Ludlovian slumps and crinkles in Wales

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Abstract: The early Ludlovian (Gorstian) basin in central Wales and Borderlands was the locus of two classical developments of synsedimentary slump facies, defining its southeastern and northwestern slopes, with a narrow intervening basin-floor characterised by mostly northerly bottom (density) current flow. The relationships between the slump facies and these contemporaneous sediment gravity flows are dependent on the processes of gravitational slope failure. These are inferred from three styles of synsedimentary deformation: macroscopic slump folding, surficial mudflow, and the penetrative fabrics manifest as parting-plane crinkle marks and disjunctional/endogenous cleavage.

Submarine mass movements: slumps

The basinal Ludlovian facies in Wales and the Borderlands are renowned as a record of synsedimentary deformation — slumping — attributed to submarine slope failure (Jones 1937; Straw 1937; Earp 1938, 1940; Bailey 1962, 1964, 1969; Woodcock 1976a, 1976b). In the west of the outcrop, in J. R. Earp's Kerry area, the classic recumbent slump folds of the Gorstian and earlier Ludfordian (Fig.1) suggest slow, southeasterly, downslope creep of poorly fossiliferous, partially consolidated, thin-bedded ('flaggy'), laminated, grey basinal siltstones, not greatly different to the undisturbed sediments with which the slumped units are inter-layered. The well-defined slump folds reflect the rheology of these sediments and their probably slow rate of deformation. Individual recumbent folds' vertical dimensions (Fig. 1) commonly suggest that the initial slope failure was superficial, involving only the creep and roll-over of the uppermost layers of slope sediment, and a subsequent basal detachment of the slumped mass. The synsedimentary nature of this deformation is clearly shown by the sharp erosive contact between the slump-folded unit and the overlying undisturbed sediment layers. Fluid density flows (turbidity currents) provide the likeliest agent for the implied seafloor erosion (Fig. 1); and, given the palaeocurrent evidence for directions of flow *along* the slump slope (Bailey 1964, 1969), some of these currents must have operated on a scale sufficient to overwhelm and plane-off the seabed relief created by the slumping.

The slumped units tend to occur in metre to decametre packages, featuring internal discontinuity planes and intercalated undeformed layers. These packages and undeformed intervals reach a combined thickness in the Kerry and SW Clun Forest areas of more than 700 m (Earp 1938), occupying much of the Gorstian's thickness. The lack of appreciable change in character over this interval implies long-term maintenance of bathymetric relief on the basin's west flank, despite relatively high rates of basin floor accumulation (but see below).

The often-recumbent geometry of the slump folds and the average NE–SW azimuthal tendency of their axes suggest the trend of the persistent, or repeatedly rejuvenated, controlling palaeoslope, which has been interpreted to incline down to the southeast. However, strict parallelism between slump-fold axes and this slope trend is not to be expected, since the likely vagaries of the seafloor relief and rates of sediment supply could entail piecemeal downslope movements — each moving mass having lateral, along-slope limits, where the transitions from moving to stable accumulations would form downslope-directed shear zones, with slump folds locally drawn into parallelism and thus departing from the general fold vergence.

Knife-sharp contacts between the recumbently-folded, often metre-scale slumped units, and the undisturbed layers that they override (Fig. 1, also see figures in Straw 1937 and Earp 1938) suggest a frictionless contact. Possibly, the gradual downslope gravitational creep, implied by the coherent folding, evolved into detachment along a basal 'gravity-gliding' plane. Such mass gravitational movements are initiated and maintained by the generation of high pore water pressure (PWP), or 'over-pressure', in buried, water-saturated, sediment layers. Enhanced PWP has the effect of reducing the grain-to-grain transmission of overburden stress within buried sediment layers. This reduction of the burial-related effective normal pressure acting on the affected sediment layers can cause reduction of resistance to gravitational shear, with consequent slope-related failure. It can occur spontaneously where compressive dewatering of buried sediment layers ultimately fails to keep pace with the rate of sediment loading. Loss of shear resistance can also be a response of buried water-saturated layers to the stimulus of seismic shocks, which can disrupt the grain-to-grain transmission of normal stress within a porous granular sediment. In effect, this instantly transfers the slope-related gravitational shear applied by the overburden from the granular mineral framework to the pore fluid. The failure layer then becomes 'quick'. The widespread evidence of Gorstian submarine mass movement in Wales suggests contemporary tectonic stimuli.

