TOWARDS AN ORIGIN FOR BIDEFORD BLACK

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Cornford, C., Jones, M. and Scrivener, R.C. 2011. Towards an origin for Bideford Black.
Geoscience in South-West England, **12**, 356-363.

Bideford Black is found in two forms – sheared 'coal seams' and organic rich shales or carbargillites. Both have been exploited commercially in the 19th and first half of the 20th Century, with the coal worked for fuel, and the carbargillites as mineral pigments - 'Bideford Black' *sensu stricto*. A collection of nine samples of coal and carbargillite were assembled from the Bideford area forming an east-west section running from the East-the-Water Mine, via Bideford High Street to the coast at Greencliff and Abbotsham. Treated as coals these samples showed mean vitrinite reflectance values between 1.66 and 2.58%Ro, with 3.81%Ro being found at Greencliff. This compares with the coeval strata to the north and south in the range 4.4-5.0%Ro. The Bideford area is thus equivalent to low volatile bituminous to anthracite coal rank, compared with meta-anthracites as the norm elsewhere in the Crackington and Bude formations of North Devon and North Cornwall. A 'thrust-back thrust' popup would typically explain anomalously low maturity within a thrust belt, which suggests that the Bideford Formation comprises an allochthonous nappe.

Reflectance measurements of the nine Bideford Black samples was made with linearly polarised light allowing the determination of maximum and minimum reflectance which adds precision to estimates of maximum burial. By analogy with reflectance gradients of other Upper Carboniferous sequences, a maximum palaeo-burial of between 5,700-8,100 m is indicated for the Bideford Black levels of the Bideford Formation.

Organic petrographic examination shows all the Bideford Black samples to be fairly mono-maceralic, comprising uniform vitrinite with minor inertinite and locally exinites (cutinite). This maceral association has been attributed to palaeo-'log jams' formed within river channels during flood events, and agrees with the local association of the Bideford Black 'seams' with the channel sands of the formation. Knowledge that the Bideford Black accumulations were initially log jams could assist any future exploration for new deposits – should they make a surprising return to commercial exploitation.

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Keywords: Bideford Black, Carboniferous, coal, vitrinite reflectance.

INTRODUCTION

Bideford, described by Charles Kingsley (1855) as *"The little white town"* in the second line of his novel Westward Ho! has a black side. Traditionally this was in East-the-Water, and it stems from an unusual feature of the local geology. The local strata are the sandstones and shales of the Upper Carboniferous 'Culm Measures' (Figure 1), which consist locally of the Westward Ho! Member of the Crackington Formation (Waters *et al.*, 2009) up to the level of the Mermaid Pool Sandstone, overlain by the Bideford Formation approximately to the Cornborough Sandstone, and then with sedimentary and/or tectonic contacts, to the Bude Formation.

The Bideford Formation and Westward Ho! Member appear to be a delta prograding into the Variscan foredeep basin in which the Bude and Crackington formations were deposited in shallower and deeper water respectively. The Bideford Formation includes a series of about 9 shale-to-sand cycles reflecting increasing energy from base (mudstones with occasional thin suspension-flow silts sometimes reworked into isolated ripples) via occasional sand filled channels with bank collapse features to the cycle top comprising the abrupt arrival of massive cross bedded sands reflecting the arrival a major channel sequence into the area (de Raaf *et al.*, 1965; Li, 1990). Bioturbated surfaces containing burrows and roots (palaeosols; Hoffman, 1992) are frequently found on top of these channel sands along with sporadic 'coal seams'. These surfaces appear to reflect subaerial delta-top to flood plain conditions developed on top of the channelized and crevasse-splay sands and prior to abandonment and recommencement of inter-distributary muds. Coal lenses and sporadic layers can also be found within the channel sand complexes, which Hoffman (1992) describes as 'drift wood'.

Two types of Bideford Black were mined, one high quality glossy lumps of lustrous graphitic appearance (Figure 2 right), and the other a dull earthy material (Figure 2 left). Records show that 4 seams were exploited as fuel, while a fifth seam to the south, the 'Paint Seam', yielded the mineral pigment, Bideford Black (Claughton, 1975; R. Gould personal communication).

