Devonian rift-related sedimentation and Variscan tectonics – new data on the Looe and Gramscatho basins from the resurvey of the Newquay District

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The geological resurvey of the Newquay District (Geological Survey Sheet 346) has resulted in stratigraphical and structural revision. The Devonian successions form part of the Looe and Gramscatho basins and broadly young to the south throughout the area. Deposition of the green to purple mudstones and sandstones of the Whitsand Bay Formation (Dartmouth Group) had initiated by the latest Lochkovian and was conformably succeeded by the sandstones, mudstones and bioclastic limestones of the Bovisand Fomation (Meadfoot Group). The newly defined Trendrean Mudstone Formation (Meadfoot Group) is dated as mid-Emsian or younger on the basis of palynological studies. These three formations respectively record the transition from lacustrine/fluvial through shallow marine to outer shelf/slope depositional environments during Lower Devonian rifting and the development of the Looe Basin. The lowermost part of the Gramscatho Basin succession is represented by the undated Grampound Formation (Gramscatho Group) that has a faulted contact with the underlying Looe Basin succession. It predominantly comprises mudstone but includes sandstone-dominated 'packets' (Treworgans Sandstone Member) consistent with an outer shelf and/or slope depositional environment along the northern margin of the Gramscatho Basin. The conformably overlying Porthtowan Formation (Gramscatho Group) comprises mudstones and sandstone-mudstone couplets and is entirely deep marine. Variscan primary deformation (D_1) resulted in isoclinal folding and an associated axial planar cleavage throughout both successions. The 'Watergate Bay Antiform' of earlier workers is discounted; the associated outcrop geometry of the Dartmouth and Meadfoot groups is thrust-controlled. D_2 deformation is developed around Porth Joke (Looe Basin succession) and intensifies southwards towards the Gramscatho Basin, probably in response to the NNW thrusting of the northern 'parautochthonous' margin of the Gramscatho Basin over the southern margin of the Looe Basin. An anomalous 900 m wide zone of steeply dipping S_2 cleavage around Penhale Point is interpreted as primarily reflecting reorientation by a large-scale southwards-verging monoformal F_3 fold. The structural complexity within the boundary zone possibly reflects a pre-Devonian basement fault influence upon: (i) the transition from shelf to deep marine depositional environments during the Lower-Middle Devonian, (ii) Variscan thrust juxataposition (D_1 and D_2) of the Looe and Gramscatho basin successions, and (iii) D_3 post-Variscan extensional reactivation and reorientation of earlier fabrics.

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Introduction

The Newquay district (Figure 1) is largely underlain by low-grade regionally metamorphosed Devonian sedimentary rocks assigned to the Looe and Gramscatho Basin successions (Leveridge and Hartley, 2006). It lies almost entirely within the parautocthon of the SW England Variscan belt, to the north of the Carrick Thrust (Holder and Leveridge, 1986). In the original resurvey, four lithostratigraphical units of Devonian age were defined; the Dartmouth Beds, Meadfoot Beds and Staddon Grits (all Lower Devonian), and the Ladock Beds/Grampound Grit (Reid and Scrivenor, 1906). In addition, the large-scale Watergate Bay antiform was proposed to account for stratigraphical repetition and there was recognition of the complexity of outcrop scale folding, cleavage and faulting (Reid and Scrivenor, 1906).

Most subsequent work on Devonian sedimentation and Variscan tectonics has primarily focussed on the southern third of the district that corresponds to the Gramscatho Basin (e.g. Holder and Leveridge, 1986). In contrast to areas along strike in SE Cornwall, Plymouth and South Devon, relatively little has been published on the northern two-thirds of the district that corresponds to the Looe Basin; exceptions include Sanderson (1971), Henley (1974), Holdsworth (1989), the unpublished PhD of Steele (1994), and data contained within province-scale syntheses, e.g. Dearman *et al.* (1971), Hobson (1976), Shackleton *et al.* (1982), Hobson and Sanderson (1983) and Coward and Smallwood (1984).