Downslope movement may trigger immediate relaxation and PWP reduction, restoring shear resistance and bringing movement to an end. If this does not occur there will be mass movement dictated by the extent of the slope and the over-pressured failure plane and the

__Figure 1__. Metre-scale Gorstian recumbent slump-fold (length of walking pole 1.35 m, scale divisions 5 cm) in finely flaggy siltstones, Ring Hole section, western slump facies, Earp's Kerry area (SO 1202 8377–SO 1219 8371). Note the sharp erosive truncations at the contact between the slump-folded rock and the overlying undeformed siltstones. Also, the equally sharp, but apparently non-erosive contact between the latter 10 cm undisturbed siltstone accumulation and the overriding slumped mass, implying that the emplacement of this latter mass exerted no shearing force on the seabed sediments.

latter's burial depth. The geometry of the recumbent slump folds and the development of endogenous cleavage (see below) implies downslope resistance to the moving masses. If, however, the basal failure plane, in response to this resistance, breaks through to the sediment surface without up-slope loss of the basal overpressure (see Nugraha *et al.* 2020 for a large-scale present-day example), then there is the possibility that the sliding mass, with impetus from its momentum and the gravitational potential energy of its upslope continuation, will override the sea floor. The resultant 'instantaneous loading' of the overridden water saturated sea floor sediments can have the effect of generating a new surface of high PWP and minimal shear resistance, allowing the momentum of the slumped mass to cause it to 'aquaplane' beyond the limits of the initiating slope (Bailey 1967; Woodcock 1976a).

The Kerry area slumping suggested the southeasterly-directed Gorstian to early Ludfordian palaeoslope on the basin's western flank. Contemporaneous slumping on the opposite, northwest-facing slope of the narrow basin occurred from the Eppynt area to Radnor Forest, becoming evident again to the north around Bishop's Castle (Straw 1937, 1953; Bailey 1969; Woodcock 1976b). The palaeobathymetric influence of the Church Stretton–Brecon anticlinal fault plexus, separating the Midland Shelf Sea from the thicker basinal sections to the west, is clearly indicated. Latterly, the slumped units became similar in character to those of the Kerry and SW Clun Forest areas, involving tough, thinly-layered ('finely flaggy'), laminated siltstones (Wilsonia Shales of Straw 1937; Striped Flags of Woodcock 1976a). But much of the earlier Gorstian slumping on this flank of the basin involved a different facies — more homogeneous, often poorly-bedded, rubbly-, hackly- or spheroidal-weathering, somewhat calcareous mudstones. These commonly contain randomly-scattered and fragmentary, shallow marine, shelly fossils that weather-out leaving rusty casts (Cyrtoceras Mudstones, Straw 1937, 1953; slumped shelly mudstone facies, Bailey 1969). In the Radnor Forest area, around Hundred House, and at Builth and Cwm Craig Ddu, separate packages up to 45m in thickness, feature stacks of these recumbently folded shelly mudstones, internally partitioned and separated by intercalations of undeformed, less fossiliferous, flaggy, laminated siltstone. However, in the more distal, west Radnor Forest exposures, the slumped units involved the folding and even re-folding of the graded calcareous siltstones locally associated with north-northeasterly-flowing palaeocurrents (Fig. 2; Bailey 1969; Bailey and Woodcock 1975; Woodcock 1976b, figure 2). Similar graded shelly siltstone beds can also be seen resting on the eroded tops of the slump units.

__Figure 2__. Author's 1967 field sketch of the slump-folded and re-folded graded calcareous turbidites, Cwm Blithus, west Radnor Forest, SO 1665 6150.

Figure 3. *(A, right) The upper part of a 0.5 m Gorstian mudflow deposit (scale bar scored on joint face, 10 cm); eastern slumped shelly mudstone facies, small quarry above Hundred House (SO 1132 5331). Note the homogeneous character of the mudflow unit, the discordant orientation of the entrained laminated olistoliths, and the scattered nature of the fossils (weathering pits on the joint surface). The load casting of the immediately overlying, lighter coloured, laminated siltstone suggests that this layer was deposited while the mudflow was still liquid. Contrast the flow's general character, with that the following smoothly and thinly bedded, graded shelly siltstones, and (B, below) with the associated and undisturbed, smoothly-splitting, laminated siltstones.*