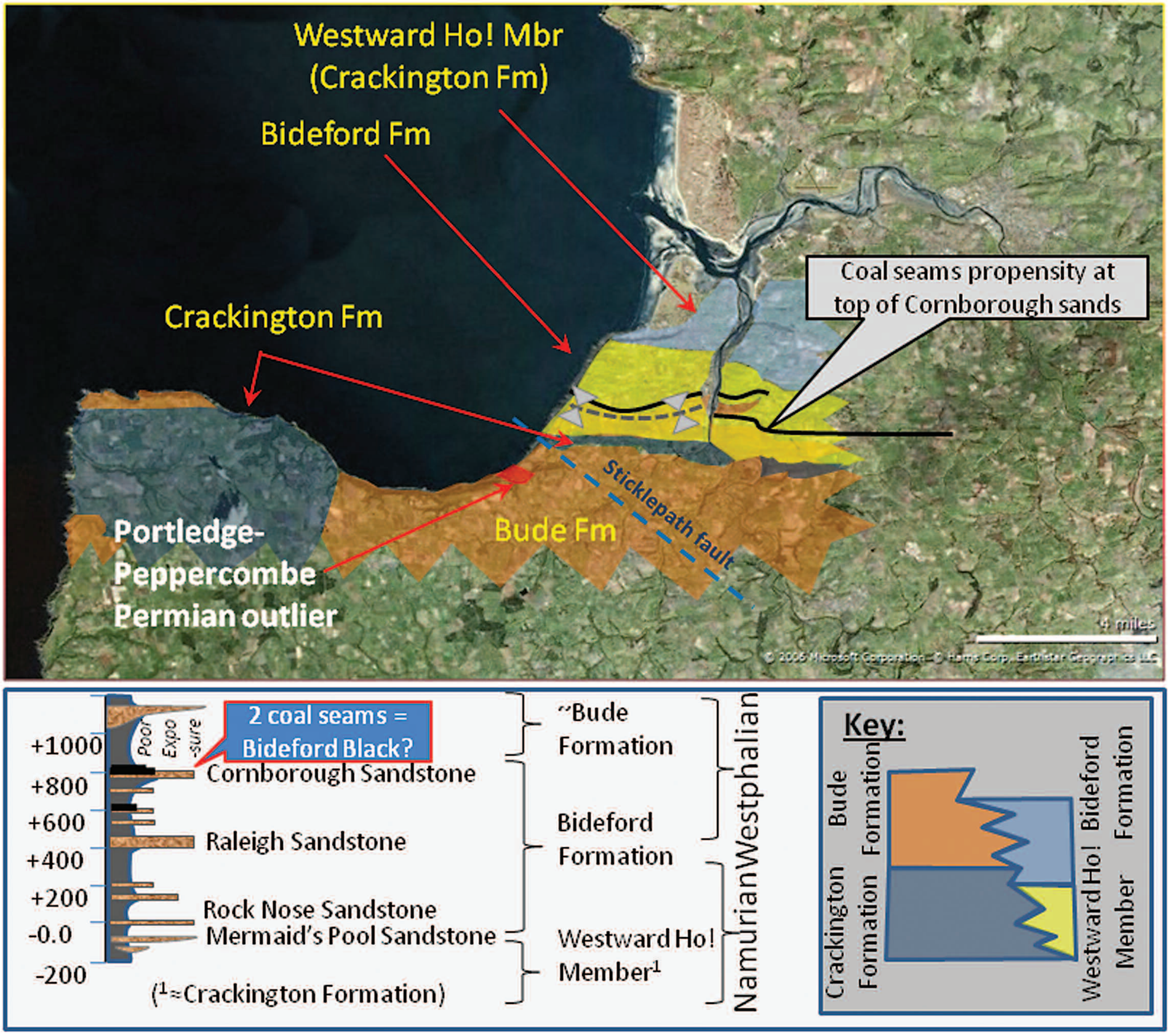

Figure 1. *Location of the Bideford Formation and Westward Ho! Member in the context of the Bude and Crackington formations draped over Microsoft's Google Earth map of Bideford Bay and adjacent coastal areas.*

Figure 2. *Samples of Bideford Black: (**a**) dull carbonaceous shale (left Sample BB-5) and (**b**) massive lustrous (graphite-like) meta-anthracite (right BB-9).*

SAMPLES AND ANALYTICAL METHODS

A collection of nine Bideford Black samples have been assembled from various sources, reflecting the outcrop extending from the coast at Greencliff to the old mine workings at East-the-Water (Table 1). The sample locations are shown in Figure 1 and are listed in Table 1.

For microscopy examination, a representative split of each sample was mounted in araldite, ground flat and polished with progressively finer silicon carbide then diamond pastes. The mount was then fixed to the rotating stage of a microscope photometer, and the reflectance measured relative to a standard using an oil-immersion objective with linearly polarized light of 546 nm wavelength. The microscopist then identified vitrinite particles and measures the reflectance of between 20 to 50 particles per sample. The values are used to create a histogram, and if multi-modal, one histogram mode is selected as representing the 'true' reflectance of the sample. An average (arithmetic mean) of the selected mode is then reported. The actual measurement error is small, but the selection of which particles are 'true vitrinite' (specifically telo-collinite) gives rise to most of the scatter in mean values reported here and in most studies (Borrego *et al.*, 2006).