The resurvey of the Newquay Sheet was undertaken between 2003-2006 and complements the earlier extensive investigation of the Looe Basin, undertaken as part of the resurvey of the Plymouth Sheet (Leveridge *et al.*, 2002), and the Gramscatho Basin, undertaken as part of the resurvey of the Falmouth and Mevagissey sheets (Leveridge *et al.*, 1990; Leveridge, 2006). The purpose of this contribution is to summarise some of the new data pertaining to the Devonian successions, including stratigraphical and structural revisions, which have emerged during this re-survey. These findings are then discussed in the wider context of Devonian basin development and Variscan tectonics in SW England (e.g. Leveridge and Hartley, 2006).

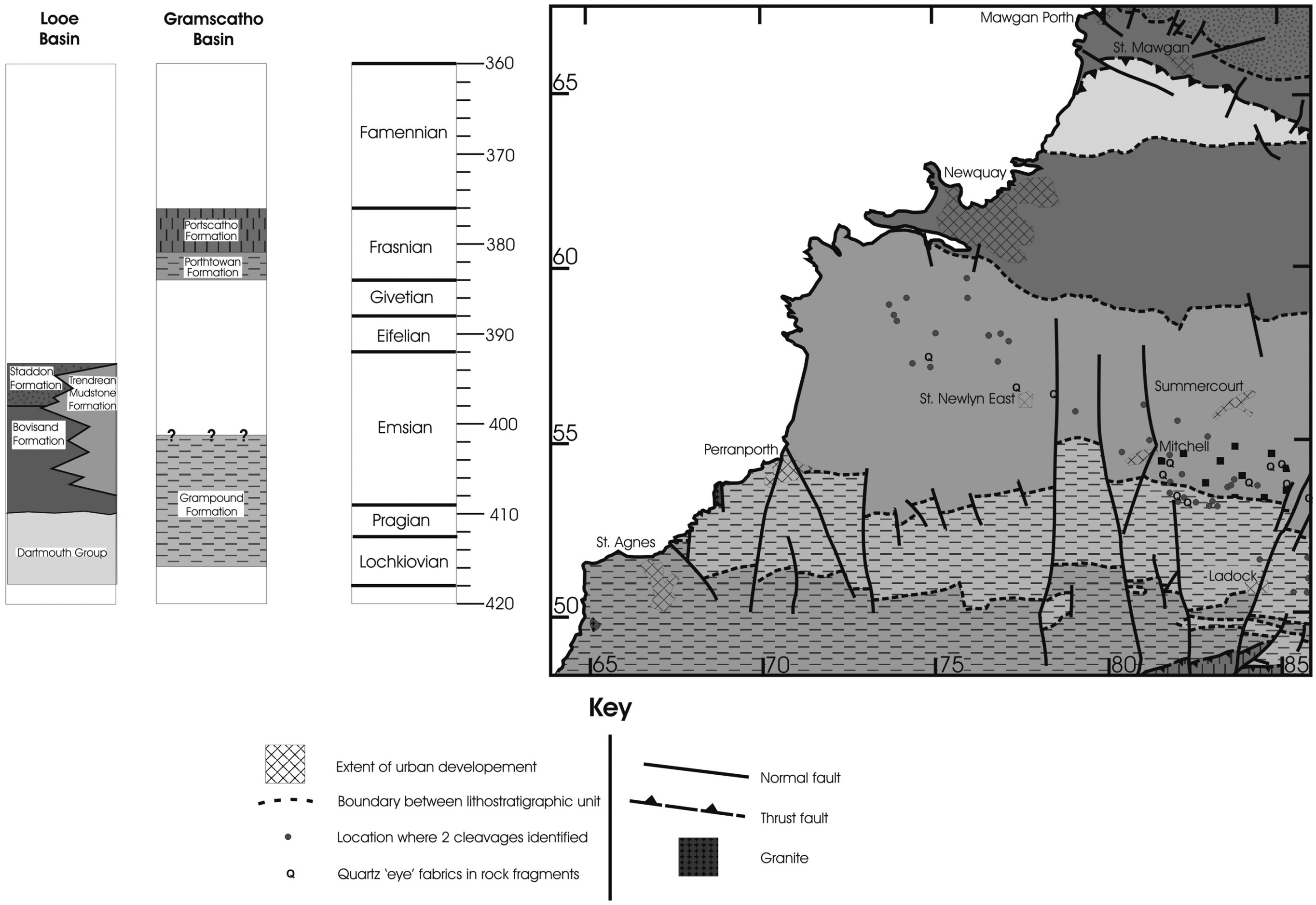

Figure 1. *Sketch geological map of the Newquay district. Ornaments for formations are indicated in stratigraphical column, which also shows ages of lithostratigraphical units discussed in text.*

