A periglacial ground-ice structure in the Upper Greensand (Cretaceous) at Lyme Regis, Dorset, UK

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Gallois, R.W. and Sole, D.T.C. 2014. A periglacial ground-ice structure in the Upper Greensand (Cretaceous) at Lyme Regis, Dorset, UK. *Geoscience in South-West England*, **13**, 316-320.

Disturbed bedding structures in the Upper Greensand at Lyme Regis are interpreted here as indicative of the growth and subsequent thawing of ice masses in permeable sediments in a periglacial climate. The processes involved are similar to those of the present-day formation of closed-system pingos in northern Canada and Siberia. In east Devon and west Dorset the Cretaceous Upper Greensand Formation comprises a lower part of weakly calcareously cemented glauconitic sandstones overlain by glauconitic calcareous sandstones and sandy calcarenites. Throughout much of east Devon and west Dorset, the upper part of the formation was partially or wholly decalcified, probably during the Palaeocene. As a result, the thickness of this part of the formation is reduced by up to 60%. Where well exposed over a distance of several hundred metres at Black Ven, Lyme Regis, the decalcified beds have subsided more or less evenly and have retained their bedding features and stratigraphical integrity except in a small area where the presumed ground-ice structure is present.

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Keywords: periglacial, pingo, ground ice, Cretaceous, Upper Greensand, Dorset.

Introduction

In east Devon and west Dorset, where the Upper Greensand Formation caps an extensive dissected plateau, the upper, more calcareous part of the formation, is much affected by dissolution (Gallois, 2004a). At Black Ven, where this part of the succession is continuously exposed over a distance of 600 m in the back scarp [SY 3491 9344 to 3558 9334] of the Black Ven landslide complex, the thicknesses of the Whitecliff Chert and Bindon Sandstone Members are reduced by up to 60 % in comparison with the unweathered sections west of Lyme Regis in Ware Cliffs [SY 237 916] as a result of the loss of calcium carbonate clasts and cements by dissolution (Figure 1). The dissolution process appears to have taken place slowly and evenly throughout the section with the result that the bedding remains more or less horizontal and the stratigraphical succession is maintained (Figure 2).

Black Ven cryoturbation structure

A westerly expansion of the scarp face as a consequence of renewed landslide activity in 2012 exposed an area in the upper part of the scarp face where the boundary between the Whitecliff Chert and the Bindon Sandstone is disturbed and appears to have locally subsided by up to 4 m over a distance of *c.* 50 m (Figures 3a and b). The base of the Whitecliff Chert is not exposed in the disturbed area, but comparison with the undisturbed outcrop 100 m east, shows that it has also been displaced downwards by up to 4 m. Within the disturbed structure, the glauconite-rich sandstone at the base of the Bindon Sandstone (here weathered to a clayey, fine-grained glauconitic sand) shows marked lateral variations in thickness and appears to have behaved as a fluid. In the unweathered exposures in Ware Cliffs and elsewhere on the east Devon coast, the cherts in the Whitecliff Chert and Bindon Sandstone occur as regular lines of nodules and lenses (Gallois, 2004b, figure 3). The cherts are fractured in the disturbed structure, but have mostly retained their relative stratigraphical positions (Figures 3b and d). The Upper Greensand sediments involved in the structure can be divided into three broad types on the basis of bulk permeability. The clayey fine-grained sands at the bases of the Whitecliff Chert and Bindon Sandstone act as an aquitard; where partially or wholly decalcified at outcrop or at shallow depths the fine-grained Foxmould sands are moderately to highly permeable; decalcified calcarenites and calcareous sandstones of the Whitecliff Chert and Bindon Sandstone are highly permeable.

