) calcite cement from sample NDCS1.1 and (b, lower) dolomite-ankerite cement from sample NDC9.1. All measurements taken from a single population of inclusions as defined by Guscott and Burley (1993).

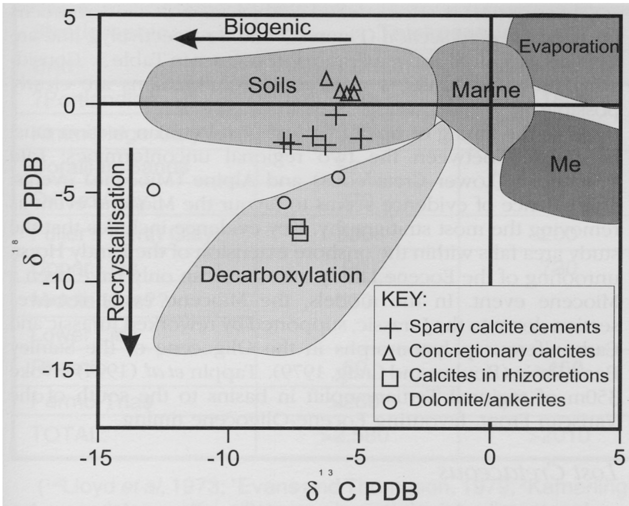

Figure 5. Cross plot of oxygen and carbon isotope compositions for all carbonate cement types. Typical isotope compositional fields shown for modern environments and diagenetic processes. Me - methanogensis. Arrows show effect of increasing biogenic input (lighter $\delta^{13}C$) and recrystallisation at higher temperatures (lighter $\delta^{18}O$).

and early diagenesis. The coarse crystal size is also inconsistent with growth during pedogensis. One reconciliation of this paradox is that the calcite has recrystallised at higher temperatures than those at which it was initially precipitated. This would explain the variable LVRs and spread of T_h values, these being a function of re-setting as internal inclusion pressures increased with progressively deeper burial and associated higher temperatures. If the calcite cements recrytallised at 60°C, then the oxygen isotope compositions indicate that the water from which they reprecipitated was isotopically heavy, typical of evolved diagenetic waters (Figure 6, upper).

An alternative explanation is that the higher temperatures result from the presence of hot-water springs emerging from the Permian desert floor. In a post-orogenic setting this may be plausible. Indeed, calcite-filled fractures through the underlying Bude Formation sandstones may have sourced such hydrothermal fluids, and syn-sedimentary fault movement (Gayer and Cornford, 1992) may have promoted fluid flow.

For the ferroan dolomite-ankerite cements, low IGVs indicate late formation, post-dating the mechanical compaction during initial burial. Their occurrence in cavities within rhizocretions may indicate survival of residual porosity or the development of secondary porosity during burial. Abundant primary fluid inclusions delineate growth zonation during cement precipitation. The texture and fluid inclusion T_h values of 70°C point to these being burial cements. If the ferroan dolomite-ankerite cements precipitated at 70°C then the oxygen isotope compositions indicate that the water from which they precipitated had an oxygen isotopic composition of +2 to +3‰ SMOW, typical of evolved marine or diagenetic waters (Figure 6, lower).

The combination of petrography, fluid inclusion microthermometry and stable isotope geochemistry thus suggests that the Permo-Triassic sediments of the Peppercombe-Portledge half graben were extensively cemented with pedogenic concretions and shallow groundwater cements prior to burial. During burial, temperatures attained at least 70°C, causing the early calcite cements to recrystallize and their fluid inclusions to reset, whilst dolomite-ankerite precipitated in any remaining void spaces in the sediments, both within intergranular pores and in cavities within rhizocretions.

BURIAL HISTORY AND GEOTHERMAL MODELLING

The question then arises, can burial within the Peppercombe-Portledge half graben produce temperatures of 70°C as required to