Clues as to the environmental provenance of the slumped shelly mudstone layers come from their resemblances to a later, regressive, slump-free, Ludfordian facies — Straw's Orthonota Mudstones (massive siltstone facies, Bailey 1969, Bailey and Bailey 2019). This later Ludfordian shallow marine facies is thought to owe its massive, rubbly-weathering character and typically scattered, often fragmentary, shelly fauna to pervasive bioturbation of the sediments. The Gorstian slumped shelly mudstone facies is thus seen as a record of pre-Ludfordian development of a benthic palaeo-environment of extreme bioturbation, located in a slumping-prone upper slope setting. The characteristic shelly component of the slumped sediment includes corals, bryozoa and robust brachiopods (Straw 1937), inferred to be washed-in elements from the margins of a still-shallower, early Gorstian marginal carbonate facies, fringing the Midland Shelf. Even though evidence for this carbonate fringe is not seen at outcrop, its presence is additionally indicated by the abundant richly-shelly gravity flow units in the east of the earlier Gorstian basin, notably the 0.5 m graded limestones west of Bishop's Castle (Bailey 1969, fig. 60).

The character of the eastern, slumped shelly mudstone facies is not, however, wholly a matter of extreme pre-slumping bioturbation. Straw (1953) suggested that the richly fossiliferous, sometimes near mono-specific, decimetre-thick, 'thin slumps' of his Cyrtoceras Mudstones in the Cwm Craig Ddu road section, SW of Builth Wells, represented marine mud flows — surficial gravity flows that imported the indigenous benthic shelly faunas of the upper slope. More generally, decimetre-scale, structureless, rubbly-weathering or spheroidal-weathering mudstone beds, though lacking well-defined slump folds, show wavy internal lamination patterns suggestive of viscous flow. Even where such evidence and the rich, allochthonous, brachiopod faunas are lacking, the prominently homogeneous nature of the mudstone beds strongly contrasts with the undisturbed, often laminated flaggy siltstones and occasional thin beds of shell debris, in a fashion consistent with emplacement by mud flow. The scale sometimes achieved by such flows is shown by a massive, half-metre, slumped shelly mudstone unit quarried near Hundred House (Fig. 3A). It strongly contrasts with the associated smoothly splitting, laminated, flaggy 'background' sediments (Fig. 3B) and is capped by a laminated calcareous siltstone with load casts that sank into its surface after it had come to rest, signalling a still unconsolidated state. Again, the stimuli for such flows may have involved seismic shaking of surficial high water-saturated slope muds; while the 'instantaneous loading' of the seafloor along their flow-path would have favoured the flows' advance beyond the foot of the initiating slope.

Crinkles and cleavage

Both the western, slumped siltstone facies and the eastern slumped shelly mudstones of the Welsh Borderlands Gorstian are characterised by crinkle-marked parting planes (Fig. 4A). These pronounced parting lineations, also found in otherwise little-deformed rock, generally parallel the slope trends inferred from the average orientations of the associated slump folds. Similar crinkles are also seen to pervade some of the homogeneous units, thought to represent mudflows (Fig. 4B). They express a pervasive millimetre-scale deformation which is clearly syn-depositional, since it can affect discrete 20–90 cm intervals — stratigraphic 'domains' — in otherwise undeformed strata. Where laminated sediments are involved, the asymmetric crinkling of the parting planes can be seen to result from compressive micro-faulting and folding resembling tectonic fracture cleavage (Straw 1937; Williams and Prentice 1957; Woodcock 1976b). In some cases, crinkles develop on the bedding surfaces *within* individual recumbent slump-folds, similar in geometry to that in Figure 1. They align with the folds' axial traces, while on joint planes orthogonal to bedding, recumbent similar folds occasionally show pervasive fabrics resembling axial planar cleavage (Author's unpublished field notes 1967; Woodcock 1976b). Such fabrics could be expected to appear as parting-plane crinkles. However, crinkle-marks do not invariably show the expected parallelism with the individual slump folds with which they are associated, or with the palaeoslope configuration suggested by the average orientation of such folds. Firstly, otherwise undeformed siltstones and mudstones may show partings with more than one crinkle-marking trend, implying either conjugate patterns of deformation, or successive episodes of deformation with markedly different local stress patterns (Fig. 4A). Such divergent trends are even observed on slump-folded parting planes, one trend paralleling the recumbent fold's axial azimuth and the other at a high angle to it. Secondly,

