

Depositional environments, Windermere Supergroup, late Ordovician to Silurian, Northern England

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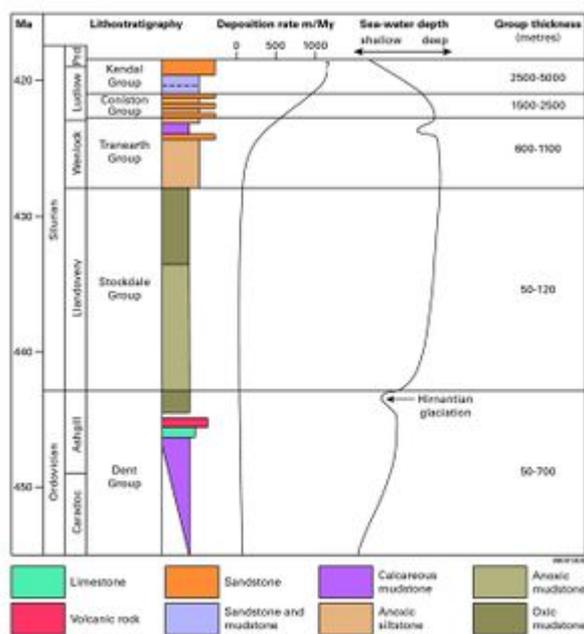
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Introduction



Variations in sedimentation rate and sea level during deposition of the Windermere Supergroup (after Rickards and Woodcock, 2005). Prd = Pridoli.26). P916057.

The Ordovician, Caradoc to Ashgill, Dent Group records a marine transgression across the remains of the Borrowdale Volcanic Group arc and its Skiddaw Group basement. Transgression may have been initiated by postvolcanic, thermal subsidence, although the intrusion of the major subvolcanic plutons at about 450 Ma, is more or less synchronous with the onset of Caradoc sedimentation in the north and east of the Lake District region. The ignimbritic Yarlside Volcanic Formation confirms that some local volcanicity continued into the Ashgill.

The transgression was clearly intermittent and topographically controlled, with the assemblage of carbonate and locally derived clastic lithofacies consistent with deposition on a shallow marine shelf. In the southern Lake District outcrop, four depositional cycles were separated by periods either of emergence and erosion or of nondeposition. Further east, in the Howgill Fells and at Cross Fell, the first three of these cycles are not developed and the equivalent stratigraphical interval shows continuous deposition in an oxygenated marine environment (respectively the Cautley Mudstone and Dufton Shale formations). The late Ashgill volcanoclastic mass-flow deposits (Appletreeworth Formation, Cautley Volcanic Member etc.) are apparently marine, but may well have been followed by nondeposition and erosion in a relatively shallow-water setting prior to the Ashgill Formation transgression. Thereafter, a fall in sea level during the Hirnantian glaciation ([P916057](#)) may have been the trigger for emplacement of the Ashgill Formation's mass-flow, pebbly mudstone member.

The postglacial rise in global sea level, coupled with regional subsidence of the Avalonian continental margin (perhaps the initial, flexural response to collision with Laurentia subsequent upon the closure of the Iapetus Ocean — this large-scale tectonic concept was introduced and described [Northern England – introduction to geology](#)), created the marine environment for Llandovery deposition of the Stockdale Group. Fine-grained sediment was deposited either as hemipelagic fall-out or from small, low-density turbidity flows. The dominance of black, carbonaceous and pyritous mudstone devoid of bioturbation in the Skelgill Formation indicates anaerobic depositional conditions. The prevalence of these anoxic conditions in the early Llandovery can be attributed to physical and biogeochemical changes in the oceans during the deglaciation that followed the Hirnantian ice age.

The lithological transition into the Browgill Formation records an increase in availability of fine-grained clastic detritus, introduced by low-density turbidity flows. There was also an increase in the volcanic ash contribution to the sediment budget, though this does not necessarily mean that the source volcanoes were local. Background conditions continued to be anaerobic until the later stages of Browgill Formation deposition. Then, in the late Llandovery, oxygenated environments became established, as required by the haematite-rich red beds of the Hebblethwaite Member and the absence of black mudstone amidst the grey shales of the Far House Member. There may have been an additional topographical control on the distribution of these oxygenated enclaves.