ORGANIC PETROGRAPHY AND OPTICAL PROPERTIES OF BIDEFORD CARBON

Carbons generally exhibit uniaxial negative optical properties. From low rank huminite via bituminous coal and anthracite to graphite both the reflectance and the anisotropy increases (Forrest *et al.*, 1984; Houseknecht *et al.*, 1997; Kilby, 2001; Marques *et al.*, 2009). Commonly vitrinite reflectance is measured without polarized light and without rotating the stage: this gives a single mean reflectance value for each particle measured. Rotating the stage will generally record a maximum and minimum reflectance for each particle, the exception being if the anisotropic carbon particle happens to be sectioned by the polished surface orthogonal to the optic axis. Treating carbon as an disorganised crystal with a uniaxial negative optical indicatrix suggests the all particle orientations (relative to the polished surface) will record the maximum reflectance on stage rotation, but only sections cut parallel to the optic axis will record the true minimum reflectance (Cornford and Marsh, 1976).

For the study of Bideford Black, the mean, maximum and the minimum are reported. The difference between these numbers is termed the bireflectance, and is indicative of the anisotropy of the sample. Reflectance of kerogen particles in general and vitrinite particles in particular increases with burial depth and temperature. In cases where tectonic inversion and erosion has bought the sample near to, or at the surface, it is the maximum palaeo-burial depth, or more specifically the maximum palaeo-temperature event, that is recorded by reflectance. In contrast, the anisotropy is more influenced by the overburden pressure, the 'layering' of the aromatic molecules in the vitrinite being parallel to the bedding where the maximum pressure is the lithostatic load (Crelling *et al.*, 2005). Thus both vitrinite reflectance and anisotropy can be used to place limits on the maximum palaeo-burial of uplifted strata. In addition to burial, proximity to igneous intrusions, hydrothermal flux and shearing in fault planes (Andrews *et al.*, 1996; Houseknecht *et al.*, 1997) can increase the reflectance of organic matter, with graphite (16.4%Ro_{max} and 1.6% Ro_{min}) being the extreme high temperature end member in most cases.

The reflectance results are detailed in Table 1, and show the mean reflectance values of the Bideford Black samples range from 2.09%Ro to 3.81%Ro. This range is in agreement with previous measurements on dispersed particulate carbonaceous material in shales of the Bideford Formation and Westward Ho! Member (Cornford *et al.*, 1987). The background maturity of the Bude and Crackington formations to the south (Hartland Quay and Bude coastal sections) was found to be about 4-5%Ro (Cornford *et al.*, 1987), with measurements of about 3.1%Ro, rising to 4.1%Ro in the Rusy Fault zone on the southern margin of the basin (Andrews *et al.*, 1996). The geographic spread of the mean reflectance values is shown in Figure 3.

In the Bideford area, the highest values in this and an earlier study occur at Greencliff adit, this possibly resulting from the

Sample Code	Source	Date	Collected	Description	$\%R_{max}$	$\%R_{min}$	$\%R_{mean}$
BB-1	East-the-Water mine[1]	Circa 1960	Richard Scrivener	Crumbly carbonaceous mudstone	2.97	1.80	2.58
BB-2	Excavation, Bideford High Street	1990	Frank Holmes	Crumbly carbargillite	2.23	1.63	2.03
BB-3	A39 cutting W of Kenwith viaduct	1987	Chris Cornford	Dirty coal seam, blocky - lenticular fracturing	2.97	1.58	2.51
BB 4	Mouth of addit at Greencliff	1988		Fractured coal in weathered loose block	4.34	2.76	3.81
BB-5	Raleigh Sst Cornborough	1987		Carbonaceous fault smear	2.72	1.46	2.30
BB-6	Greencliff	1988		Coal scare in minor sandstone	2.37	1.54	2.09
BB-7	Cornborough Sandstone	1992		Mudstone clast in intra-formational conglomerate	1.82	1.34	1.66
BB-8	Greencliff	1985		Coal scare in loose block	3.34	1.77	2.82
BB-9	East-the-Water relief road	2002		Glossy sheared coal in fractured oxidized wall rock	3.01	1.37	2.49

Table 1. *Details of nine samples of Bideford Black used for the optical study. 1BGS sample from Howard St L Cookes, Bideford Black mine owner, collected in situ from the workings at East-the-Water.*