DEVONIAN STRATIGRAPHY

The distinguishing features of the Devonian formations are usually well exhibited on the coast, with the exception of the area between Perranporth and St Agnes that is adversely affected by contact metamorphism associated with the St Agnes and Cligga Head granites. Bedding strikes east-west throughout much of the area; hence along the coast, which is oriented almost north-south, a detailed dip-section is exposed. Inland, the distribution of lithostratigraphical divisions is mapped from the association of brash fragments, exposures in small quarries and geomorphological features. Superposition of the formations here, and elsewhere in the Gramscatho and Looe basin successions (e.g. Leveridge *et al.*, 1990; Leveridge *et al.*, 2002), indicate that the rocks generally young from north to south. In this order, the formations encountered are: Whitsand Bay Formation (Dartmouth Group); Staddon, Bovisand and Trendrean Mudstone formations (Meadfoot Group); and the Grampound and Porthtowan formations (Gramscatho Group). The nature of each of these is described below.

Whitsand Bay Formation (Dartmouth Group)

The oldest lithostratigraphical unit is exposed in Watergate Bay (SW 840 649 to SW 832 634), where it comprises thinly interbedded red, green and grey mudstone with siltstone and some thin to medium-bedded pale grey fine sandstone, which sporadically preserve planar laminations and ripples (Figure 2a). The mudstone is locally micaceous. Towards the top of the formation, thin beds of sandstone become more common, and phosphatic concretions occur in the mudstones. The Whitsand Bay Formation has a gradational upper contact with the Bovisand Formation. The formation is very poorly exposed inland; the landscape is typified by gently sloping, low hills, cut by some steep gorges.

Pteraspids, acanthodians and a possible *Coccosteus* were recorded in Reid and Scrivenor (1906), with *Pteraspis cornubieus* receiving particular mention. White (1956) showed that the latter represented *Protaspis, Rhinopteraspis (Althaspis) leachi and R. dunensis* indicative of the Early to Mid Siegenian (latest Lochkovian – Early Pragian). Data gathered here and elsewhere in the province indicates that these fossils are from the upper part of the group, which probably extends well down into the Lochkovian (Leveridge *et al.*, 2002). Palynomorphs from Watergate Bay yield a late Lochkovian – Early Pragian assemblage (Davis, 1990).

There is insufficient sedimentological data to constrain the depositional environment in the Newquay area. Elsewhere, the formation has been interpreted as reflecting deposition in a predominantly lacustrine environment (Smith and Humphreys, 1991; Leveridge *et al.*, 2002). The presence of phosphatic concretions towards the top of the formation may be controlled by periodic marine incursions (Humphreys and Smith, 1989).

Bovisand Formation (Meadfoot Group)

The formation crops out on the coast around, and to the south of, Watergate Bay where overall beds dip to the south. It conformably overlies the Dartmouth Group at SW 832 634 (Figure 1). Thin to medium beds of sandstone (fine- to medium-grained greywackes, with some local beds of quartz arenite), siltstone and mudstone are inter-bedded with sporadic thick to very thick sandstone beds (Figure 2b); these are commonly the result of bed amalgamation. Normally graded bedding, coarsening and thickening-up sequences cross and parallel lamination and loading structures are well preserved in the sandstone-rich beds. Sporadic carbonate cemented sandstones, typically 0.5 m thick, are characterised by brown honeycomb weathering and were shown on the 1906 geological map as beds of limestone (e.g. around Lusty Glaze).

Thin- to thick- bedded bioclastic limestones that include fragments of crinoid, coral and brachiopod (e.g. Reid and Scrivenor, 1906) are numerous around SW 824 625. Pale green weathering thin tuffaceous beds are also locally present in the northern part of Watergate Bay and were recognized during the initial resurvey (Reid and Scrivenor, 1906). Fish fragments are evident in the basal beds of the unit.