The Black Ven structure resembles some of those caused by the repeated growth and melting of ground ice in the near-surface, active permafrost layers that form in periglacial climates. The most common and best documented of these structures are ice wedges and pingos. Geomorphological features and sedimentary deposits have been described from Dartmoor (Evans *et al.*, 2012) and Exmoor (Harrison *et al.*, 1998; 2001) that have been interpreted as evidence for local ice sheets, but there is no published evidence for the presence of an onshore continental ice sheet in South-West England. However, periglacial conditions were present throughout southern England for periods of tens of thousands of years during the cold phases of the Pleistocene, ending *c.* 10,000 years ago (Williams, 1965). These gave rise to a wide range of erosional and depositonal cryoturbation features (Te Punga, 1957). There are extensive deposits attributed to the action of multiple freeze-thaw cycles of ground ice in the SW region, notably sandy and gravelly Head Deposits up to tens of metres thick in many valleys, frost-shattered scree debris and block fields adjacent to the outcrops of harder rocks, and creep folds in Jurassic mudstones (Hutchinson and Hight, 1987;

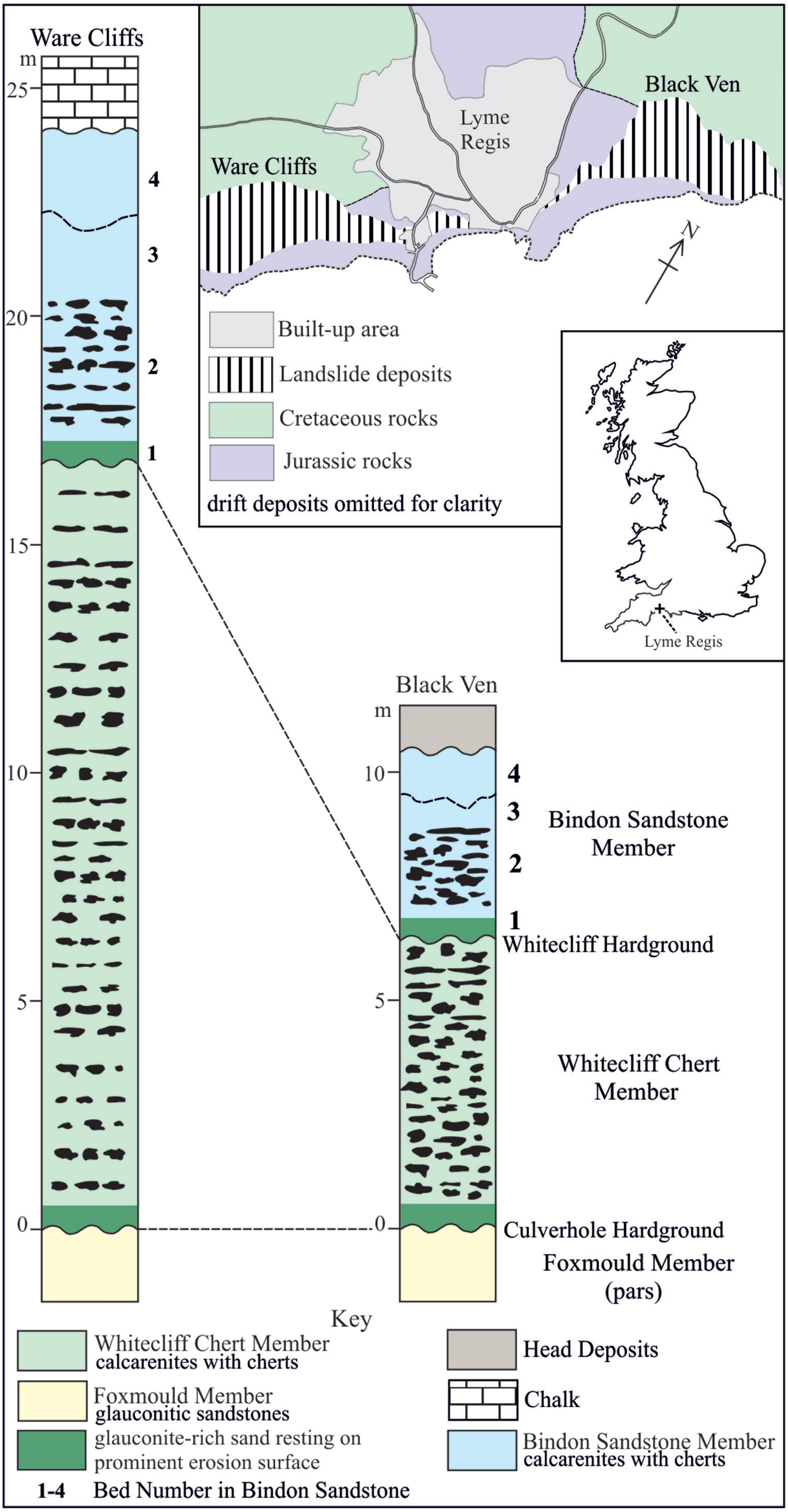

Figure 1. *Generalised vertical sections for upper part of the Upper Greensand Formation of the Lyme Regis area: intact succession at Ware Cliffs and decalcified succession at Black Ven.*