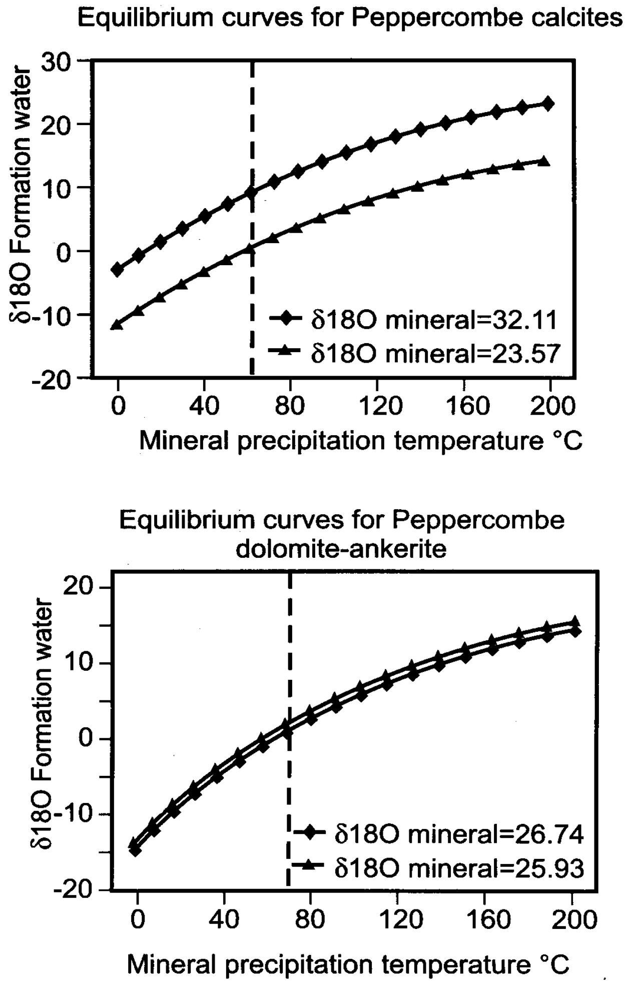

Figure 6. Equilibrium fraction curves for calcite and dolomite cements showing inferred water $\delta^{18}O$ comnpositions assuming precipitation temperatures of 70°C as determined from fluid inclusion microthermometry.

recrystallize the calcite cements and precipitate the dolomite-ankerite cements, or do these temperatures demand extraformational migrating hot fluids? In order to reconstruct the burial and thermal history of the Permo-Triassic strata, the missing stratigraphy (both deposits and uplift) as well as the heat flow history are deduced from contiguous preserved stratigraphy. This information is then entered into a software package (Platte River's BasinMod® 1-D) to calculate the burial and thermal history of the section in terms of a one-dimensional (1-D) thermal geo-history model.

Strati graphy and lithologies

Putative Permian and Westphalian (Carboniferous) rocks are currently exposed at the sampled location. Based on regional rather than local preserved geology, a speculative burial history is constructed for the Portledge-Peppercombe area (Table 3 and Figure 7). Limits are placed on missing thicknesses and associated lithologies on the basis of published accounts of adjacent or analogous deposits.

Quaternary

Locally derived, poorly bedded, matrix-supported breccia occurs at the eastern end of the Portledge section, near the stream mouth and mediaeval 'fish ponds'. These periglacial `head' sediments, preserved in valley fills, represent the typical thicknesses repeatedly deposited and eroded during the Quaternary glacial-interglacial cycles.

A nominal thickness of 25m of coarse clastics is included in the model to represent these sediments.

Lost Neogene and Paleogene

This is generally accepted as a period of uplift and erosion in South West England, though the evidence is far from convincing. Small Eocene-Oligocene basins - such as the Bovey, Petrockstow and offshore Stanley Bank basins - are associated with the line of the Sticklepath-Lustleigh fault (Edwards and Freshney, 1982). The line of this strike-slip fault is mapped as cutting the coast some 2km to the north-east of Portledge stream mouth, and the study area is broadly a down-faulted part of the erosional plateau through which the fault cuts. This designates the area as a possible onshore extension of the Lundy Horst (Tappin *et al.,* 1994). Evidence for Tertiary erosion also derives from the Orleigh Court gravels some 5km to the south-east of Portledge, attributed to *in-situ* ?Pliocene dissolution of an Upper Chalk section (Edwards and Freshney, 1982). Additionally, the products of Oligocene erosion of the Culm filled the Petrockstow Basin, some 15km further south-east, with approximately 660m of section being proved by drilling.

