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THE TREDORN NAPPE, NORTH CORNWALL: A REVIEW

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The limits of the Tredorn Nappe are redefined to include a newly recognised area of California Slate Formation (Famennian-Tournaisian) south-west of Camelford. Restoration of the nappe emphasises close stratigraphic similarities with the autochthonous Kate Brook Slate Unit developed between Dartmoor and Bodmin Moor. In both areas peak greenschist metamorphism can be linked to contact metamorphism associated with the early rise of the granite batholith, prior to the development of northward-directed thrusting. Within the deformation chronology of the area, this is dated as late in D1 to D2a. Subsequent nappe detachment by northward-directed D2a thrusting and D3 extension removed the sequence from the heat source and retrogressive metamorphism ensued. Conflicting evidence regarding the origin and age of the Davidstow Anticline is appraised, and a compromise solution to the problem is offered.

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INTRODUCTION

The concept of the Tredorn Nappe in north Cornwall was introduced by Isaac *et al.* (1982) to describe structural relationships involving Devonian and Carboniferous successions at the north-eastern margin of the Bodmin Moor granite. Outer shelf and basinal facies of the Tintagel Succession (Freshney et al., 1972) were described as having overridden rise and rise-margin sequences of the Petherwin Nappe on the Trekellend Thrust. Both nappes were related to an extended period of northward-directed D2 thrusting, characterising the area between Dartmoor and Bodmin Moor. Within the footwall of the Trekellend Thrust, Stewart (1981a) mapped mesoscale north-facing folds; an observation confirmed by detailed palaeontological analysis of sequences in small-scale folds. Isaac *et al.* (1982) imply from fold symmetry and cleavage-bedding relationships, the possible presence of north-facing recumbent folding in the Tredorn Nappe, a view at variance with interpretations on the north Cornwall coast (e.g. Freshney *et al.*, 1972).

The Tintagel Succession was initially placed conformably within a continuous Middle Devonian - Upper Carboniferous sequence involved in a regional south-facing overfold. This sequence was later shown (Selwood *et al.*, 1985) to be an amalgam of distinct but coeval successions. Selwood and Thomas (1986) extended the concept of the Tredorn Nappe to embrace the whole of the Tintagel Succession developed in north Cornwall and correlated the tectonic break, observed in coastal sections at the base of the nappe, with the Trekellend Thrust. A revised map of formations lying within the nappe, west of the area investigated by Stewart, was presented by Warr (1989), who recognised (1988) that the tectonic break at the base of the structure was a composite of late D2 thrusting and D3 extensional faulting. The structure and metamorphism characterising the Tintagel High Strain Zone (Sanderson, 1979), which extend into the Tredorn Nappe, die out southwards. The metamorphism has not been related either to stratigraphy or D2 thrust structures; rather, variations in grade have been attributed (Warr and Robinson, 1990) to initial diastathermal heating, followed by burial metamorphism due to late back-thrusting of Upper Carboniferous sequences from the Culm Basin southwards across the area.

STRATIGRAPHY

The stratigraphy of the Tredorn Nappe (Figure 1), which ranges in age from Famennian to Visean, has been extensively documented (Freshney *et al.*, 1972; McKeown et al., 1973; Selwood and Thomas, 1986; Warr, 1991). Thick greyish green slates of the outer shelf facies characterise the Devonian. Minor variations distinguished in early investigations, have been abandoned by recent workers as metamorphic features. Currently all are included within the Tredorn Slate Formation, and the economically important roofing slate quarried at Delabole is distinguished as a member within it. The oldest slates are undated, but conodont analysis (Stewart and Selwood, (1985)