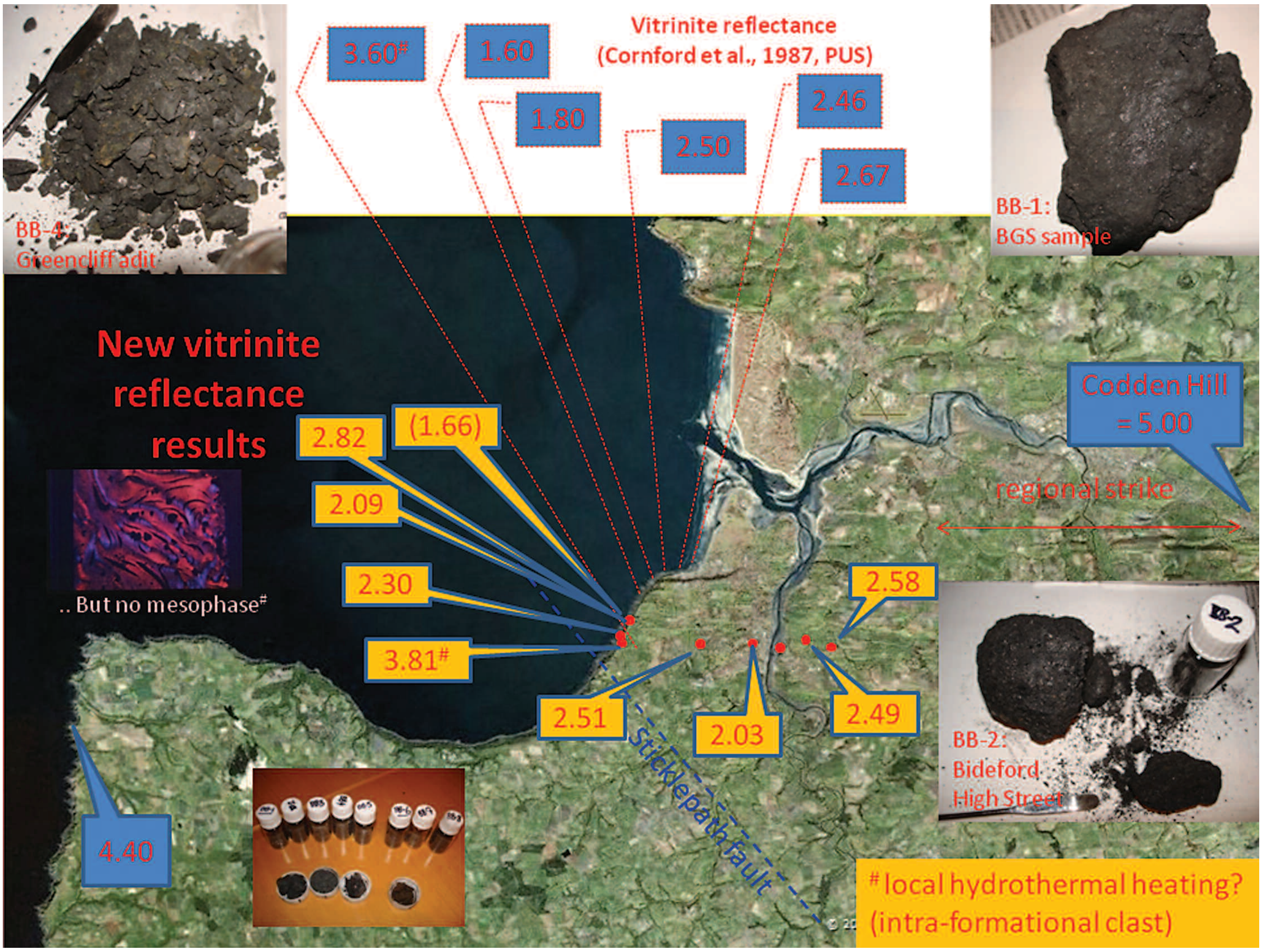

Figure 3. *Geographic spread of vitrinite reflectance data showing old (blue boxes) and new (yellow boxes) mean values.*

proximity to the Sticklepath Fault and/or to hydrothermal alteration. However no highly anisotropic mesophase textures were seen – sometimes a feature of hydrothermal flux (Gray *et al.*, 1998). Excluding the Greencliff sample (BB-4), these data confirm a low reflectance, maturity, and hence burial for the Bideford Formation relative to the regional norm of 4-5%Ro. The measurement of the anisotropy of the vitrinites adds precision to estimates of burial, as explained in Figure 4.

