TRIASSIC PALAEO-PRESSURE AND LIASSIC MUD VOLCANOES NEAR KILVE, WEST SOMERSET

C. CORNFORD

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Between Kilve Pill Mouth and Lilstock, the familiar limestone pavements of the Blue Lias of the West Somerset coast contain domed structures some 1.2 m high and 2-3 m in diameter. The line of 4 currently visible domes (October 2002) runs approximately north northeast orthogonal to, and in the hanging wall of, a major east-west striking fault. On closer inspection, the currently visible domes comprise limestone outer 'shells' and disrupted mudstone 'cores': in one case with a 'crater', at the crest of the dome. The 'crater' is filled with relatively unstructured 'tufa-like' carbonate that 'flows' through a breach in the crater wall. The crestal crater demonstrates fluid escape at the sea floor rather than just mud diapirism in the deeper sub-surface. Comparison of the organic matter in the shale core of one dome with 3 samples of adjacent Liassic shales shows less kerogen (TOC) and lower oil-potential, and tentatively suggests a higher maturity level for the core shales. The escape of hot water would explain these observations. Association with post-Lias faults (if not circumstantial) suggests syn-sedimentary movement, and possible connection with underlying overpressured Triassic rocks as seen at Watchet. Pressure modelling suggests that a diagenetic rather than purely compactional seal is required, with an imperfect seal in the intra-Trias evaporites required to bleed pressures up into the Lias section in early Liassic times. Further work is planned.

C. Cornford, IGI Ltd., Bideford, Devon, EX39 5HE, U.K.
(E-mail: *chris@igiltd.co.uk*).

INTRODUCTION

The coastal outcrop of the Blue Lias on the north coast of West Somerset is characterised by metre thick shales separated by limestone beds (Palmer, 1972). The shales are potential oil-prone source rocks but are immature with respect to oil generation (Cornford, 1986). With shallow dips, the limestones form 'pavements' on the foreshore. Some 1,100 m east of Kilve Pill Mouth (NGR ST 155 450) between the cliff-top brick lookout and the modern Naval Tower in the direction of Lilstock (Figure 1), one of these limestone pavements is uplifted to form a line of unusual domed structures. The domes in the carbonate pavement are prominent as a result of the erosion of the overlying thick mudstone unit, but no cross-sections have been found in the current cliff line. At this location, the interval on the foreshore and cliffs lies in the Angulata zone (Unit C of Palmer, 1972), with the limestone pavement capping the domes being approximately Palmer's bed C-115.

FIELD DESCRIPTION

The line of 4 currently visible domes (October 2002) run approximately north north-east, adjacent but at right angles to one leaf of the major WNW-ESE (Lilstock) fault (Figure 2a). The domes are within the hanging wall of this relatively major fault, and their lineation would seem to demand a transfer fault approximately at right angles to the general WNW-ESE 'down-to-the-graben' trend: no structure or offset of the normal fault trend is, however, seen at this location. The domes fall in the area to the east of where relay ramps have formed linking the North Quantock and North Exmoor faults (Peacock and Sanderson, (1999). Bowyer and Kelly (1995) and Dart *et al.* (1995) have demonstrated that east-west normal faults cutting the Lias on this coast represent the earliest phase of extension, but no faulting is observed to be syn-sedimentary. The later compressional (inversion) phase is evidenced by reverse movement on the previously normal faults, together with approximately north-south strike-slip faults plus left- and right-lateral conjugates. It is noted that the line of domes parallels the orientation of the Hinkley Fault to the east (Whittaker, 1980).