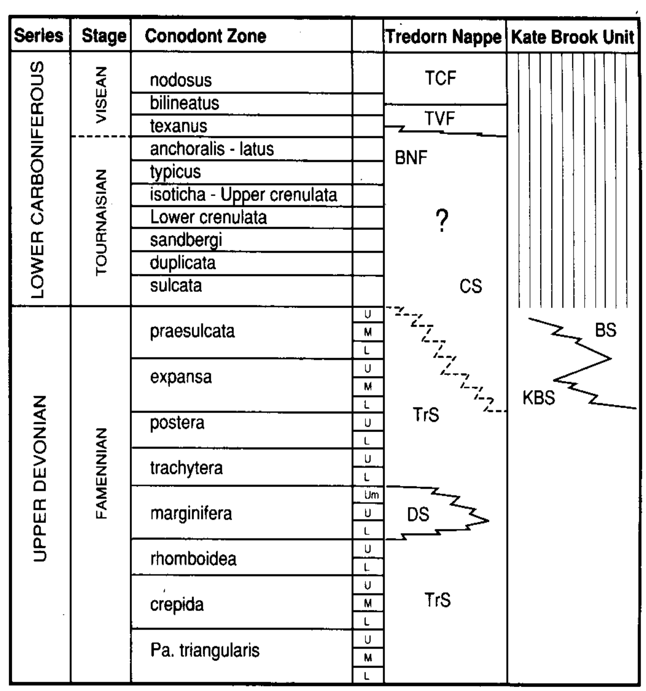

Figure 1: Successions in the Tredorn Nappe and Kate Brook Unit.
TCF, Trambley Cove Formation; TVF, Tintagel Volcanic Formation; BNF, Barras Nose Formation; CS, California Slate Formation; TrS, Tredorn Slate Formation; DS, Delabole Slate Member; KBS, Kate Brook Slate Formation; BS, Burraton Slate Formation.