A standard set of vitrinite properties (%Ro_{max}, %Ro_{min}) are tabulated by van Krevelen (1992), and mean reflectance can be calculated and related to the relative depth of burial of Westphalian strata using a well substantiated trend shown in Teichmüller (1996). This allows the surface measurements of reflectance taken from the Bideford-Westward Ho! outcrops to be related to their palaeo-burial as shown in Figure 4. To take two examples, the low reflectance Cornborough Sandstone (BB-7) minimum and maximum reflectance values project to the appropriate van Krevelen (1992) trends and predict maximum burial to 5.4 to 5.8 km (blue construction arrows). The higher reflectance measurements from sample BB-4 taken near the Greencliff adit project to a narrow range of 8.1 to 8.3 km of maximum burial. Though in the same range as previous estimates of maximum burial based on mean reflectance (Cornford *et al.*, 1987), the measurement of the maximum and minimum reflectance values allows the prediction of maximum burial with less error.

Origin of Bideford Black

The polished samples of Bideford Black were examined under standard coal petrographic conditions with vertically incident white light and oil immersion objectives (Figures 5 and 6). Typical coals contain the three major maceral groups vitrinite (lignified tissue), inertinites (fossil charcoal from forest fires) and liptinites (spores, pollen, resin and cuticle). For UK Carboniferous coals an average V:I:L ratio is approximately 60:30:10, though considerable variation is seen between seams and within a single seam from area to area. Surprisingly, all 9 samples of the Bideford Black were strongly biased towards vitrinite. In the massive glossy form there was little bedding seen, but bedding was developed in the dull carbonaceous shale form. In this sense the samples were not typical coals or coaly shales. Bireflectance, as discussed above, is important to distinguish the optically anisotropic vitrinite from the optically isotropic inertinite. Though both vitrinite and inertinite may have the same reflectance value depending on the orientation of the polished surface relative to the optical axes, rotation of the microscope stage under linearly polarised light will show anisotropic vitrinite to systematically vary its reflectance. In contrast, the reflectance of inertinite, which is isotropic (Komorek and Morga, 2007), will remain constant upon stage rotation. Vitrinite exhibits uniaxial negative optical symmetry, so strictly, a vitrinite particle sectioned orthogonal to its C-axis will be isotropic, but statistically this is a rare occurrence.

Given the position of the major Bideford Black deposits in, or on, the top of the channel sands of the Bideford Formation (Raleigh Sandstone and Cornborough Sandstone), the presence of fairly pure vitrinite points to a deposit formed from logs (ligno-cellulosic tissues) with diminished leaf and spore material of the liptinites and any minimal oxidized wood or charcoal from the inertinites. Where seen (Figure 6c), exinite material contrasts with the reflectance of the vitrinite (e.g. van