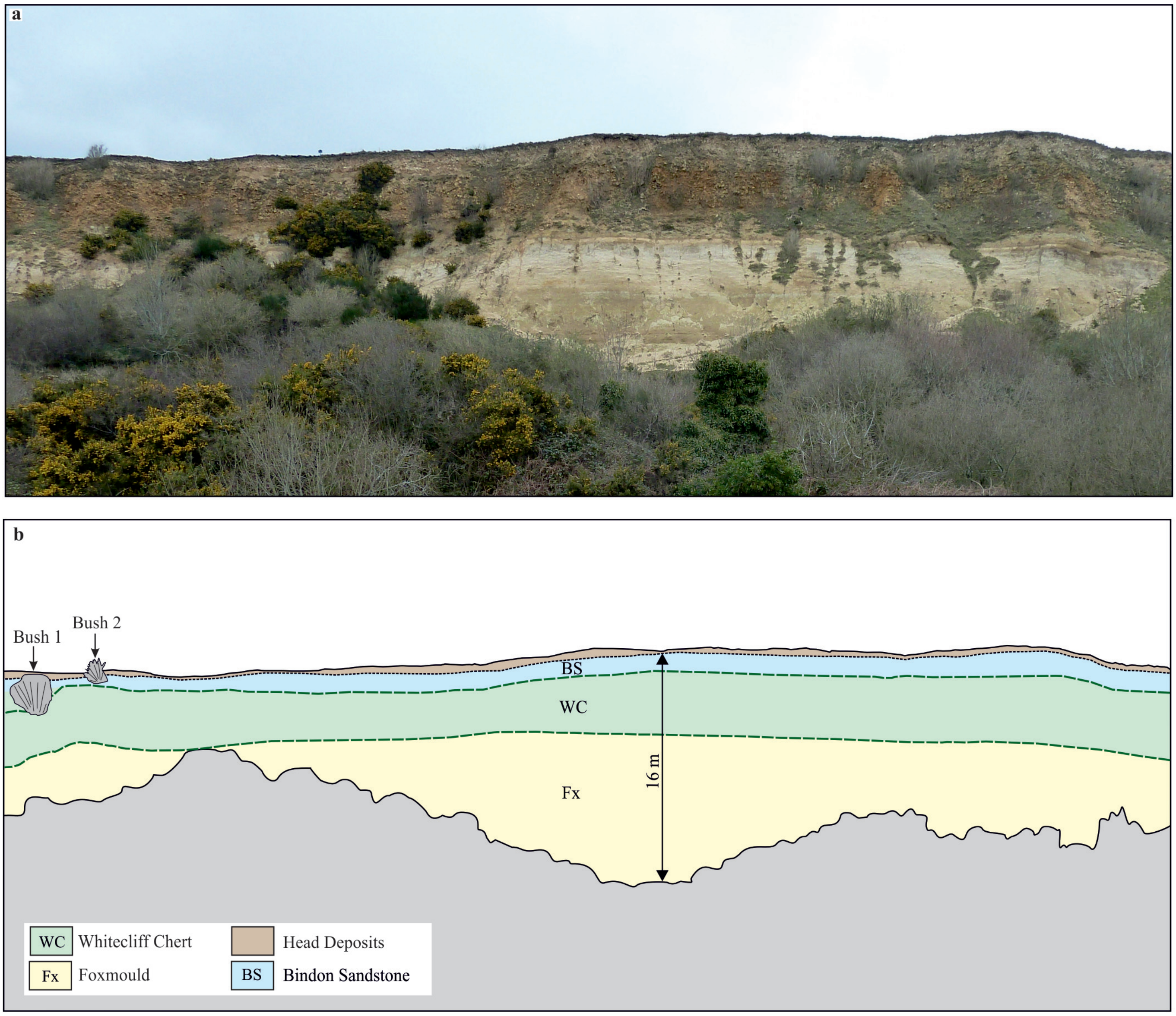

Figure 2. *(**a**) The Upper Greensand outcrop in the back scarp of the Black Ven landslide complex showing undisturbed Foxmould overlain by decalcified Whitecliff Chert and Bindon Sandstone. Photograph uncorrected for parallax and perspective. (**b**) Geological interpretation of (**a**).*