Inland, the formation is characterised in the brash by fragments of medium-grained sandstone, variably dark grey, blue-grey and less commonly grey-green, with subordinate mudstone and siltstone, typically laminated. Exposure is restricted to small quarries (most commonly extracted for building stone) and small cuttings (e.g. around the gate of Kestle Mill Farm [SW 854 593]). Typical landscape features of areas underlain by the Meadfoot Group include steep valley sides and broad-crested hills. Evidence from brash is plentiful, and suggests that towards the top (south) of the group, there is an overall decrease in grain size: dark grey mudstone with thin beds of fine-grained sandstone is predominant around Coswarth [SW 868 597].

The lithologies, faunal assemblage, and sedimentary structures are consistent with the marine shelf depositional environment proposed for the Bovisand Formation further east (e.g. Richter, 1967; Pound, 1983; Leveridge *et al.*, 2002). Sporadic thin tuffaceous beds attest to syn-depositional magmatism. Background sedimentation was dominated by mud and was supplemented by episodic incursions of fine and medium-grained sand, possibly representing input during higher-energy (storm) events from a near-shore environment.

The range of facies and depositional environments recognized in SE Cornwall (Leveridge *et al.*, 2002) does not appear to be fully developed; in particular, there is little evidence for shoreline facies. The Newquay succession might therefore represent a deeper-water equivalent of the Bovisand Formation further east. The succession fines upwards (to the south); this probably reflects a progressive deepening of the depositional environment and drowning of source areas. No diagnostic biostratigraphical assemblages were obtained during the resurvey, but further to the east the formation is of Pragian – Mid Emsian age (Leveridge *et al.*, 2002).

Trendrean Mudstone Formation (Meadfoot Group)

This is a newly defined formation within the Meadfoot Group. The type locality is a low road cutting along an abandoned lane north of Trendrean Farm (SW 8340 5752). This unit encompasses the provisionally named 'Perran Shales' and some of the Meadfoot Beds of Reid and Scrivenor (1906). Here, and from evidence in brash across the area, it comprises dark grey, locally black, mudstone with some laminae of siltstone (with sharp bases fining upwards to mudstone) and fine-grained, dark grey sandstone. East-west striking bodies of siltstone (with some thin beds of fine-grained sandstone) are present within the formation (Figure 2c); they comprise very thin beds of dark grey siltstone, beds of dark grey mudstone, some thin beds of fine sandstone and horizons of brown/beige weathering carbonate (e.g. north of Arrallas at SW 884 544 and also at SW 878 558). Pale siltstone and beige fine sandstone is