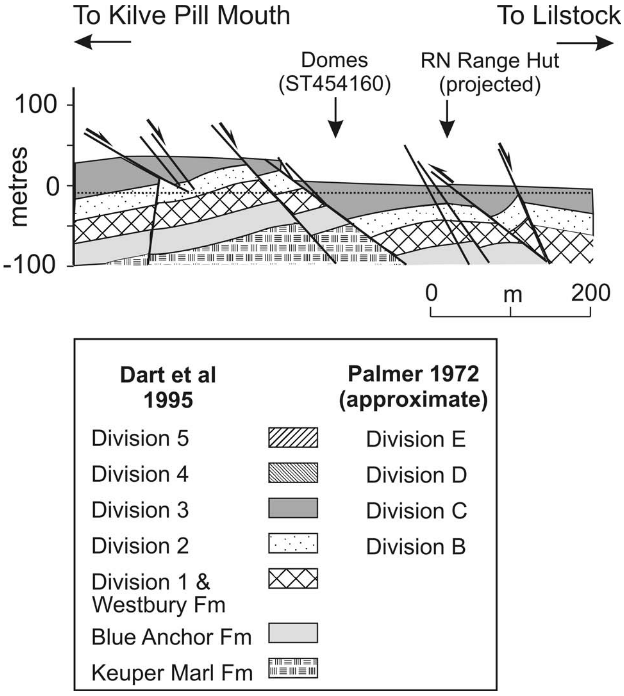

***Figure 1**. Stratigraphic cross section of the cliffs between Kilve Pill Mouth and Lilstock with the location of the Liassic mud volcanoes (units B …E as defined by Palmer, 1972).*

On closer inspection the 4 currently visible domes comprise limestone outer shells covering mudstone cores (Figure 2b). Unlike the normal structured shales which show lamination, bioturbation, or are massive, the mudstone core of the dome shows 'disrupted shale' features with feint contorted laminations. The domed limestones are jointed (Figure 2a, b) without any calcite veining, 'dry' jointing being recognised as the latest phase