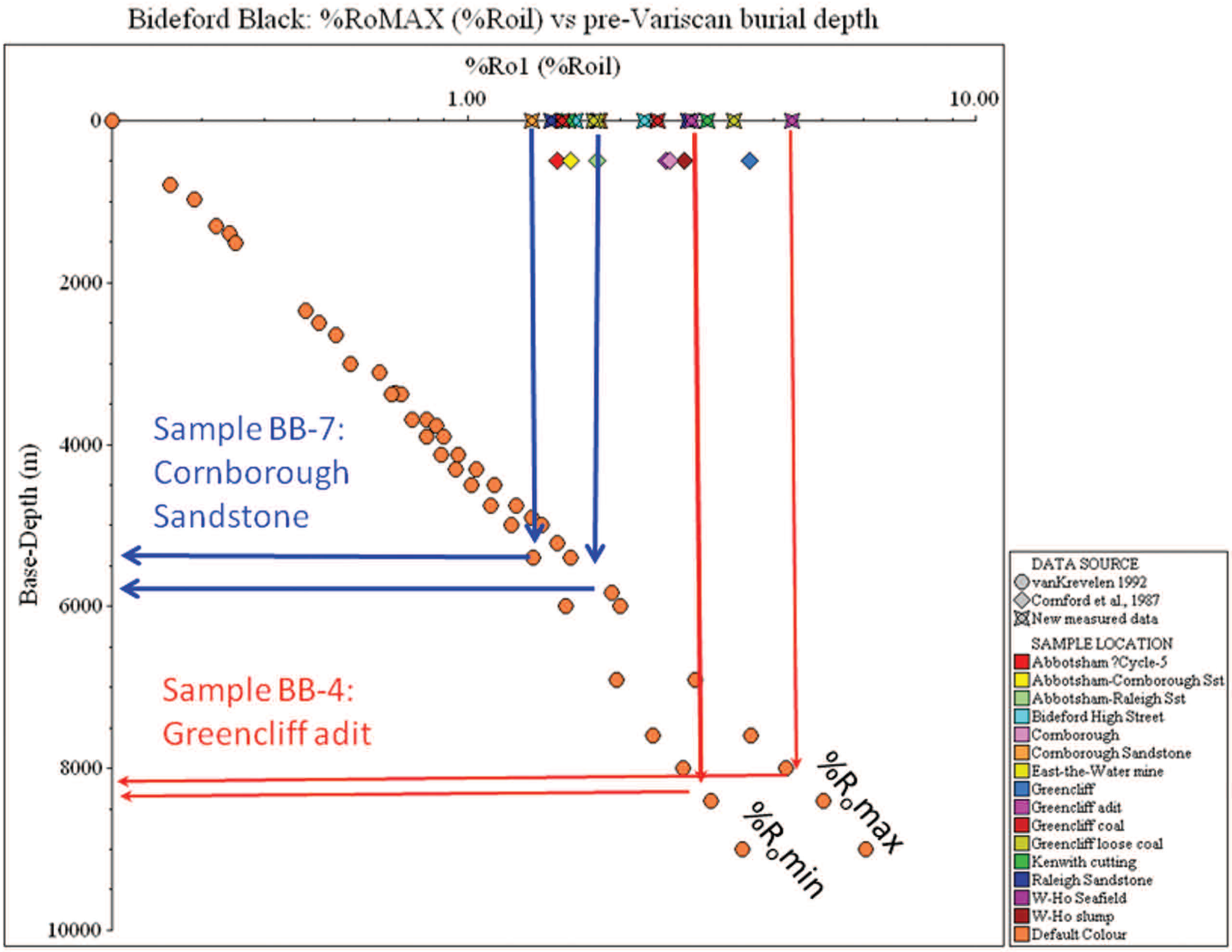

Figure 4. *Reconstructing the maximum burial for the Bideford Formation based on maximum and minimum vitrinite reflectance values as detailed in Table 1.*

Krevelen, 1993, page 373; Komorek and Morga, 2007) suggesting a lower maturity level than measured (Table 1) since vitrinite and exinites merge to a common reflectance coalification path at about 1.6%Ro.

This type of mono-maceralic assemblage has been described from log jams developed in river channels, sometimes at abandonment (Gibling *et al.*, 2010; Eble *et al.*, 1994; Hendrix *et al.*, 1995). In some cases, the log jams may be silicified (Schroeder, 1988; Campanian deltaics) but there is no evidence for this in the Bideford Formation. Elliott (1985) and Higgs (1999) have associated log jams with large floating 'rafts' of peat detached during hurricanes or tsunamis, which floated out into deep water before sinking to form a patch of allochthonous seam coal. Given the association with channel sands in the Bideford Formation, this is not a likely scenario.

It seems that the characteristic of palaeo-log jams is that the 'coal' comprises relatively pure ligno-cellulosic stem and trunk material leading to a relatively pure vitrinitic layer, with the lighter and smaller spores and leaf material including cuticle being largely carried further downstream. As can be seen in the modern images of log jams (Figure 5) it is not surprising that the massive glossy form of Bideford Black lacks bedding. The lack of inertinite can also be explained by the fine grained nature of the residue from forest fires. Some part burned trunks (semi-fusinite) may be trapped in the log jam, but the evidence for the Bideford Formation suggests this is rare.

This explanation of the origin of massive Bideford Black, also explains why, as far as the history of exploitation has revealed, the deposits are sporadic and 'lenticular'. If the Bideford Black deposits again become commercial – difficult to envisage under present circumstances – then exploration may be guided by knowledge of the direction and extent of the channel systems forming the major sands of the Bideford Formation. Such a model would provide a guide to the location and geometry of new deposits.

SUMMARY

Bideford Black is found in two forms – sheared 'coal seams' and organic rich shales or carbargillites. The thermal maturity of the organic matter is reproducibly low along the strike (mean vitrinite reflectance = 1.66-2.58%Ro) compared with the coeval strata to the north and south (4.4-5.0%Ro). High reflectance Bideford Black ($3.81\%R_o$mean) is found at Greencliff. The Bideford area is thus equivalent to low volatile bituminous to anthracite coal rank, compared with meta-anthracites as the norm elsewhere in the Crackington and Bude formations of North Devon and North Cornwall.

Reflectance values of nine Bideford Black samples was made with polarised light allowing the determination of maximum and minimum reflectance on the optically uniaxial negative vitrinites. This allows the calculation of the bireflectance which adds precision to the maturity determination. In addition both maximum and minimum reflectance can be used to establish a maximum palaeo-burial between 5,700-8,100 m for the Bideford Black level of the Bideford Formation. A 'thrust-back thrust' popup would typically explain anomalously low maturity within a thrust belt, which suggests that the 'Bideford nappe' may be allochthonous.