Gallois, 2010). There are comparatively few published records of well-defined ground-ice structures. Frost-patterned ground and ice-wedge casts have been recorded on Dartmoor (Palmer and Neilson, 1962) and at coastal localities in Cornwall (James, 2004; Ealey, 2012).

Method of formation

The method of formation proposed for the Black Ven structure is similar to that described for the formation of hydraulic (open-system) pingos and ice lenses that form at shallow depths in the active permafrost layer (Washburn, 1973). When the air temperature is low enough to initiate the freezing phase, the surface layer freezes and water trapped between this layer and the permafrost migrates laterally to form ice masses. The thickness of the active layer in present-day permafrost areas varies from a few centimetres to up several metres (Osterkamp and Burn, 2002). The principal factors that affect the thickness are the climate, which governs the amount of heat available to be transferred into the ground and the near-surface beds, and the permeability of the sediments. Permeable beds such as the decalcified beds at Black Ven enable heat transfer to take place more effectively, and result in a thick active layer. In the Black Ven example it is envisaged that in the freezing phase, water in perched water tables above the two clayey glauconitic sand aquitards was trapped between permafrost in the Foxmould and a frozen surface layer, and contributed to the formation of ice lenses at two different levels (Figure 4a).

During the melting phase, excess water in the chert-rich beds of the Bindon Sandstone drained freely to the surface or laterally to a nearby cliff face. That in the Whitecliff Chert was locally trapped beneath the upper glauconite-rich bed. When combined with the meltwater in this bed, the clayey glauconitic sand became partially fluidised and migrated laterally to produce marked variations in its thickness (Figures 3b and 4b).

In addition to the disturbances within the structure, the whole of the upper part of the formation within this area has subsided by up to 4 m. Part of the underlying Foxmould must therefore have been removed from the system to enable this to happen. The landslide complex is thought to have been initiated at a time of high sea level in the Pleistocene temperate climate of Marine Isotope Stage 5e and to have become reactivated during the present temperate phase (Gallois, 2008). If this is the case, then the back scarp of the landslide might have been as little as 100 m south of the present-day scarp face during the periglacial climates of the latter part of the