***Figure 4**. (A, above) Loose slab with parting planes showing two, possibly three crinkle mark trends, Wilsonia Shale slumps, Old Quarry, Llanddewi'r-cwm, SO 0350 4880. (B, right, top) Massive, unlaminated siltstone with pervasive crinkling/cleavage. The lack of a bedding-related fracture pattern suggests a possible homogeneous mudflow, subject to post-depositional slumping-related compression. Length of hammer 27 cm. Roadside quarry, Llyn Helyn, Radnor Forest area, SO 1655 5825. (C, right, middle) Disjunctive cleavage in otherwise undeformed strata, stream-side exposure, Ring Hole section, western slump facies, Earp's Kerry area (SO 1202 8377–SO 1219 8371). (D, right, bottom) Conjugate disjunctive cleavages, locality as for (C). Scale rule 25 cm.*

domains within otherwise undeformed strata may show a pronounced spaced cleavage at a high angle to the bedding (Fig. 4C), with the suggestion of conjugate sets (Fig. 4D; also see Straw 1937, plate 1). Since it occurs in otherwise undeformed intervals, this endogenous, or disjunctive cleavage (Engelder and Marshak 1985) implies layer-parallel compression of laminated seafloor accumulations. The domain cleavage thus seems to represent a surficial deformation where the rheology of the sediments and/or their foot-of-slope location promoted limited micro-folding and -faulting, rather than slump-folding; but it must be borne in mind that in these instances the local amount of movement actually in evidence is no more than that suggested by the deformation.

It seems that the common forms of crinkling involve either:

1. Surficial downslope sediment creep; or

2. The 'shunting' of surficial lower slope and basin-floor sediments that resisted and were laterally compressed by the contiguous gravitational mass movements.

Both such processes can accommodate the evidence of crinkles with divergent trends, though this seems more likely with mechanism (2). Both record strain that must have involved the de-watering and consolidation of the deformed stratal domain. As with the macroscopic slump units, both also imply a shallow detachment surface, with a sliding body both experiencing and applying compression when it encounters frontal or lateral reaction to its motion (mechanism 2, above). This would affect both the basin floor facies and previously-emplaced mass movement deposits, as is suggested by the pervasive crinkling of homogeneous mudstone (mudflow?) layers (Fig. 4B). Likewise, the occasional tendency of the recumbent slump-folds in the eastern, slumped shelly mudstone facies to weather to 30 cm long, bedding-parallel, 'pencils' suggests the presence of endogenous/disjunctive cleavage at a high angle to the bounding surfaces of the slumped unit (Engelder and Marshak 1985). Multi-phase deformation, consistent with the above 'shunting' effect of repeated slope failures, is seen in the evidence for refolding of slump folds in Radnor Forest's classic Cwm Bir section (Fig. 2; Woodcock 1976b).

Palaeobathymetry

If slumps and (by association) crinkle-marks denote palaeoslopes, a key question is whether the mapped extent of these affects strictly defines slope limits. For example, where slumps are intercalated with laminated and graded beds that are indicative of fluid density flows *parallel* to slump slope, how are these two lines of evidence to be reconciled? Did the episodic syn-sedimentary deformation evidenced by the slump folds and crinkle-marking extend into the basin floor realm of density current flow (Bailey 1967; Bailey and Woodcock 1975; Woodcock 1976a); or were the along-slope bottom currents more akin to present-day oceanic contour currents*?* In both the western and eastern slump facies of the elongate Gorstian basin, the evidence has been read as indicating that the recumbent slump folds and more liquid mud-flows invaded the lateral limits of the basin's axial zone of northward density-current flow, even, on occasion, causing deformation of basin floor turbidites (Fig. 2; Bailey 1967, 1969; Bailey and Woodcock 1975; Woodcock 1976b). This basinward advance could be a tectonic effect, the episodic spread of the western slump facies that Earp (1938) demonstrated in the Kerry area suggesting tectonic changes in the basin's configuration, involving a Gorstian structural inversion advancing basinwards from the Twyi Lineament on the west.

Tyler and Woodcock (1987), however, reinterpreted the previously-defined silt-turbidite facies (Bailey 1964,1969) (their Bailey Hill Formation) between the two Gorstian slump developments as mostly a hemi-pelagic outer shelf facies with tempestites (graded calcareous siltstones), deposited by NNW-flowing density currents generated by storm-wave stirring on the Midland Shelf, to the east. This implied a westward deepening outer shelf contiguous with the Midland Shelf Sea, with a further, stepwise, down-to-the-west, deepening across the line of the Twyi structural lineament, at the limit of the Bailey Hill Formation's present outcrop (Tyler and Woodcock 1987, fig. 5C).