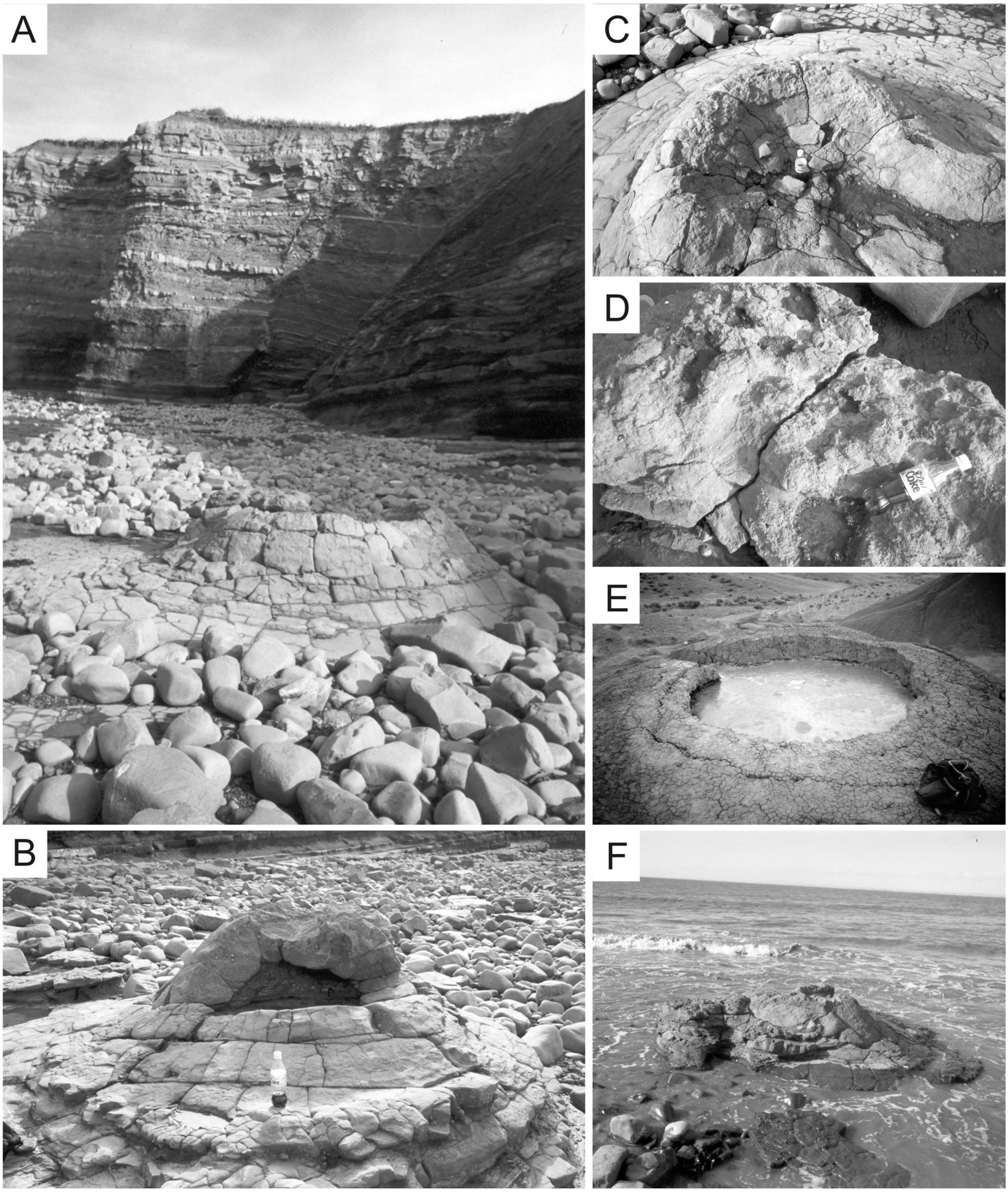

***Figure 2**. Fluid escape domes in the Lower Lias of the coast of West Somerset. (a) Relationship of the most inshore dome with one branch of the Lilstock fault in the background. (b) Another dome showing complete cover of jointed limestone pavement over disrupted mudstone core. (c) Cone at crest of dome showing tufa-type limestone fill and breaching (lower right). (d) Detail of tufa limestone fill. (e) Similar breached mud volcano in the northern foothills of the Tien Shan mountains, NW China. (f) Line of domes running out to sea in direction of the island of Steep Holm. Scale in figures (b), (c), (d) = 500 ml coke bottle = 220 mm high.*

of pressure release on uplift (Peacock and Sanderson, 1999).

In one case, a 'crater' penetrates the crest of the dome, and this is filled with relatively unstructured carbonate. The crater carbonate appears to be tufa-like (Figure 2c, d), being more porous, softer and of lighter colour than the typical grey micrites of the limestone beds. No macrofossils were found in the crater-fill carbonate. The east side of the crater rim is breached, and the 'tufa' appears to have formed whilst 'flowing' through the breach (Figure 2c).

Where the limestone pavement is merely domed (Figure 2b), the structures could derive from shale diapirism, with no movement of plastic shale or fluid across the essentially complete limestone layers. If these were the only structures, the domes might merely reflect an active mud diapir in a deeply buried bed exentuated by compactional drape. Such deformation could have occurred at any depth below the surface (e.g. up to ~1,200 m) where the shales and micrites were reacting in a plastic way. Deep development would be required if the north-south lineation of the domes were controlled by the north-south strike-slip faulting (Bowyer and Kelly, 1995), and hence the late inversion phase of the basin.

However, the evidence of the crater at the apex of one dome is indicative of flux to the palaeo-surface through the limestone layer and where the crater is filled with a cone of 'tufa-like' limestone, a positive feature is indicated on the Jurassic sea bed. In this case, the north-south alignment of the domes suggests a syn-sedimentary lineation, i.e. prior to normal, reverse and strike-slip fault development. Such an early expression of a north-south lineation may reflect a Palaeozoic basement lineation affecting the overlying Mesozoic. Sea floor mounds may form the basis for a reef or bioherm (Hovland and Judd, 1988) with the carbonate being the skeletal material of the organisms living on the sea floor mound. Since no macro-fossils are seen, the carbonate is likely to be a result of bacterial or algal activity (Werne *et al.*, 2001).