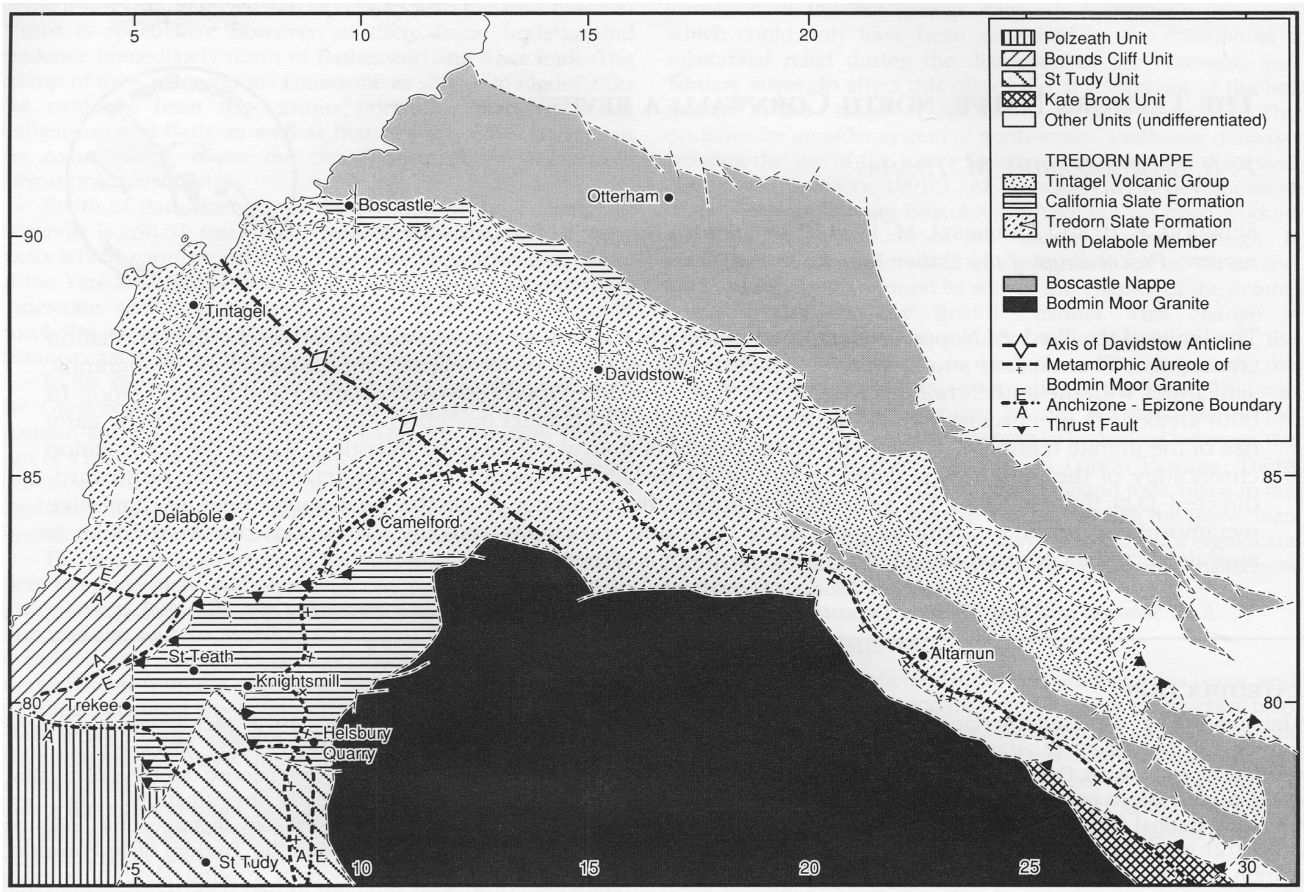

Figure 2: Geological map showing distribution of Tredorn Nappe. Partly after BGS 1:50,000 Geological Sheets 322 (Boscastle) and 323 (Holsworthy), Stewart (1981b) and Wan- (1989). Anchizone/epizone boundary after Wan¯ and Robinson (1990).

has indicated an Upper to Uppermost *marginifera* zone age for the Delabole Member and an Uppermost *marginifera* to Lower *trachytera* zone assemblage from the overlying slates. The conformably succeeding Dinantian succession, much attenuated by tectonism, is of basinal facies and incorporates an important volcanic episode, which has been extensively documented (Freshney *et al.,* 1972; Robinson and Read, 1981; Robinson and Sexton, 1987; Rice-Birchall and Floyd, 1988). Only horizons about the Devonian-Carboniferous boundary need further comment.

This interval, marked by a world-wide eustatic rise in sea level, is characterised by black basinal mudrocks that persisted as background sediment throughout the Dinantian. The sequence immediately overlying the Tredorn Slate was represented on the first printing of the Geological Survey Boscastle (322) Sheet as the Yeolmbridge Formation, but on subsequent maps and in the accompanying Memoirs (Freshney *et al.,* 1972; McKeown *et al.,* 1973) featured as the Transition Group. Neither term proved satisfactory; the first is an age equivalent facies variant, and the second, an unacceptable usage of the term "Group". Stewart (1981b) who recognised the unit north-east of Bodmin Moor, proposed the term California Quarry Formation, with a type locality at California Quarry [SX 0902 9084] near Boscastle, which yielded *Gattendorfia* Zone trilobites (Selwood, 1961). We suggest that California Slate Formation is a more acceptable designation for this unit, which can be mapped continuously inland for some 13 km in the northern limb of the Davidstow Anticline (Warr, 1989). Comparable black slates were mapped by Wilson (1951, P1. XX1) north of Treligga Common [SX 046 854], Trebarwith, within lithologies now identified as Tredorn Slate. This would suggest that the California Slate Formation represents the culmination of outer shelf submergence by basinal black argillites initiated in late Devonian times.

An extensive development of the California Slate is now recognised for the first time on the north-western flank of the Bodmin Moor granite (Figure 2). It lies in an area south of the Tredorn Slate that was previously identified as Middle Devonian Slate (Reid *et al.,* 1910; Warr, 1988). Outside the metamorphic aureole, the black slates, which characteristically show abundant small voids after pyrite, show varying degrees of silicification, ranging from a slight pervasive hardening to the development of thin cherry seams and nodules. Thin tuffs are also sporadically developed. Locally the slates are micaceous and include grey micaceous sandstones yielding a Shelly fauna, showing the chloritic preservation characteristic of the Tredorn Slate. At Helsbury Quarry [SX 088 791] an abundant, though rather poorly preserved phacopid trilobite and stropheodontid brachiopod fauna has been recovered; the presence of *Strophonelloides reversa* (Hall) indicates a late Devonian age. A comparable fauna has been obtained from a roadside exposure near Knightsmill [SX 0769 8051]. From south (Helsbury Quarry) to north (Boscastle area) therefore, a diachronous base to the formation is indicated, which almost certainly reflects the progressive northward onlap of black basinal sediments across the area in Devonian-Carboniferous boundary times. The formation shows a structural thickness of 350 m, considerably greater than the 37 m recognised previously (Freshney *et al.,* 1972). Whilst this increase undoubtedly reflects the newly extended stratigraphic range into the Devonian, it may also bridge part of the missing Tournaisian record in the Tintagel Succession in the Boscastle area. The upper boundary of the California Slate is everywhere faulted, however, the lithologies of the formation suggest that a conformable passage

Into the stratigraphically overlying Barras Nose Formation (late Tournaisian to early Visean) is likely.