The basins associated with the Sticklepath-Lustleigh fault are of two types - tear-apart basins at jogs in the wrench-fault (Bovey and Petrockstow basins), and the broader preserved half-graben as seen in the offshore Stanley Bank Basin. There is no evidence that the Portledge-Peppercombe area floored a pull-apart basin, but it is possible that the Stanley Bank Basin extended to cover this area of the North Devon coast. In terms of orientation (E-W) and form (northern bounding normal fault) the Bristol Channel Marginal Basin of Tappin *et al.* (1994, Figure 48) shows some similarities with the Portledge-Peppercombe structure. A maximum preserved thickness of 340m of mid-Oligocene silt, clay and lignite is estimated for the Stanley Bank Basin from seismic and drilling evidence (Brooks and James, 1975; Edwards and Freshney, 1982), and -300m for the Bristol Channel Marginal Basin of Tappin *et al.* (1994). If linked via a river with the Petrockstow Basin (as suggested by Edwards and Freshney, 1982), the Portledge-Peppercombe area would have been part of this depositional system.

Alternatively, the offshore Lundy granite, lying on the relatively upthrown side of the Sticklepath-Lustleigh Fault, was intruded during the Eocene (Arthur, 1989; Thorpe and Tindle, 1991; Roberts and Smith, 1994; Tappin *et al.,* 1994). The Lundy granite and associated intrusives must have been roofed by a substantial thickness of sediment. Gravity evidence suggests that the granite island lies on the eastern margin of a larger and more basic igneous body. The Lundy granite cooling ages (dykes 44.6 - 56.4my; granite 58.7 my; Roberts and Smith, 1994) predate the sedimentary fill of the mid-Oligocene Stanley Bank Basin by some 15-25 million years, begging the question: 'Into what did the Lundy granite intrude and what was its cover?' The answer could be Devono-Carboniferous, Permo-Triassic or Jurassic-Cretaceous sediments. The Oligocene Stanley Bank Basin may thus have developed as a consequence of the thermal collapse of the batholith feeding the Eocene Lundy volcanic centre. In this case the Tertiary fill would then not have reasonably extended as far as the North Devon coast.

The sinistral Peppercombe wrench fault runs parallel to the Sticklepath-Lustleigh Fault (Figure 1) and cuts the Permo-Triassic fill of the Portlege-Peppercombe half graben (Gayer and Cornford, 1992). The sinistral movement on the Sticklepath Fault created the Oligocene-filled Petrockstow and Stanley Bank basins. This indicates at least some movement of the study area to be of Oligocene age.

Thus two options are possible for the Portlege-Peppercombe area during the Paleogene:

➤A thickness of ~300m of Paleogene strata representing a south-easterly extension of the Stanley Bank Basin, with uplift and erosion during the Neogene

➤Progressive uplift and erosion of Mesozoic rocks during the Tertiary with sporadic local deposition in the defined, fault-related basins (e.g. Petrockstow Basin).

These options were modelled as 'thick' and 'thin' overburdens for the preserved section (Figures 7 and 8 respectively), and are listed as minimum and maximum thicknesses in Table 3. Considering individual units, a number of combinations are clearly possible.

As to the timing of uplift, the lost post-Permian section must be divided between the two regional unconformities: Late Kimmerian (Lower Cretaceous) and Alpine (Miocene) events. The balance of evidence seems to favour the Miocene event as removing the most stratigraphy. Key evidence includes that the study area falls within the onshore extension of the Lundy Horst: unroofing of the Eocene Lundy intrusives can only have been a Miocene event. In the models, the Miocene event removes section down to the Jurassic, supported by reworked Jurassic and Carboniferous palynomorphs in the Oligocene of the Stanley Bank Basin (Boulter and Craig, 1979). Tappin *et al.* (1994) invoke 350m of regional Tertiary uplift in basins to the south of the Variscan Front, favouring Eocene-Oligocene timing.

Lost Cretaceous

Un-abraded flint gravels with Campanian fossils at Orleigh Court some 5 km distant from the Portledge-Peppercombe outlier provide evidence for Chalk deposition in the area (Edwards and Freshney, 1982). As with the outlier, the Orleigh Court occurrence lies just to the south of the trace of the Sticklepath Fault (taken as the markedly linear section of the valley of the River Yeo). By analogy with the thinning of the Chalk westward out of the Weald Basin, a thinned deposit may be expected in North Devon. The *in situ* dissolution plus fluvial transport in the Haldane Hills in South Devon has left some 20m of flint 'gravel' which represents a much greater thickness of initial Chalk.

No Chalk is recorded as preserved in the offshore geology of the inner Bristol Channel (Evans and Thompson, 1979). The basin flank well 103/18-1 penetrated less than 50m of preserved Chalk, which also crops out locally at the seabed. Some 1000m of Upper Cretaceous Chalk is estimated for the Outer Bristol Channel Basin (Tappin *et al.,* 1994). As an estimate, between 50 and 400m of Chalk cover is modelled for the Portledge-Peppercombe area.