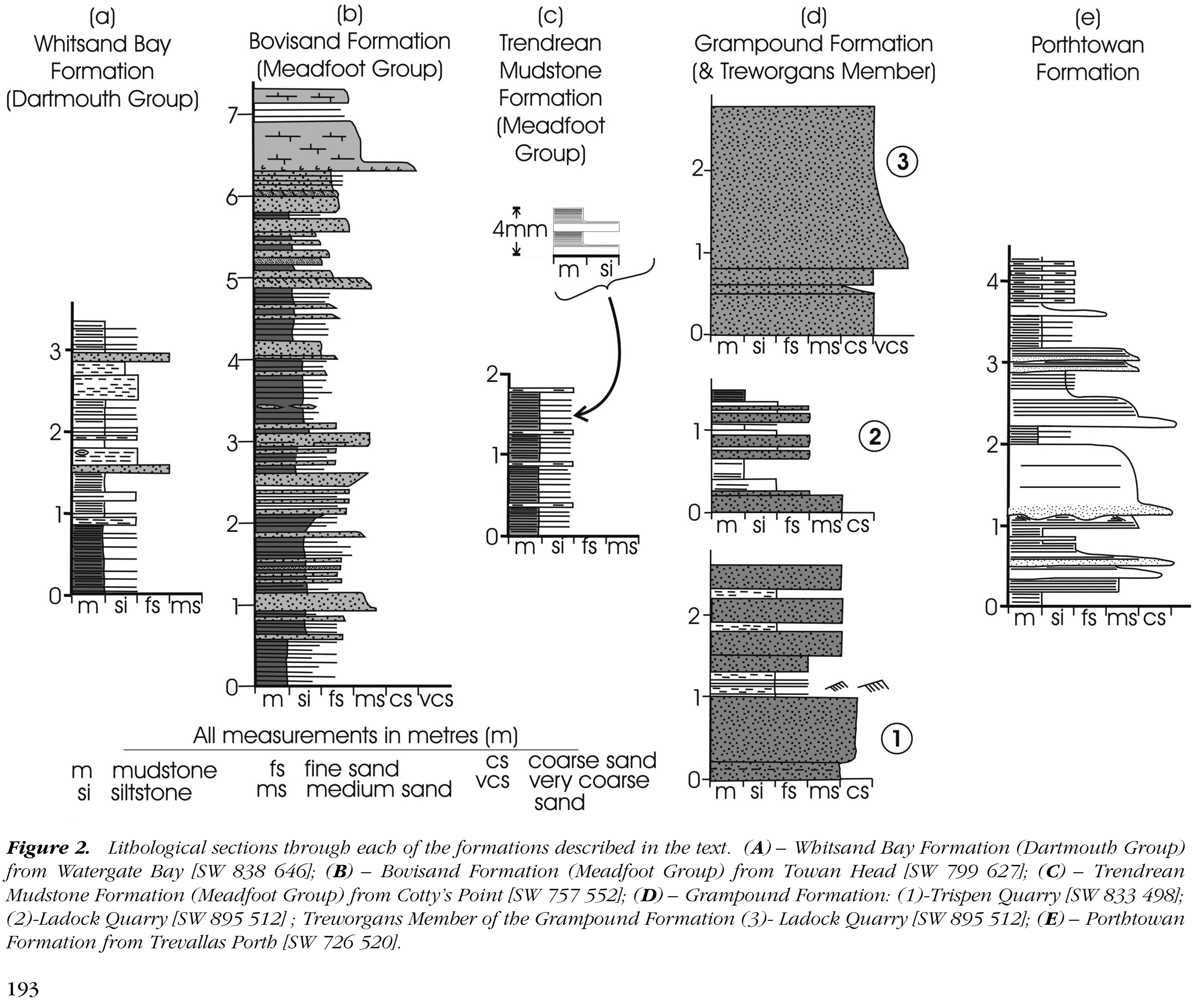

Figure 2. *Lithological sections through each of the formations described in the text. (**A**) – Whitsand Bay Formation (Dartmouth Group) from Watergate Bay [SW 838 646]; (**B**) – Bovisand Formation (Meadfoot Group) from Towan Head [SW 799 627]; (**C**) – Trendrean Mudstone Formation (Meadfoot Group) from Cotty's Point [SW 757 552]; (**D**) – Grampound Formation: (1)-Trispen Quarry [SW 833 498]; (2)-Ladock Quarry [SW 895 512] ; Treworgans Member of the Grampound Formation (3)- Ladock Quarry [SW 895 512]; (**E**) – Porthtowan Formation from Trevallas Porth [SW 726 520].*

locally present, the latter south of Trevessa Farm at SW 867 552 and SW 879 561.

Palynomorphs indicate a ?Mid-Emsian or younger age for this formation (Molyneux, 2006). Sedimentation primarily reflects a combination of hemipelagic and fine-grained turbiditic deposition. An outer shelf environment is favoured on the basis of its position between the Bovisand Formation (north) and Grampound Formation (south), but the sedimentary evidence would also be concordant with deposition in deep marine slope or basinal environments.

Grampound Formation, including the Treworgans Sandstone Member (Gramscatho Group)

In the first detailed survey of this area (Reid and Scrivenor, 1906), some of the rocks within this formation were included in the 'Ladock Beds' or 'Grampound Grit', a term used for geographically widely distributed rocks now assigned to the Portscatho, Carne and Roseland Breccia formations. The definition of the Grampound Formation used here is that given in Leveridge (2006), which refers to a more restricted sequence.

The formation is exposed along the coast, from just south of Perranporth [SW 755 545] to north of Trevellas Porth [SW 725 522], where it comprises laminae and thin beds of quartzo-feldspathic siltstone and fine sandstone, some displaying normal grading and cross-lamination (Figure 2d). The formation extends inland across the district, though the width of outcrop is variable from 2 to 3.5 km, due in part to folding, associated east-west trending faults, and subsequent brittle faulting. Inland, brash derived from this formation has variable proportions of dark grey mudstone, laminated brown to olive-grey siltstone, and grey-brown or blue-grey fine-grained sandstone. The latter of these lithologies has typically well-rounded grains and is deposited in beds of regular thickness.