Anaerobic conditions were re-established early in the Wenlock allowing deposition of the distinctive, laminated mudstone and siltstone that comprises the Brathay Formation. The lamination probably arose from a periodic (and possibly annual) fluctuation in the supply of silt and organic material, with the former being introduced either by hemipelagic fall-out or by low-density turbidity flows. A more substantial input of turbidite sand during the later part of the Wenlock Period created the Birk Riggs Formation. A range of sedimentary features therein, including channels, flute and groove casts on bed bases, and cross-lamination in the upper parts of beds, provides evidence of palaeocurrent orientation and hence of basin geometry. Though some of the evidence is contradictory, the Birk Riggs Formation can be most simply interpreted as a series of small, overlapping turbidite fans dispersing sediment towards the south-west along the axis of a depositional trough.

A late Wenlock, eustatic fall in sea level temporarily restored aerobic conditions; deposition of the calcareous Coldwell Formation resulted ([P916057](#)). A varied, benthic fauna became established and included trilobites, brachiopods and bioturbating organisms. The graded, silty beds were probably deposited from waning and possibly storm-generated sediment flows into relatively deep water. Thereafter, towards the end of the Wenlock Period, sea-level rise and accelerating basin subsidence combined to re-establish deeper water, anaerobic conditions with a return to Brathay-style sedimentation; the Wray Castle Formation was the result.

The rate of basin subsidence increased abruptly into the early Ludlow as loading of the Avalonian

continental margin by the over-riding, leading edge of Laurentia gathered momentum. Turbidity flows poured into the deepening basin and thick sequences of graded sand and silt built up as the Coniston Group. Its sandstone-dominated formations record intervals of turbidite fan growth; the intervening siltstone-dominated formations record intervals of less vigorous sedimentation that might have been induced by temporary rises in sea-level. The turbidite beds contain a characteristic assemblage of sedimentary features, and analyses of those that provide an indication of palaeocurrent direction show that the turbidite fans were mostly supplied from the north-east and built-out towards the south-west. This pattern is fairly well maintained across the southern Lake District outcrop but appears to be more complex in the Howgill Fells. The composition of the sandstones (and of a derived acritarch microflora) suggests that their constituent sediment was eroded from the Scandian Orogen, then developing at the margin of Baltica. The dominance of turbidity current flow directed towards the southwest, along the axis of the depositional trough, would be compatible with such a source.

The relatively mature 'recycled orogen' compositional character of the Coniston Group continues upwards into the dominantly silty Bannisdale Formation, and a similar, south-west directed palaeoflow can also be deduced. The turbidity currents depositing the Bannisdale Formation siltstone were of lower density than those depositing the Coniston Group's sandy beds, but a very thick sequence resulted nevertheless. Remarkably, approximately 4 km of strata built up in the duration of a single graptolite biozone, which in the late Silurian was probably equivalent to a maximum of 1 million years; a sedimentation rate of at least 4 mm per year. An anaerobic environment had persisted from Coniston Group times, but towards the top of the Bannisdale Formation an increase in bioturbation marks a change to more oxygenated sea-floor conditions. At the same time, subtle compositional changes imply a shift in sediment source.

Both of these trends are more fully developed in the Pridoli Kirkby Moor Formation. The calcareous and bioturbated members (hitherto the Underbarrow Formation) and the locally rich benthic fauna attest to deposition in an oxygenated environment. At the same time, the appearance of sedimentological evidence for storm-influenced deposition suggests a dramatic shallowing of the basin ([P916057](#)). In the uppermost part of the formation this tendency culminates in red beds and siltstones that may have been deposited under tidal conditions. It is clear that by Pridoli times the sedimentation rate exceeded the basin subsidence rate and the Windermere Supergroup sedimentary basin was filled. In parallel with this, sediment composition and palaeocurrent distribution patterns suggest that the Scottish Southern Uplands terrane had become the source of the deposited sediment. The long-standing tectono-sedimentary influence of the Iapetus Ocean had ended and the scene was set for the terrestrial Old Red Sandstone.

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