Regionally, the Lower Cretaceous is well developed in the Bristol Channel, with approximately 200m of Wealden penetrated in well 103/18-1 (Tappin *et al.,* 1994). Preservation rather than deposition restricts this unit to the basin axis to the north of the Stanley Bank Basin. A Gault and Greensand package (Albian-Cenomanian) is also present in all wells, comprising 13m in well 103/18-1 (Tappin *et al., op cit).* No detailed dating is available for the Wealden facies of the Bristol Channel, but it probably represents Ryazanian - Albian sedimentation (Tappin *et al. ,op cit),* which co-exists with the late Cimmerian uplift event. It remains an area of speculation to decide whether the Portledge-Peppercombe area was a source of, or a depocentre for, the Wealden fluvial systems? Extremes of -50m (erosion) to +250m (deposition) are modelled as Lower Cretaceous Wealden facies cover for the Portledge-Peppercombe area.

Lost Jurassic

In terms of thickness, the Jurassic - in particular the Lias - is likely to be the major cover for the preserved Permo-Triassic section. Regional summaries of the Jurassic section based mainly on seismic evidence sums to 2,200m for the main Bristol Channel Basin (Evans and Thompson, 1979) and 1,650m for the east Bristol Channel Basin (Kamerling, 1979). Some 850 m of Hettangian-Portlandian mudstones with minor sandstones and limestones are reported in well 103/18-1 in the main Bristol Channel Basin (Tappin *et al.,* 1994). The Portledge-Peppercombe area lies on the southeastern extension of the Lundy Horst, where arguably a post-Eocene feature separates the main Bristol Channel Basin from the east Bristol Channel Basin *(sensu* Kamerling, 1979).

There is little evidence of a 'littoral facies' of the Lias of the southern margin of the Bristol Channel (Cornford, 1986; Warrington *et al.,* 1995). Up to 60m of Lower Lias is preserved as an outlier on

Stratigraphic Unit[1]	Thickness (m) Main Basin[1]	East Basin[2]	Lithology(%)[3]	Comments
?Portlandian	100	180	30sst50sh20lst	Widely eroded
Kimmeridge Clay	330		shale	Also sandy facies
Corallian Sands	520	420	80sst20shale	
Oxford Clay	370		shale	
Fuller's Earth Clay	330	200	40slt60sh	
Upper Lias	90	730	40slt60sh	
Middle Lias??	530		40slt60sh	Poorly defined
Lower Lias			60sh20sIt20lst	
Rhaetic	50	>450	60sh40sIt	Not well defined
Permo-Trias	>260		60sIt40sst	
TOTAL:	>2,580	>2010	—	

([1,2]Lloyd *et al*, 1973; [1]Evans and Thompson, 1979; [2]Kamerling , 1979; [3]Tappin *et al*., 1994 with lithotypes denoted as percentages: sst = sandstone, slt = siltstone, sh = shale, lst = limestone)

Table 4. Preserved Mesozoic stratigraphy for the Bristol Channel.

the eastern flank of Exmoor at Selworthy above Porlock (Warrington *et al.,* 1995), with only slight thinning and inconclusive evidence for a littoral facies. This might indicate that Exmoor as a whole was buried under Jurassic cover until uplift and erosion in the early Cretaceous or the Neogene generated the present topography. In the offshore, seismically imaged truncation, largely at the sea bed (Evans and Thompson, 1979; Kamerling, 1979), is suggestive of erosion rather than sedimentary thinning towards the North Devon coast. In the absence of an abrupt faulted margin, the thicknesses recorded in the central Bristol Channel (Table 4) are used as the maximum palaeo-cover for the Permo-Triassic of the Portlege-Peppercombe half graben.

Based on the thicknesses recorded in Table 4, and accepting an absence of sedimentary thinning towards the Present Day coast, a Jurassic thicknesses of 2,600m and 2,000 m are used for the 'thick' and 'thin' models respectively.

Lost Permo-Triassic

The Permo-Triassic cover of the south west peninsular must be seen in the context of some 9,000 m preserved in the Plymouth Bay Basin, and over 1,500 m in the South Celtic Sea basin (Evans *et al*., 1990; Ruffell *et al*., 1994). No Permian is believed to be present in the Bristol Channel Basin (Tappin *et al.,* 1994) other than the Portledge-Peppercombe outlier, and evidence for this being Permo-Triassic is really that it is 'red coloured' and comprises 'coarse grained continental detritus'!