The Treworgans Sandstone Member, recognised in the Falmouth and Mevagissey districts to the south, has its type locality [SW 899 495] within the SE corner of the Newquay district. In the NE corner of the Falmouth sheet, the Treworgans Sandstone Member was originally assigned to the base of the Porthtowan Formation (Leveridge *et al*., 1990). It was subsequently incorporated into the newly defined Grampound Formation during the resurvey of the Mevagissey district (Leveridge, 2006). In the Newquay district, the Treworgans Sandstone Member occurs towards the top of the Grampound Formation, although complex deformation, causing duplication and excision of the sequence, makes accurate determination of stratigraphical level problematic. The member comprises amalgamated thick to very thick-bedded medium- to coarse-grained yellow-weathering sandstone (locally pebbly sandstone) with subordinate dark grey siltstone and mudstone.

These medium to coarse sandstones are sub-angular and comprise approximately equal proportions of quartz, feldspar and lithics (primarily rhyolites and basalts) (e.g. Shail, 1992); they contrast with the rounded fine-grained quartzo-feldspathic sandstones that typify the laminae and thin beds in the remainder of the formation. The textural and compositional immaturity suggests that these sandstones were derived from a compositionally distinct and/or more proximal source than the fine-grained sandstones. Alternatively, they may have largely bypassed, possibly via submarine canyons, an extended shallow marine storage/reworking that could have increased the compositional and textural maturity of the remainder of the formation. The geometry of the sandstone 'packets' is difficult to assess due to limited inland exposure, but the Grampound Formation as a whole exhibits many of the characteristics of sand-rich depositional systems developed in shelf and slope environments (e.g. Dott and Bird, 1979; Heller and Dickinson, 1985).

Reid and Scrivenor (1906) identified a decrease of mean grain size, bed thickness and overall sandstone:mudstone ratio in the Grampound Formation from east to west, consistent with a component of axial sedimentation in an east-west elongated basin. Variation in the stratigraphical level of the sandstones may reflect primary variation in sediment supply to the basin margin or proximity to submarine channels.

Leveridge (2006) has suggested that the Treworgans Sandstone Member was derived from the high separating the Gramscatho and Looe basins, whereas the finer sandstone represented overflow deposits from the Looe Basin. The age of this formation is unknown; conodonts in samples from elsewhere in the region appear to be Early Devonian (Dean, *pers. comm*., 2005) but may be reworked.

Porthtowan Formation

This formation, defined by Leveridge *et al.* (1990), incorporated rocks that were originally attributed to the Falmouth, Portscatho, Grampound and Probus series (Hill and MacAlister, 1906). In the Newquay district, it crops out along the coast from just north of Trevellas Porth [SW 725 522] to 1 km south of Chapel Porth [SW 691 484]. The type locality occurs just south of the sheet boundary, along the coastal section southwest of Porthtowan. It is dominated by hard, slaty dark grey to grey-green mudstone, with some hard, dark grey or blue-grey very thinly bedded (locally thinly bedded) fine-to-medium grained sandstone and locally developed packets, up to 20 m in thickness, comprising medium to thickly-bedded muddy sandstones, e.g. Trevellas Porth, (Figure 2e). Sandstone beds typically lack lamination, though some normal grading occurs within the thicker units of sandstone. Fining-upwards sequences are evident to the north of Resugga, around SW 856 505, where a fining-up sequence, the base of which is defined by a prominent-weathering sandstone, grades in to mudstone to the south over a distance of approximately 150 m.

A distinct break-of-slope typically marks the boundary between the Grampound and Porthtowan formations (e.g. south-east of Nansough Farm, around SW 881 552): where the Porthtowan Formation is locally sandstone-rich it creates a more defined crest than the mudstone-dominated Grampound Formation. However, in locations where both formations have similar lithologies at their boundary, no well-defined features are present and the boundary is placed purely on the change of nature of the brash (e.g. around SW 864 504). From relations in the Mevagissey district (Leveridge, 2006), it is likely that the boundary between these two formations is right-way-up and gradational in this area, although folding and faulting have modified it. This seems to support evidence from elsewhere in the province that these lithostratigraphical units may both have been deposited within the Gramscatho Basin (Leveridge, 2006).