Although an integral part of the succession characterising the Tredorn Nappe, the structural position of the newly identified area of California Slate is not immediately obvious because of faulted boundaries. To the north (Figure 2), steep high-angle faults have been mapped (Warr and Robinson, 1990); a post-granite vertical fault south of Camelford in the east, and farther west steeply inclined D2 thrusts which introduce the California Slate over the Tredorn Slate and Bounds Cliff Unit. To the south, an overthrust relationship with the St Mabyn Succession (Selwood *et al.,* 1993) has been identified; but this thrust has been substantially cut out by late, high-angle faults. Sections revealing the primary flat-lying relationships are developed in Pengenna Wood [SX 056 781] north of the A39 Trunk Road, and between Michaelstow [SX 0800 7888] and Tregreenwell [SX 0754 8023]. The Pentire Volcanic Group and St Tudy Formation of the St Mabyn Succession occur in the footwall. In the regional geology the California Slate is allochthonous and is interpreted to form a southern extension to the Tredorn Nappe.

REGIONAL STRUCTURE AND METAMORPHISM

The first deformation (D1n of Andrews *et al.,* 1988) is characterised by small-scale, recumbent folding, which faces south on a gently north-dipping, axial planar slaty cleavage (S1). McKeown *et al.* (1973) postulated large-scale recumbency; a view supported by the recognition of major stratigraphic inversion south of Tintagel (Warr, 1988), and by the recognition of California Slate at the southern limit of the nappe in a position which could approximate to a regional fold closure. Whilst some dismemberment of the succession is likely to be developed in inverted fold limbs by D1 thrusting, there is no direct evidence that this regional folding developed in a Dl fold nappe, in which Carboniferous strata were cut out in inverted succession on a southward-transporting basal thrust. Where determinable, the present floor to the structure is a composite of D2 and D3 low-angle faults involving significant northward transport.

Porphyroblasts of biotite and feldspar oblique to, and cross-cutting the S1 foliation, were interpreted by Freshney *et al.* (1972) as evidence of late thermal metamorphism possibly linked to the Bodmin Moor granite. However Robinson and Read (1981) showed the biotite to be a stable phase which grew under static conditions operating during a regional metamorphic event post-dating S1. This metamorphism has come to be associated with D2. Primmer (1985) elaborated the observations of Robinson and Read and noted an early (late D1) phase of chlorite porphyroblast generation.

In a detailed analysis of D2, Andrews *et al.* (1988) recognised an early ductile episode (D2a), overprinted by a later (D2b) brittle phase. The north-north-westward-directed D2a ductile shear led to the development of structures associated with the Tintagel High Strain Zone. F2a locally refolded D1 structures, generating zones in which S1 was transposed onto S2a. Within these zones, pre- and syn-D2a porphyroblasts record a peak M2 greenschist metamorphism. This metamorphism declined in intensity through D2b, with the development of northward-directed thrust zones which frequently reactivated D2a shear zones. Warr *et al.* (1991) suggested from b_0 values of illite, that metamorphism took place in low P facies and that a fairly steep geothermal gradient was involved.

D3 is represented by a phase of extensional deformation, characterised by north-dipping normal faults and reactivated D2b thrusts, and has commonly been associated with the final emplacement of the Bodmin Moor granite.

The origin of the Davidstow Anticline is unresolved, though the reorientation of faults around the structure has led most authors to place it late in the deformation chronology (e.g. Andrews *et al.,* 1988). This provides the most obvious explanation for the reorientation of small-scale D1 folds into reclined positions around the anticline. On the other hand, Warr (1989) has argued for a D2a age, noting that its fold axis plunges in the trend (north-north-west) of the regional stretching direction and that the ductile strain indicators are not reoriented across the structure.

DISCUSSION

Provenance of Tredorn Nappe

The scale of tectonic transport in D1 is uncertain, as the emplacement of the Tredorn Nappe is the result of north to north-north-westward transport in D2 and D3 times, from a source area currently associated with the Bodmin Moor granite (Freshney *et al.,* 1972). So located, the close similarity (apart from metamorphic grade) between the lower parts of successions (Figure 1) in the Tredorn Nappe and the Kate Brook Unit, forming the regional autochthon in the Tavistock district east of Bodmin Moor (Isaac *et al.,* 1982) is emphasised. The Upper Devonian Tredorn and Kate Brook slates are of similar age and outer shelf facies.

Apart from their post-depositional histories, both formations could be considered identical. Lower Carboniferous black argillites succeed each formation gradationally; the California Slate in the Tredorn Nappe, and the Burraton Slate, (Bull, 1982; Whiteley, 1983) in the Kate Brook Unit. Higher in the succession, sedimentary patterns in the two areas diverged somewhat, as a more dynamic environment became established in the South Devon Basin (Turner, 1982; Selwood, 1990).