Though generally assumed to be Permian on the basis of colour and clast size and shape, it is possible that the preserved redbeds of the Portledge-Peppercombe half graben are Triassic in age, equivalent to the sporadically developed Permo-Triassic 'Vexford Breccias' of the Aylesbeare Group or the breccias of the 'Wiveliscombe Sandstones' of West Somerset (Edmonds and Williams, 1985). To the east, the maximum thickness of the preserved Permo-Triassic is 660 m in the Taunton area, with thinning against positive Palaeozoic features, as in the basin between the Devonian of the Brendon and Quantock Hills (Edmonds and Williams, 1985). The West Somerset section is believed to be mainly Triassic.

A measure of the missing Triassic thickness in the study area is taken from that preserved in West Somerset to the east, with the minimum thickness reflecting thinning against the granite uplands, and the maximum thickness taken from a Bristol Channel Basin centre location. Based on these analogies, between 200m and 650m of Triassic are included in the models.

In the stratigraphic reconstruction, the preserved Portlege-Peppercombe half graben fill is assumed to be Permian, as in the Crediton Trough to the south. Given that the Present Day erosion surface truncates the section, erosion must have reduced the total Permian thicknesses. No Permian is identified, however, in the offshore wells of the Bristol Channel basin (Tappin *et al.,* 1994). The Permian deposits in the Crediton Trough to the south are of variable thickness since they fill in an irregular palaeo-topography with thicknesses up to 900m proposed (Laming, 1982). Synsedimentary tectonics has been demonstrated at the Portledge- Peppercombe

Time (my)	Surface Temperature (°C)	Heat flow (mW/m^2)	Comments…..
Today	12	57	Heat flow taken as constant
1.6	18	57	
38	25	57	Intrusion of Lundy Granite - possible heat flow spike.
50	20	57	
65	25	57	Higher heat flow values from thinned crust due to
145	18	57	extensional tectonics (opening of N Atlantic) ignored
210	22	57	Main Bristol Channel graben development
286	25	57	Late-Variscan granites intruded - possible heat flow spike;
300	18	57	Variscan mountains - upland surface temperatures
			at or south of equator