The depositional environment is exclusively deep marine (Leveridge *et al*., 1990; Shail, 1992). The majority of the mudstone-dominated succession is compatible with deposition from turbidity currents, although hemipelagites may be represented (Shail, 1992). The muddy sandstone-dominated 'packets' usually lack internal organization and suggest an origin as unconfined sediment gravity flows; their occurrence may be a function of proximity to point sources along the shelf edge or variations in sediment supply to the basin margin (Shail, 1992). A Frasnian miospore assemblage has been recovered to the south of the district, close to the upper boundary of the formation (Leveridge *et al*., 1990).

Portscatho Formation

This formation is present in the southeast of the area; it is the only formation within the Carrick Nappe, here representing the northern boundary of the allochthonous units to the south with the parautochthon to the north. These rocks were mapped in the Falmouth district (Leveridge *et al*., 1990); they comprise alternating grey or greenish grey normally graded sandstone beds (up to 2 m) with grey mudstone and sporadic beds of siltstone. Miospores and acritarchs indicate a Frasnian age for the upper part of the formation.

STRUCTURE

The Newquay district lies almost entirely within the parautocthon of the Variscan belt of SW England (Figure 1). The Carrick Thrust lies in the southeast corner of the area, and defines the northern boundary of the allocthonous nappes cropping out to the southeast. Lithostratigraphical units within the Newquay district have, in common with those of adjacent areas, been affected by multiple phases of deformation. Three phases of ductile deformation are evident from Penhale Point [SW 757 592] to the southern boundary of the sheet (Alexander and Shail, 1995): a zone where D_3 reorients S_2 to a steeply-dipping orientation can be traced inland from Penhale Point. To the north of this zone, ductile structural fabrics are less complex, with the northern part of the district, around Watergate Bay, exhibiting evidence of a single regional ductile deformation (D_1). This comprises a set of tight to isoclinal folds with fold hinges that trend ENE-WSW to E-W; axial planar cleavage (S_1) is parallel to bedding (S_0) in the limbs of folds. Folds are present from the mm to 10 m scale; they predominately face and verge to the north, though south-facing folds have been locally identified around Perranporth (Shail and Leveridge, 2005). Ductile-brittle and brittle faults affect the entire area.

A structural cross section from north to south

The most northerly lithostratigraphical boundary on the coast, between the Dartmouth Group and Meadfoot Group, is exposed on the coast in Watergate Bay [SW 841 649]. On the first survey map (GSGB, 1906), the Dartmouth Beds were shown to be at the core of an easterly plunging antiform, surrounded by the younger Meadfoot Beds. The resurvey has shown that the beds dip and young, with only local exceptions, to the south; the northern boundary of the Dartmouth Group with the Meadfoot Group is a northerly-directed thrust, placing the older Dartmouth Group locally above the Meadfoot Group (Figure 3). In contrast, further south on Whipsiderry Beach [SW 832 634], there is a right-way-up, conformable boundary between the Dartmouth Group and the Meadfoot Group, affected only by minor, late faults.

Pentire Point East [SW 781 615] is the southernmost exposure of the Meadfoot Group along the coast; inland, the boundary is expressed by a change from sandstone to mudstone dominated brash, plentiful quartz vein debris and some positive topographic features that suggest bodies of resistant vein quartz. There is no evidence of a gradational change of lithology along the boundary, though palynological studies (Molyneux, 2006) indicate a ?mid-Emsian or younger age for the Trendrean Mudstone Formation. The intersection of the boundary with the topography varies from from 5° N to 23° S (Figure 1), indicating at least partial reactivation by brittle structures, and/or modification of the boundary by folding.

Further south, within the Trendrean Mudstone Formation, increasing structural complexity is exhibited on the south side of Crantock beach [SW 778 608]. Over a 500 m section approximately across-strike, crenulation cleavage (S_2) associated with D_2 folds progressively transposes bedding and first cleavage (Figure 4a). At Porth Joke [SW 769 607], S_2 becomes the dominant fabric, which dips mainly to the south, and has quartz veining approximately parallel to it.

Inland, evidence of a second cleavage is sporadic; typically it is at a variable angle to the S_1 and appears to be a spaced cleavage, locally enhanced by some fracturing. Good examples of the latter - with variable angles between the two cleavages - are present at Gunnamanning Farm [SW 895 516].

The second regional cleavage (S_2) is typically a spaced cleavage; examples occur around Tregerles Farm. North of the farm at [SW 861 561], brash fragments show S_2 is at a high angle to S_1, whereas in those to the south [SW 864 553] S_2 dominates.