Their interpretation invokes the internal cross-lamination patterns in the graded calcareous siltstones and downplays the evidence of their erosional sole-markings, predominantly recording north-northeasterly 'axial' density current flow (Bailey 1964, 1969). The bottom current mechanisms are similar, and arguably, in this relatively confined depositional setting, the contrasting palaeocurrent interpretations might relate to different stages in the waning flow of longitudinally- and laterally-sourced fine-grained sediment gravity flows. Hence the interpretation of the Bailey Hill Formation as either an outer shelf or restricted basin facies continues to rely on the palaeobathymetric evidence provided by the patterns of Gorstian slumping.

Firstly, the adoption of the base of the silt-turbidite facies in southwest Clun Forest (Bailey 1964) as the regional base of the Bailey Hill Formation (Tyler and Woodcock 1987; Woodcock and Tyler 1993) entails that Earp's earliest episode of Ludlovian slumping in the west (1938, plate XIII) becomes closely coincident with this well-defined horizon (regionally dated by underlying shales with *nilssoni-scanicus* graptolite faunas). Thus the structural inversion used to explain the later easterly-directed spread of Kerry and Clun Forest slumping (Earp 1938; Woodcock and Tyler 1993, fig. 3) appears already to have been in progress, defining the western flank of the Bailey Hill Formation's basin at the onset of its accumulation. Similarly-dated shales immediately beneath the formation in the west Radnor Forest and Bishops Castle exposures show slumps and crinkle-marks suggesting that this earliest phase of mass movement had a basin-wide tectonic impetus.

Secondly, despite the pronounced thickening of the Gorstian, Tyler and Woodcock's palaeobathymetric model involves a 'subtle transition' from the shallower inner shelf of the Midland Platform to the deeper outer shelf located to the west. However, the onset of the protracted, large-scale slumping of calcareous shelly mudstones associated with the shelf-to-basin transition across the Church Stretton–Brecon Anticlinal Fault trend, from Builth to New Radnor (Straw 1937; N. H. Kirk unpublished map), dates from *'nilssoni-scanicus'* times, as does the emplacement of the olistostromic limestone conglomerates that regionally define the base of the Bailey Hill Formation (Bailey 1964; Tyler and Woodcock 1987; Woodcock and Tyler 1993). Such evidence implies a transition from Midland shelf to Gorstian basin with significant, long-term bathymetric relief. This is supported by meticulous mapping around Leintwardine and Wigmore rolls (Whitaker 1962, 1994) which defines westerly-sloping shelf-marginal submarine channels and a major gravitational slide scar which involved hundreds of metres of later Gorstian (formerly late Eltonian and Bringewoodian) slope sediment. This general picture suggests that a south-southwest to north-northeast trending Gorstian Welsh Basin was already tectonically established between the opposed slump slopes and was actively subsiding at the onset of Bailey Hill Formation deposition.

Less cogently, there is a marked change in the earliest, south-southwesterly-derived graded beds of the Bailey Hill Formation, between Radnor Forest and the western Kerry exposures (Bailey 1969). It involves a decline in the occurrence of graded calcareous siltstones and an increase in terrigenous graded siltstone units — beds showing these two density-current lithologies being intercalated in the intervening SW Clun Forest area. This pattern is more readily explained by density currents originating at the southern end of a narrow, northward-deepening basin, where upper slope sediments ranged from washed-over shelf carbonates to terrigenous silts.

Conclusions

The Gorstian slump facies of south-central Wales and the Borderlands feature outstanding examples of synsedimentary folding and cleavage development. They define the location and trend of the narrow Welsh Basin's western and eastern palaeoslopes. This palaeobathymetry can be reconciled with the contemporary pattern of density current flow if it is understood that the loci of the palaeoslopes were subject to episodic tectonically-induced migration and rejuvenation and that the detached slump masses and mudflows on both flanks could advance to the lateral limits of the basin's axial zone of density current flow (Bailey 1967; Woodcock 1975a). The pattern of laterally-derived slump units and longitudinal sediment gravity flow seems preferable to the interpretation of the Bailey Hill Formation as an outer shelf facies, subtly transitional with the Midland Shelf Sea (Tyler and Woodcock 1987, Woodcock and Tyler 1993).

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