Table 5. Thermal History used for modelling the Portledge-Peppercombe area

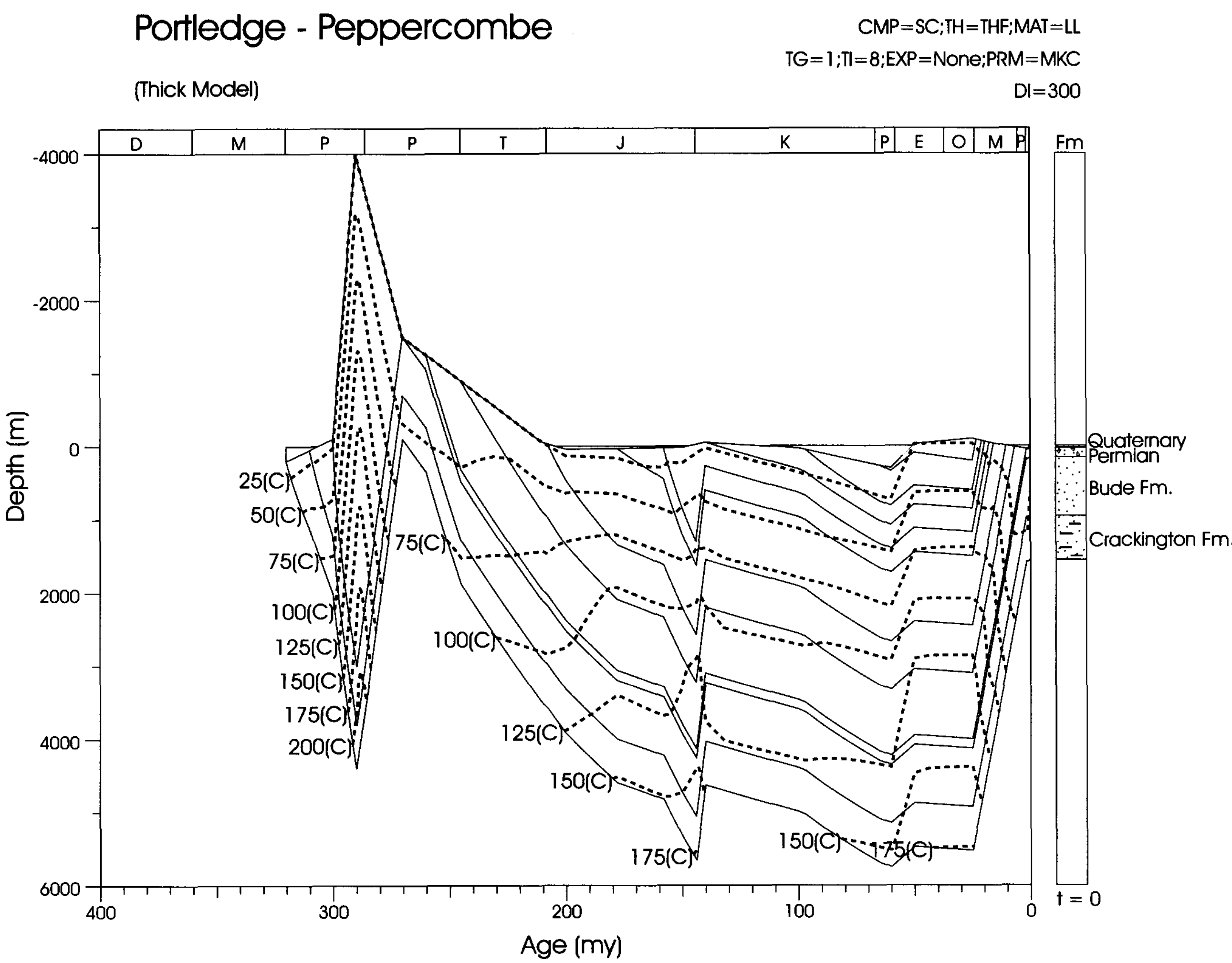

Figure 7: Maximum thickness burial history model for the Portledge-Peppercombe section.

Time	Maximum thickness model		Minimum thickness model[1]		Comments ...
(m.y)	Depth (m)	Temperatures (°C)	Depth (m)	Temperatures (°C)	
270	0	25	0	25	Late Carboniferous - early
260	198	30	179	27	Permian surface
250	1,005	47	310	30	conditions
225	1,871	75	609	42	
200	2,482	95	962	56	
175	3,066	120	1,511	79	
150	3,912	133	2,186	94	
125	3,396	110	2,461	104	
100	3,562	111	2,433	97	
75	3,933	122	2,468	96	
50	4,102	142	2,461	111	Ignoring Lundy
25	4,230	145	2,430	107	
20	3,354	111	1,939	83	
15	2,478	79	1,447	60	
10	1,680	44	1,014	43	
0	155	16	155	17	near surface today

[1] A thinner section is justifiable if the Jurassic thinned out of the Bristol Channel Basin - see text.

Table 6. Modelled temperature histories for basal Permian at Portledge-Peppercombe for maximum and minimum burial thickness models.