Whatever the origin of the doming, the way the limestone has flexed around the mounds suggests that on formation the carbonate layers were plastic, being sufficiently flexible to dome up but sufficiently coherent to avoid slumping. Though looked for, no slumping deformation was observed on the palaeo-slopes of any of the 4 domes observed. The post-compactional slopes are ~1:1.4 today. This confirms a degree of early carbonate cementation, as invoked by Hallam (1964).

GEOCHEMICAL ANALYSES

Four shale samples were taken for analysis, two from an area of un-faulted shale from Palmer's (1972) Bed C119 on the wave-cut platform to the east of Kilve Pill Mouth (samples 4a and 4b), and two from the area of the fluid escape domes (samples 6 and 7). The two Kilve Pill Mouth samples represent the two common shale types: a strongly laminated 'paper shale' and a more massive shale with more carbonate (stronger reaction to hydrochloric acid) and hence more blocky weathering. The bioturbated marls and limestones of the typical limestone-shale cycle were not analysed.

The shale samples from the area of the domes comprise the disrupted shale from a dome core and a sample of laminated shale caught up in fault breccia about 1 metre to the north of the last visible dome. The dome core sample was taken from a dome lacking a cone (Figure 2b), and hence was not necessarily an active vent on the Liassic sea floor.

Results of the TOC and Rock-Eval pyrolysis analysis, together with the sterane mass fragmentograms (m/z 217) from gas-chromatography mass-spectrometry (GC-MS) are shown in Figure 3. Interpretation of these parameters, largely in the context of North Sea oils and their Upper Jurassic source rocks, is discussed by Cornford (1998).

The extracts from the shale samples 4a and 4b can be considered as representing the background organic matter of the more organic-rich Liassic shales at this location. Based on the TOC and Rock-Eval results both these shale samples are rich but immature oil-source rocks: the pyrolysis yields are 24.5 kg/tonne and 26.9 kg/tonne respectively. Contrary to most source rocks, the laminated shale is slightly less organic-rich than the blocky-weathering more homogenous and carbonate-rich shale sample. With land-plants characterised by C29 steranes and marine algae by C27 steranes, the m/z 217 mass fragmentograms point to a mixed kerogen type, with a dominance of land plant exinites. Both transmitted white light and UV-excitation fluorescence identifies a kerogen of a bacterially degraded amorphous aspect: the original material is brown and appears to be of humic and exinitic origin. This agrees with the sterane carbon number distribution which points to a major molecular input from terrigenous plants.