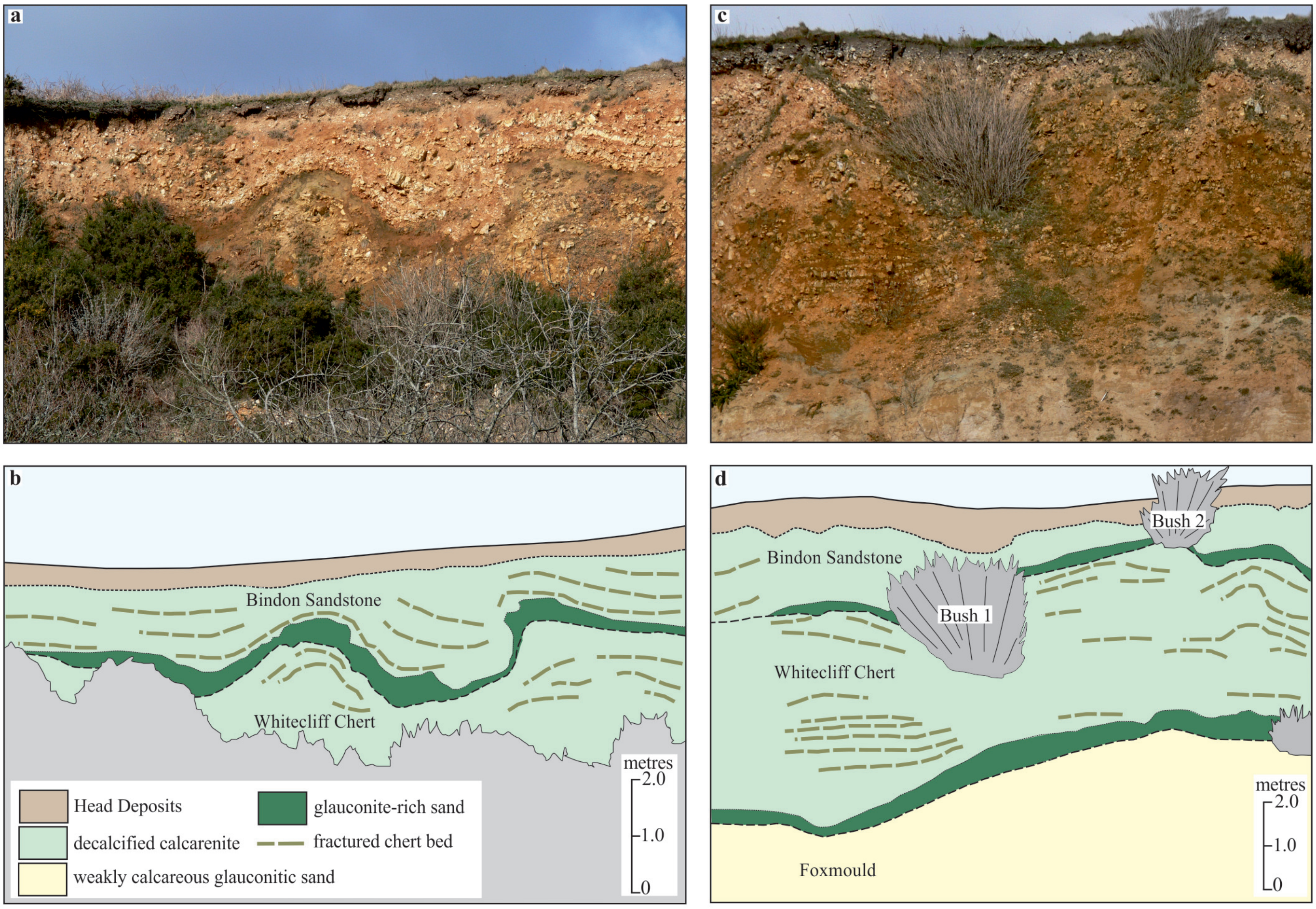

Figure 3. *Cryoturbation structure in decalcified Upper Greensand, Black Ven. (**a**) and (**b**) collapse structure picked out by the glauconite-rich bed at the base of the Bindon Sandstone. (**c**) and (**d**) section 50 m east of (**a**) showing minor disruption of the glauconite-rich beds at the bases of the Whitecliff Chert and Bindon Sandstone. Photographs (**a**) and (**c**) uncorrected for parallax and perspective. See Figure 2 for eastwards continuation in undisturbed beds. Gap between sections (**a**) and (**c**) c. 10 m.*