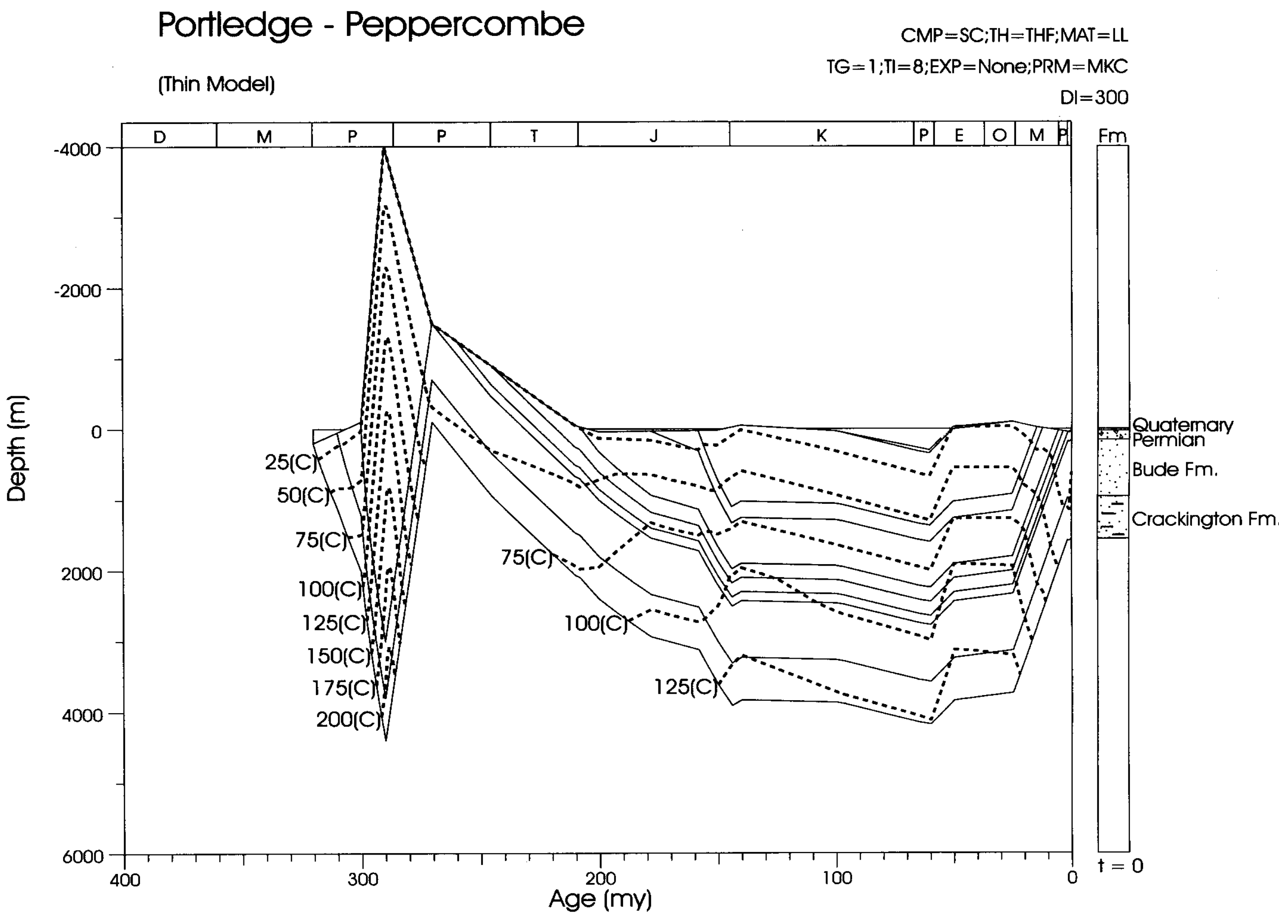

Figure 8: Minimum thickness burial history model for the Portledge-Peppercombe section.

location (Gayer and Cornford, 1992), suggesting rapid lateral changes in thickness. The missing Permian is thus modelled as 200m for a minimum (thinning towards the granite massif) and with 900m as a maximum by analogy with the Credition Trough.

Preserved Permian and the Variscan Orogeny

Preserved 'Permian' molasse as measured at the Portledge coastal outcrop is 130 m (Gayer and Cornford, 1992). In effect, this is the only 'fact' in the model. The base of the Permian is taken as the well-exposed Variscan unconformity surface. Vitrinite reflectance measurements estimated the Variscan uplift at between 5 km and 8 km for this part of the coast of North Devon (Cornford et al., 1987). Some 8 km of late Variscan uplift was added to both models.

GEOTHERMICS

The Present Day heat flow of the North Devon area is 57mW/m^2 (Wheildon *et al.,* 1981; Allen and Holloway, 1984). The nearest measurements to the Portledge-Peppercombe area being 67, 55 and 54mW/m^2, but with values doubling towards the Variscan granite batholith. Palaeo-events suggesting elevated heat flows are the intrusion of the Eocene (Thulian) Lundy granite to the north and the Permian Dartmoor Granite and Exeter volcanics to the south. The Fremington Dyke, some 6 km to the northeast, is the nearest igneous body (Roberts, 1997), but is dated as being late Variscan (292.4±7.1 my) and hence pre-dates the Permian elastics. In the absence of the development of hydrothermal cells, such intrusions have a limited spatial and temporal effect on geothermal gradients and hence observed sediment temperatures in the surrounding rocks. Cornford *et al.* (1987) found the organic metamorphic aureole for the northern margin of the Dartmoor Granite to be restricted to <1 km at the present day erosion surface. The absence of evidence for hydrothermal mineralisation in the Permian redbeds suggests no far-field effect needs to be modelled for either Variscan or Thulian intrusions (Table 5).

Surface temperatures, currently averaging 12°C (interglacial) and estimated as 0°C (glacial) at this peri-glacial location, were higher in the more distant past, both due to the northerly drift of the European plate, and the lower north-south (polar-equator) temperature gradient during most of the Mesozoic and Tertiary. The surface temperatures in Table 5 are taken from a review of North Sea and North Atlantic surface temperatures based on oxygen isotopic ratios for benthonic shell carbonates (Cornford, 1998).