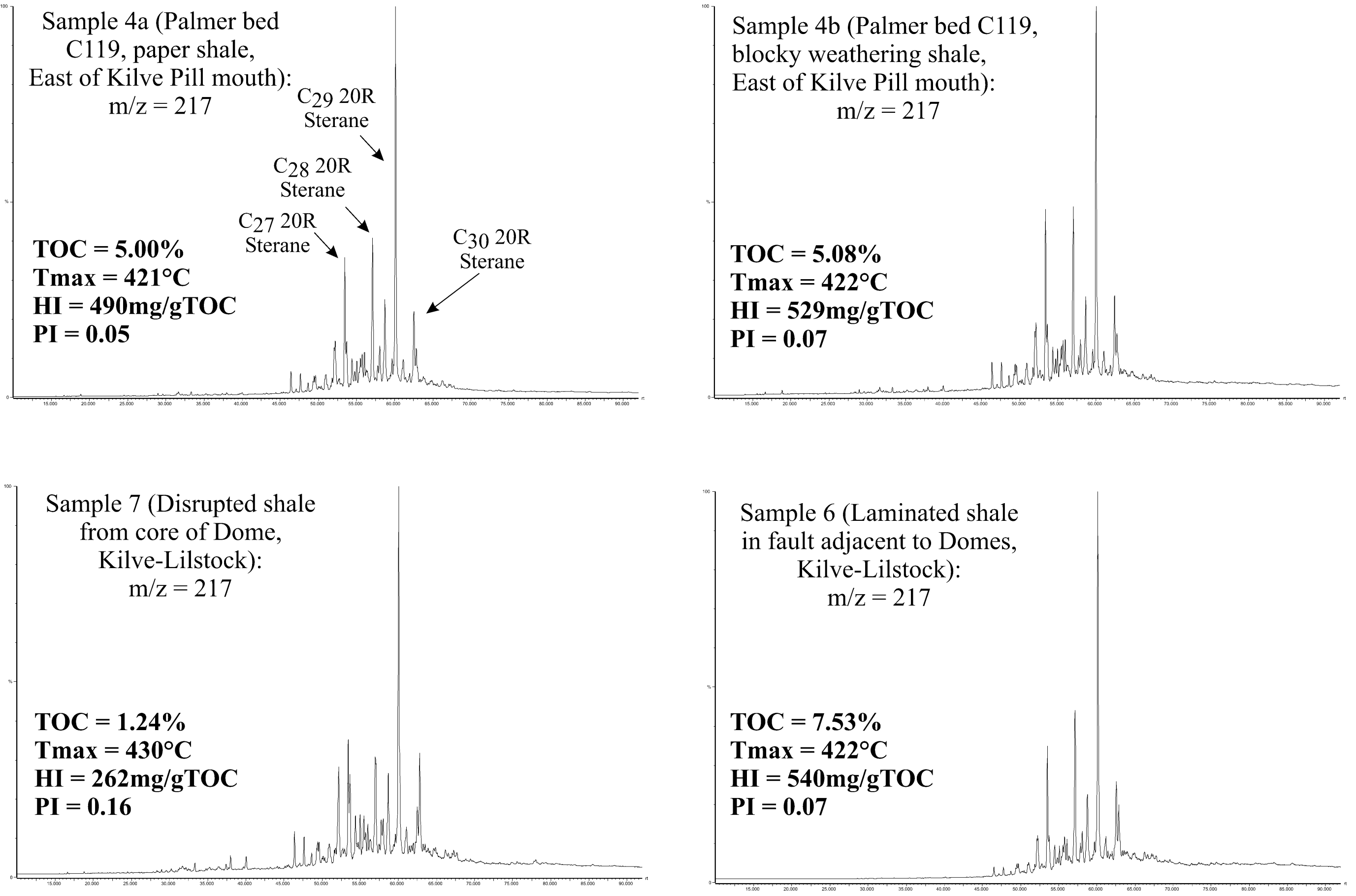

Figure 3. *Geochemical analyses of shales from a location away from domes (upper, Samples 4a and 4b), and from a dome core and adjacent fault zone (lower, samples 6 and 7). The GC-MS m/z 217 traces show three major peaks of 20R isomers at C27, C28 and C29 (dominant). The TOC and Rock-Eval pyrolysis data are also shown. Abbreviations: m/z = mass/charge, HI = Hydrogen Index, PI = Production Index, S1/(S1+S2), Tmax = pyrolysis temperature at maximum generation of S2 peak.*

The shale clast caught up in the adjacent fault plane (Sample 6) appears very similar in terms of the organic geochemical analyses to the typical Liassic shales (samples 4a and 4b). The TOC and Hydrogen Index are both high (Figure 3), with the pyrolysis yield of 40.7 kg/tonne. The maturity parameters Tmax and Production Indices are also very similar to the two Kilve Pill Mouth shales. The same level of maturity is also indicated by a similar level of sterane isomerisation (m/z 217 mass fragmentograms).

By comparison, the organic matter of the disrupted shale in the core of the dome is quite different (Figure 3, Sample 7). It contains poor quality mainly gas-prone source rock with much lower TOC and Hydrogen Index values than the normal shales (samples 4a and 4b). With a TOC of 1.24% and a Hydrogen Index of 262 mg/gTOC, a kerogen mix of 25% Type II oil-prone and 75% Type III gas-prone components is indicated at the maturity Tmax of 430°C. Visual kerogen descriptions are not currently available for this sample. In terms of maturity parameters, the Tmax and Production Index values (430°C and 0.16 respectively) suggest an enhanced maturity level relative to the three other shales.