Organic petrographic examination shows all the Bideford Black samples to be unusually mono-maceralic, comprising uniform vitrinite with trace inertinite and no exinites. This

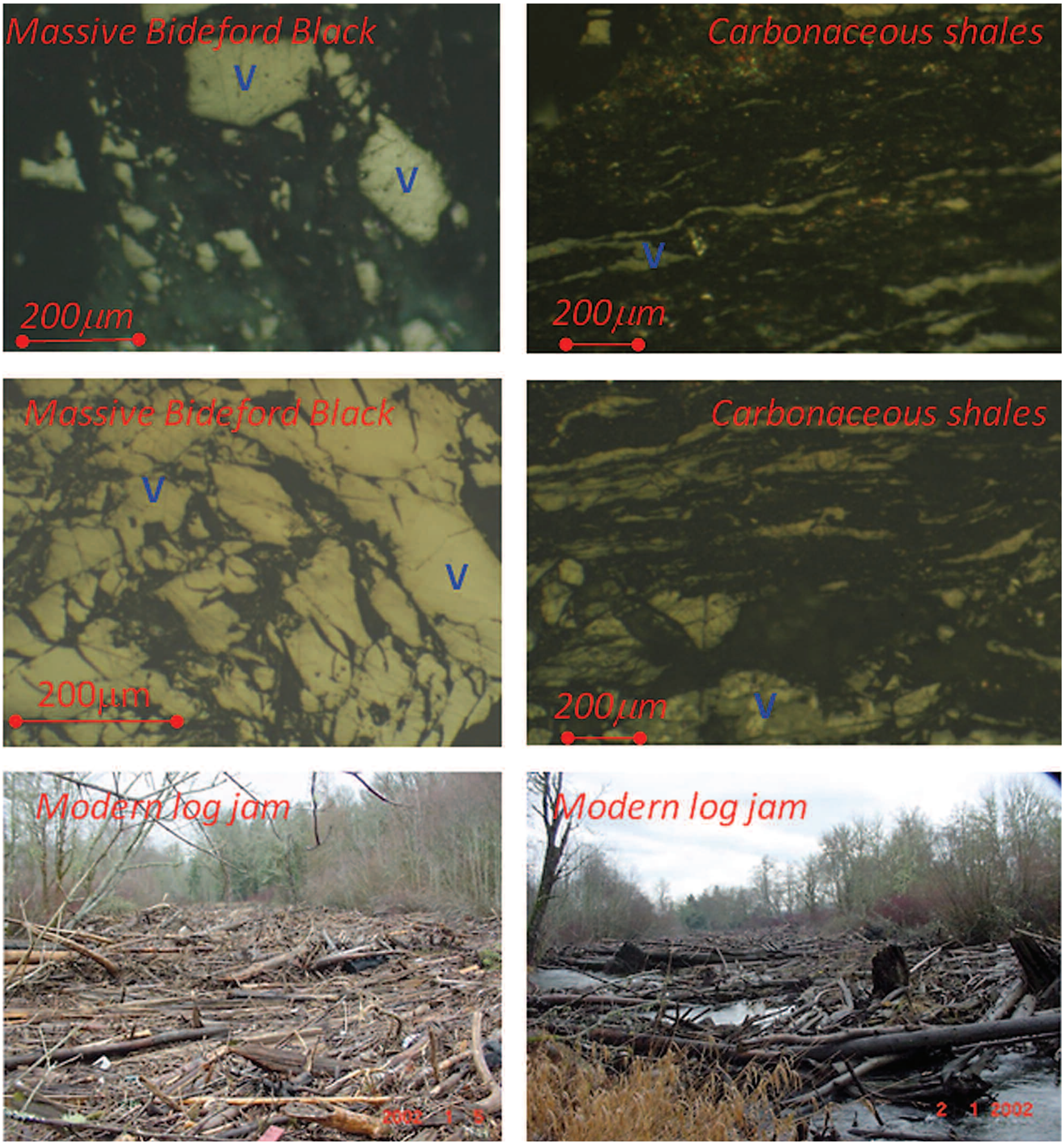

Figure 5. *Organic petrography of the Bideford Black in the massive glossy form (upper and mid left) and in the matt carbonaceous shale form showing bedding (top and middle right) with some modern images of log jams in river channels (Alberta, Canada). V = vitrinite.*

maceral association is relatively rare, and has been attributed to coal bodies (as opposed to laterally extensive seams) that formed from 'log jams' formed within river channels as a result of major flood events. Here the vitrinite precursors (lignin-rich tree trunks and branches) are concentrated, with the lighter spores, leaves, etc., being carried downstream. The absence of inertinite points to the lack of forest fires, or that the fine charcoal (fusinite) is also carried downstream. Knowledge that the Bideford Black accumulations were initially log jams, could assist any future exploration for new deposits – should they return to commerciality.