MODELLING RESULTS

The burial history based on maximum thicknesses is shown in Figure 7, and on the minimum thicknesses in Figure 8. The minimum thicknesses are the sum of the regionally plausible minima. It could be argued that the preserved Bristol Channel geology thinned dramatically towards the present coast to produce a thinner 'minimum' section, but this is rejected in the absence of sedimentary or structural evidence for shoaling or condensation. Temperatures based on a constant heat flow, with thermal conductivities and heat capacities of the lithology mixes modified by burial (compaction) and temperature effects, are overlain as isotherms on the burial histories. The modelled temperatures of the basal Permian (i.e. Variscan unconformity surface) through time are detailed in Table 6.

Even the minimum assumed stratigraphic thicknesses are sufficient to produce burial temperatures in excess of the 70°C required to account for the fluid inclusion data in the carbonate cements of the Portledge-Peppercombe Permo-Triassic section. Considerably higher temperatures (>140°C) can be attained if maximum burial thicknesses are assumed.

In terms of sensitivities, the modelling results are sensitive to the mineralogy and grain size of the lost Permian to Tertiary sections. For a constant heat flow, and a given thickness of sediment, a more sand-rich lithology (quartz thermal conductivity = 7.7W/m°C) produces lower temperatures whilst a mudstonedominated lithology (illite thermal conductivity = 1.7W/m.°C) produces higher temperatures, since:

Heat Flow	=	Geothermal Gradient	x	Thermal Conductivity
mW/m2		°C/km		W/m.°C

If the basal Permian is required to reach 70°C under burial geothermics, some 950m of Jurassic is required for the thinner model. This implies a substantial thickness of Mesozoic cover over the Palaeozoic of south west England, and supports the proposal for widespread Mesozoic cover of the adjacent Palaeozoic outcrops (Cope, 1984, 1994, 1997).

CONCLUSIONS

A sequence of carbonate cements is preserved in the Portledge-Peppercombe Permo-Triassic elastic sediments. The earliest calcite cements are groundwater calcretes formed in a semi-arid depositional setting. Associated nodular and tubular calcites are pedogenic in origin and represent fossil root structures. All these calcites initially precipitated at stable geomorphic surfaces under ambient Permo-Triassic surface conditions although they now contain two phase, low salinity, variable LVR fluid inclusions with measured T_h values of 59-148 °C from a single sample.

Later dolomite-ankerite cements record precipitation from moderately saline aqueous fluids at ca 70°C as determined from fluid inclusion microthermometry. Such temperatures are readily attained from burial alone invoking only minimum Permian-Recent sediment thicknesses based on the regional preserved stratigraphy. Maximum sediment thicknesses inferred from offshore basin stratigraphies result in significantly higher temperatures that reach 140°C. The dolomite-ankerite cements are thus considered to have formed during burial at temperatures recorded by the fluid inclusion T_h measurements. The calcrete calcite cements, by contrast, recrystallised during burial and their fluid inclusions reset at minimum temperatures of 60°C. The 1-D basin modelling thus indicates that no additional heat is required to explain the temperatures recorded in the calcite and dolomite-ankerite cements. Ingress of hot, extraformational fluids related to proximity to faulting or from nearby igneous intrusions (such as the Lundy Granite) is not required.

The basin modelling, constrained with the temperature history recorded in the fluid inclusions from carbonate cements in the Portledge-Peppercombe Permo-Triassic elastic sediments, further implies that a substantial thickness of Mesozoic cover has been removed from South West England, consistent with the proposal by Cope (1984; 1994; 1997) that the adjacent Palaeozoic sequences had a regional Mesozoic cover. On the basis of regional stratigraphy, the balance of evidence suggests most of the uplift took place during the Neogene.

ACKNOWLEDGEMENTS

Calum MacAulay at SURRC is thanked for undertaking the isotope analysis of the carbonate cements. Ross Garden, Paul Wright and Journal referees Rod Gayer and Duncan Pirrie all made constructive suggestions for improvements to a hastily produced first draft of the manuscript. Brian Williams is thanked for his patience whilst those improvements were made, and without Sally Cornfords' dedication in finishing the figures we would not have made the deadline.

BG Technology kindly provided financial assistance for the production of the colour plates.

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