The sterane m/z 217 distribution of the dome core shale extract is subtly different from the other shales. Comparison of the m/z 217 and m/z 218 mass fragmentograms suggests the differences could be attributed to a small change in the 20R → 20S sterane isomerisation and the more advanced generation of diasteranes in the dome core shale.

ORIGIN OF THE MUD VOLCANOES AND SOURCES OF PRESSURE

Sea-floor mounds, mud volcanoes and shale diapirism, all suggest over-pressure (i.e. pore fluid pressures in excess of the hydrostatic gradient). Organic geochemical analysis of the shale core has been undertaken and isotopic analysis of the 'crater' carbonate and comparison with the background micrite of the normal Lias limestones is planned. These analyses are designed to differentiate between a number of possible escaping fluids:

Formation water – Liassic pore water resulting from compaction of Triassic pore water saturated with calcium sulphate (Watchet gypsum: Stoneley, 1983) or sodium chloride (Somerset salt field: Whittaker, 1972)

Non-hydrocarbon gases – carbon dioxide or nitrogen, escaping from deep Carboniferous coals or carbargillites (analogy with NW Germany: Littke *et al*., 1995)

Hydrocarbons (methane, ethane, etc., or oil: Schumacher and Abrams, 1996) seeping during the early Jurassic from the pre-Permian section which was matured during Variscan burial (Kelm and Robinson, 1989)

Fluid inclusions within calcite associated with the faulting at Kilve has been reported to contain oil droplets. However, the shale within the fault adjacent to the domes (Figure 3, Sample 6) shows no evidence for migrated hydrocarbon (low Production Index, highly immature sterane isomers). Thus the third possibility above is not indicated.

The dome core shale produced pyrolysis S1 yields and molecular markers which were a little different from the surrounding shale beds. An increase in Rock-Eval Tmax from a background of 422°C to 430°C and the Production Index (S1/(S1+S2)) from a background of 0.06 to 0.16 is noted. The enhanced Production Index could result from staining by migrated hydrocarbon or increased maturation, but the higher Tmax value can only be attributed to maturity or a different kerogen type. These differences in the analysed dome core shale relative to the other shales could be accounted for by: (1) Additional maturation. Given that they are fluid escape structures, the fluid was most probably hot aqueous (hydrothermal) fluids, since oil is contra-indicated. The very low heat capacity of gases also precludes these fluids as heating significant rock volumes. (2) Difference in organofacies (low TOC and Hydrogen Index correlating with differences in the molecular fingerprints)

Given the small differences between the 'normal' and dome core shales, discriminating between these two models must await the results from the petrographic and isotopic analysis of the 'crater' carbonate.

This association of the domes with the major faults bounding the Bristol Channel Graben, suggests the pressure forming the domes may derive from deeper in the section. Stoneley (1983) argued that the fibrous networks of gypsum seen in the Mercia Mudstones at West Bay, Watchet resulted from overpressuring of the Triassic section. There are two periods when overpressure may have occurred: i) During burial, and escape of overpressure into the Lias. If so the overpressuring of the Upper Trias must have been at least initiated soon after the onset of Liassic sedimentation. ii) During late Cretaceous or Tertiary uplift, in which case it could not be responsible for syn-sedimentary Liassic structures. Only Option i) could explain the fluid escape domes in the Lias.

Based on recent discussions of the maximum and minimum thicknesses potentially covering the Permian of the Bristol Channel (Burley and Cornford, 1998), by Angulata Zone times the Mercia Mudstones capped by Carnian salt would have been some 60 compacted metres below the sediment water interface, which equates to some 100 m decompacted to Liassic burial. This relatively small vertical distance suggests that a proto-Lilstock fault could have been bleeding off fluid from overpressured Triassic strata, possibly sealed below evaporites as seen in the Somerset Salt Field (Whittaker, 1972). This model can be tested.