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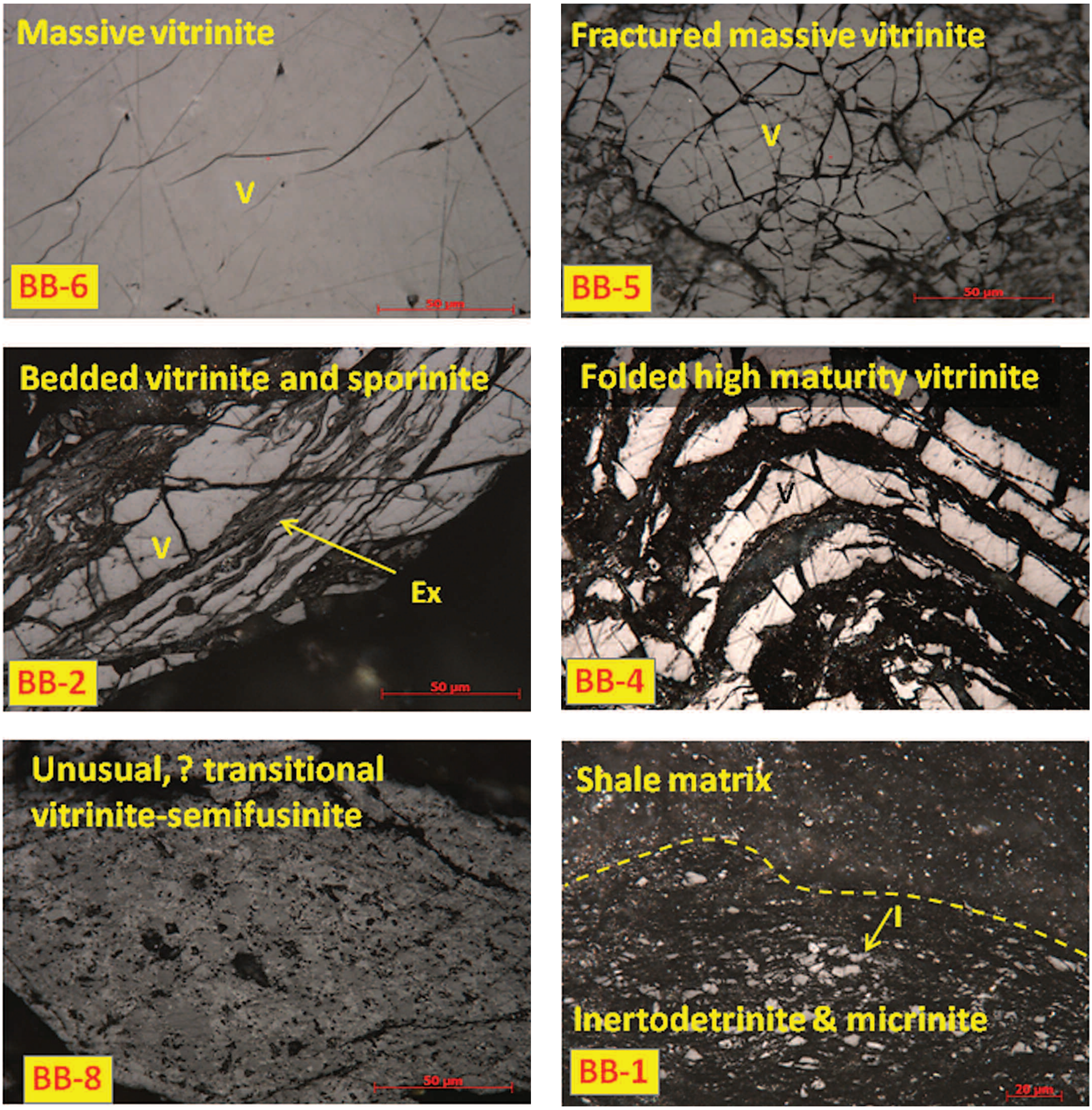

Figure 6. *Details of coal macerals see in the Bideford Black samples (V=vitrinite; Ex = exinite (cutinite and sporinite); I = inertinite). Micro-photographs thanks to Wayne Knowles (unpolarised white light).*

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