The Kate Brook Unit is overthrust by northwardlytransported D1 (Greystone Nappe) and D2 nappes developed from the South Devon Basin (Isaac *et al.,* 1982). In contrast to the Tredorn Nappe, no evidence has been reported to suggest that it was deformed prior to the thrusting events. Both these structural units are juxtaposed (Figure 2) by a gentle north-east-dipping normal fault developed immediately north of Trebartha [SX 2645 7734] at the north-east margin of Bodmin Moor. This fault brought the Tredorn Slate from the south in post-D2 times, against a thin sliver of Greystone Nappe overlying the Kate Brook Slate. Assuming that the Tredorn Slate was not significantly allochthonous prior to D2, it is reasonable to predict that both formations were deposited contiguously. To the west, the sequence probably terminated at the eastern margin of the Trevone Basin, which appears to have been controlled by deep-seated movements on a fracture system, now expressed by the St Teath-Portnadler. Fault Zone (Selwood, 1990). This reconstruction presupposes no significant post-depositional transcurrent movement on the fault zone. No movement on this fault zone has taken place since the emplacement of the Tredorn Nappe, which overrides the northwestern end of the fault zone without being displaced by it.

Structural similarities suggest that the Tintagel Succession, in its position marginal to the Trevone Basin, was involved in the same southward-transporting D1 backfolding characterising that basin. Eastwards along the strike, this deformation died out; terminating at the deep-seated fracture complex, now represented by the Otterham Fault Zone (Selwood, 1990). This system was probably being activated at the time by the rising batholith.

Metamorphism

Within the Kate Brook Unit, Isaac (1983a and b) identified a pre-deformation metamorphic event (M1), and related it to the contact metamorphic effects of the rising batholith. Subsequent deformation was accompanied by retrogression through lower greenschist facies to low grades of metamorphism. Isaac's chronology provides striking parallels with metamorphic events identified in the Tredorn Nappe, some 20 km westwards along strike.

In the restored position of the Tredorn Nappe, the growth of porphyroblasts indicating greenschist metamorphism late in D1, and in a static pre-D2a interval, could similarly be related to the rising granite batholith. The raised temperature so generated would have persisted into early D2 times and facilitated the development of high temperature D2a shear zones.

The appearance (Andrews *et al.,* 1988) of pre-D2a (augened) and syn-D2a porphyroblasts indicating greenschist metamorphism in the shear zones is thus explained. This persistence of raised temperatures is supported by a recalculation by Warr *et al.* (1991) of the original radiometric data of Dodson and Rex (1971). The slates of the Tintagel High Strain Zone now give a population of radiometric dates around 291 Ma, which immediately precedes the final emplacement date (290-280 Ma) of the granite. Variations in the intensity of this metamorphism observed within the nappe are likely to reflect the localisation of heat flow from the batholith. The start of retrogressive metamorphism can be associated with northward transport of the nappe during D2 and D3, which removed the sequence from the effects of the rising heat source.

Warr and Robinson (1990, Fig.3) observed that the computer-generated boundary between epizone and anchizone metamorphism in north Cornwall passes obliquely across the regional strike and that no relationship to D2 thrusting could be detected. This led them to relate the development of epizone metamorphism to backthrusting of Upper Carboniferous rocks from the CuIm Basin across the area. However, through much of its length this boundary is now seen to approximate to the D2 and D3 faults determining the southern boundary of the Tredorn Nappe (Figure 2). This gives an epizone signature to the whole nappe. Only west of the Trekee Fault does the epizone/anchizone boundary deviate markedly beyond the Tredorn Nappe. Here an association with a D2 thrust emplacing the Pentire Succession over the Bounds Cliff Succession is indicated. Outliers of highly sheared rock about Treore Farm [SX 0235 8030] suggest that this thrust formerly extended farther north; possibly this area of epizone metamorphism within the Jacket's Point Slate is linked to local footwall metamorphism.

Davidstow Anticline

Although convincing arguments have been presented by Warr (1989) to support his interpretation of the Davidstow Anticline as a D2a ductile shear structure, there remains a body of field evidence quoted by earlier authors which argues for a later origin. In particular, faults variously described as D2 thrusts (e.g. Andrew *et al.,* 1988) and/or D3 normal faults (Warr, 1989) map concordantly with bedding around the fold.