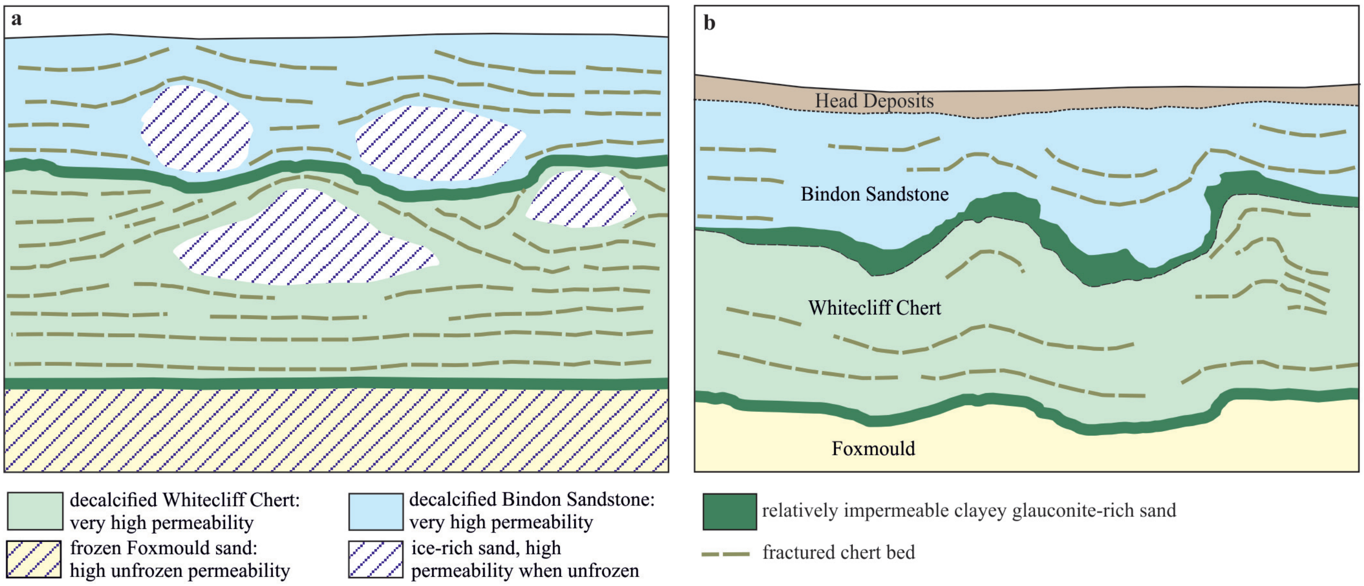

Figure 4. *Suggested mechanism for the formation of the cryoturbation structure. (**a**) Frozen phase: ice-rich masses form in the highly permeable decalcified Whitecliff Chert and Bindon Sandstone and cause disruption of the bedding. (**b**) Melting phase: meltwater in the Bindon Sandstone escapes to the surface or laterally to a nearby cliff face; meltwater in the Whitecliff Chert causes the overlying glauconite-rich bed to become oversaturated and partially fluidised; meltwater in the Foxmould trapped beneath the lower glauconite-rich bed cause fluidised pathways to open up and discharge sand/water mixtures to springs in the nearby landslide scarp face.*

Pleistocene. It is suggested here that during the melting phases the Foxmould sand became locally fluidised, a process that has been observed to occur at the present time when the sands become saturated (Arber, 1940), and that water/sand mixtures were discharged at springs in the nearby cliff.

SUMMARY AND CONCLUSIONS

A disturbed structure in highly permeable loose sands with chert clasts in the decalcified Upper Greensand at Black Ven, Lyme Regis is interpreted here as a ground-ice feature that formed in a periglacial climate, probably in the late Pleistocene. The absence of similar structures in the extensive exposures in the decalcified part of the Upper Greensand on the east Devon and west Dorset coasts suggests that the Black Ven structure formed in response to a local feature. This might have been the proximity of a nearby cliff face that allowed water/sand mixtures to be discharged from the structure and cause it to subside. An additional factor might have been the temporary presence of local perched water tables in sediments that are currently >15 m above the present water table and which would have been even higher above it at times of low sea level during the Pleistocene. The laterally continuous, albeit disturbed, nature of the glauconite-rich beds and chert horizons indicates that the Black Ven structure was not formed by ice masses (open-system pingos) that broke through to the surface. On melting, such structures give rise to complex collapsed bedding features and hummocky thermokarst topography of the type described by Sparks *et al*. (1972) in East Anglia. The retention of much of the bedding in the Black Ven structure, in which the cherts are disturbed but remain close to their bedding attitudes, suggests that it formed over a short period of time, possibly even a single winter. Multiple freeze-thaw events in bedded strata commonly result in the progressive rotation of individual clasts that come to lie at high angles to the bedding.

Several authors have suggested that permafrost may not have been present throughout Devon and Cornwall during the Devensian Stage (e.g. Ballantyne and Harris, 1993), the last cold phase of the Pleistocene, or that it might have been only sporadically present (James, 2004). The latter could explain the relative scarcity of frost-patterned ground and other well preserved periglacial structures in the SW region compared to the Midlands and East Anglia. This might indicate that the climate was warmer and wetter than that of more northerly areas as the result of the influence of a weak forerunner of the Gulf Stream. If so, then deposition would have been dominated by meltwater and solifluction deposits that removed or buried cryoturbation features that formed in earlier, colder periods.

ACKNOWLEDGEMENTS

The authors are grateful to Andrew Sole for his comments on an early draft of the paper, and would like to thank Stephan Harrison and Les James for their very helpful peer-review comments.

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