PRESSURE MODELLING

The burial history of the Mesozoic of the West Somerset north coast has been simulated using 1-D basin modelling (Platte River's BasinMod™ 1-D software) and the pressure history is predicted. The thicknesses and lithologies of the preserved geology were taken from measured outcrops and well sections as summarised in Cornford (1986) and generalised in Burley and Cornford (1998). This required projecting isopachyte information from adjacent outcrops of the Bristol Channel and the Burton Row (Permo-Triassic) and Brent Knoll (Liassic) boreholes of the Somerset levels (Whittaker, 1980). The post-Liassic burial is also constrained by measured vitrinite reflectance values of 0.44 %Ro to 0.48 %Ro and associated molecular ratios (Cornford, 1986 and Figure 3).

Using Stoneley's (1983) concept of massive overpressuring within the Triassic associated with evaporites (gypsum and halite) seal and breaching thereof, a number of models were run to create excess pressure within the Trias and Lower Lias at the time of the dome development on the sea floor (i.e. Hettangian). Assuming Darcy flow and based on pore fluid and rock densities (Welte *et al*., 1997), the model outputs hydrostatic and lithostatic pressures as a function of depth (Figure 4). Compaction,

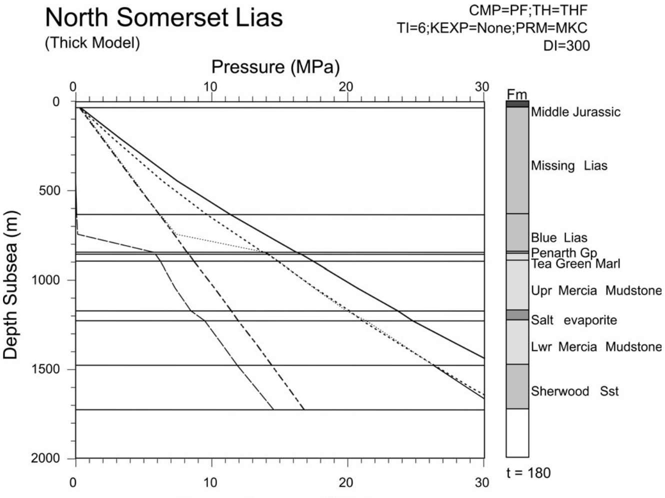

***Figure 4**. Predicted Liassic (180 Ma) pressure gradient for the north coast of West Somerset (Platte River's BasinMod™).*

hydrothermal expansion and uplift produce pore pressures in excess of hydrostatic, the difference being termed excess pressure. Pore pressures will increase until they reach near lithostatic, at which point the rock is modelled to fracture and the pressure dissipates. The pressure at which the rock fractures is termed the critical pressure and approximates to 85% of the lithostatic pressure (though this percentage varies greatly with heterogeneity and anisotropic stress).

A simple model with intra-Trias evaporites produces massive overpressuring in the sub-evaporite section but no overpressuring reaching the Lower Lias section during the early Jurassic. In this simplest case, excess pressure is the product of sediment compaction, modelled as exponential with respect to depth (Sclater and Christie, 1980). Adding the modelling of diagenesis in the form of normal quartz cementation (BasinMod™ option) increases the sealing capacity of all shales by reducing the porosity and hence permeability. Whilst increasing the sub-evaporite overpressure, this produces minor syn-sedimentary overpressure in the Lower Liassic. However, the pressure does not reach the critical pressures required to initiate rock fracturing and escape to the surface implied by the observed domed fluid escape structures.

Finally, adding silt to the intra-Trias evaporites bleeds the sub-evaporite pressure up into the overlying Jurassic sections. With 10% silt in the salt-gypsum mix of the Carnian 'Saliferous Beds', the major increase in pressure potential gradient has moved up into the Lias interval (Figure 4). Adding 20% silt fails to seal the Triassic and no overpressure is modelled at any level. Based on the description of the 'Saliferous Beds' (Whittaker, 1972), the mix with silt is quite realistic. Though only addressing simple 1-D temperature-pressure controls on the system, the models show the possibility of accounting for the fluid escape domes in terms of pressure release from the sub-evaporite Triassic during the early Jurassic. Further work on the petrography of the carbonates, isotopes, and fluid inclusions are planned to test this model.

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