Observed relationships can be reconciled if these faults are interpreted as reworked D1 thrusts. The Davidstow Anticline can be viewed as a D2a ductile surge zone *(sensu* Warr, 1989); i.e. a shear fold produced by differential northward movement on S1. Such shear movements cross-cutting and repositioning the south-verging D1 fold stack, could generate an antiform without involving layer flexure; decreasing shear upward through the pile might be expected. So deformed, the bedding-parallel Dl thrusts would come to occupy likely sites for the D3 extensional reactivation described by many authors. Whilst some primary D2a warping could explain the occurrence of reclined D1 folds around the anticline, the fact that similar reorientation of Fl affects the Bounds Cliff Unit immediately below the nappe, would appear to time this event as post-D2b thrusting. Accepting Warr's argument that the Davidstow Anticline is primarily a D2a structure, this warping would have been coaxial with the D2a extension lineation, and without plunge.

The intense shearing associated with D2a which characterises the Tintagel High Strain Zone, is known to decrease in intensity southwards across the Tredorn Nappe. This change is likely to reflect the domainal character of the shear; perhaps limited within the sheath-like Davidstow Anticline (Warr, 1989) or overriding less strained horizons on D2b and/or D3 northward-transporting faults.

D3 detachment

It is now possible to distinguish two episodes of D3 extension. An early (D3a) gently northward-inclined episode, which plays an important role in defining the floor of the Tredorn Nappe, and a cross-cutting set of more steeply inclined north-dipping faults (D3b). The Trekellend Thrust of Stewart (1981a) and the D3 normal fault at the base of the Tintagel Succession at Tregardock (Warr, 1988) appear to form part of a major D3a detachment which allowed uplifted successions to glide and spread northwards away from the rising granite batholith. The steeply north-dipping D3b faults (e.g. Stewart, 1981a) appear to be late accommodation structures related to the final emplacement of the Bodmin Moor cupola.

The Boscastle Nappe, which overrides the Tredorn Nappe on a D2a and/or D3 fault (Willapark Thrust, Selwood *et al.,* 1985; Willapark Fault, Warr, 1991), extends the Tintagel High Strain Zone northwards to the Rusey Fault and eastwards to the Otterham Fault Zone (Figure 2). Apart from differences in style associated with variations in lithology, the structural and metamorphic history of the two nappes is closely comparable. The occurrence of the Boscastle Nappe at the higher structural level suggests that it is the more far-travelled of the two structures. This would locate its depositional site south of the Tintagel Succession. As with the Tredorn Nappe, the formations represented within the Boscastle Nappe correlate closely with a succession at lower grades of metamorphism developed between Dartmoor and Bodmin Moor. Whiteley (1983) derived the paralic sediments common to both areas from the south, and extended the Boscastle Nappe eastwards at a level high in the allochthon. These sediments have been associated with the outer shelf of the South Devon Basin (Selwood, 1990), whereas the link with the Tredorn Nappe suggests a deposition on the inner (northern) shelf. It appears that shallow-water deposition was able to extend northwards across the Liskeard Rise separating the South Devon and Trevone basins (Selwood, 1990); the site of the rising cupola of the Bodmin Moor granite. In this position the sediments of the Boscastle Nappe could be expected to share the deformation history of those of the Tredorn Nappe.

CONCLUSION

The Tredom and Boscastle nappes are the product of D2b out of sequence thrusting and D3 gravity detachment, rather than conventional D1 nappes. Stratigraphic evidence suggest that the sediments now represented in these nappes north of Bodmin Moor, were deposited on a rise separating the Trevone and South Devon Basins. Here they were involved in the southward-transporting D1n deformation characterising the Trevone Basin; these movements did not persist east of the Otterham Fault Zone at the eastern margin of the Bodmin Moor granite. In late D1 to early D2a times these deformed sediments were subject to contact metamorphism, and probably further uplifted by the rising granite batholith. Subsequent D2a ductile shearing led to the development of a regional shear fold; the first episode in the formation of the Davidstow Anticline. D2b thrusting dissected this structure, and further uplifted the area as the Tredorn Nappe was initiated. From this high, emphasised by the final stages in the emplacement of the granite cupola, D3 extension allowed the nappe to be carried farther northwards on a gently inclined D3a detachment. Final adjustments to granite intrusion were accommodated by more steeply-dipping normal faults (D3b). Probably during this final phase of deformation, a broad anticlinal warping (without plunge), parallel to the D2a extension lineation, led to completion of the structure of the Davidstow Anticline and to the reorientation of earlier structures around it.

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