Further south, through Holywell Bay and southwards towards Penhale Point [SW 757 591], the orientation of the S_2 fabric is affected by a subsequent phase of folding (D_3) which causes a steepening and folding of S_2 (e.g. Alexander, 1997). Sanderson (1971), Sanderson and Dearman (1973), Holdsworth (1989) and Steele (1994), among others, have described the dominant structure in this area as of D_2 age. The axial planar cleavage associated with these folds (S_3) is typically a well-spaced crenulation cleavage, but locally it is pervasive and transposes S_2 (Figure 4b), for example at the southern end of Holywell Bay. Where quartz veining is parallel to S_2, it is disrupted by the S_3 fabric, creating 'quartz eye' structures which were first noted by Reid and Scrivenor (1906). A zone where quartz eyes and at least two phases of ductile deformation are identified has been traced inland from Penhale Point during this resurvey. The zone is displaced by three regional-scale north-south oriented faults (Figure 1) and emerges on the eastern edge of the sheet around Nankilly [SW 901 511]. In the east of the region, 'quartz-eye' structures align along the boundary between the Trendrean Mudstone Formation and the Grampound Formation, perhaps suggesting that locally these fabrics formed during tectonic movement (during D_3) along the lithostratigraphic boundary.

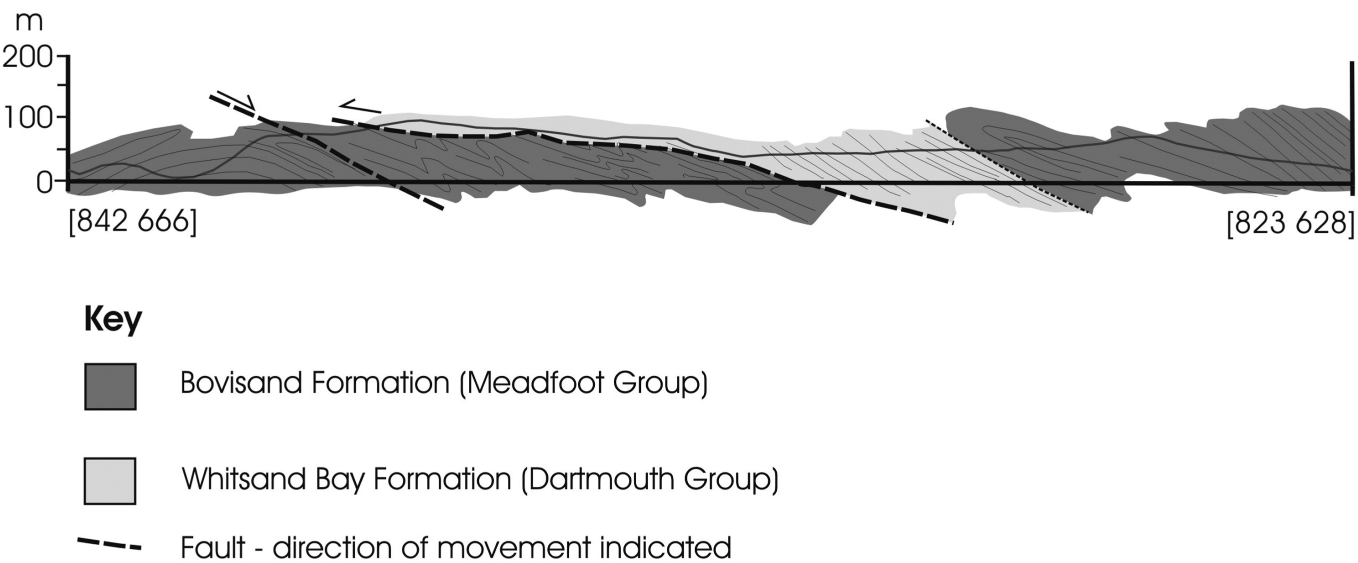

Figure 3. *Sketch cross section of the rocks exposed at Watergate Bay, along to Whipsiderry Beach, showing the nature of the relationship between the Whitsand Bay Formation (Dartmouth Group) and the Bovisand Formation (Meadfoot Group).*

On the coast, the boundary between the Trendrean Mudstone Formation and Grampound Formation is excised by a north-south fault close to Perranporth. Inland, the boundary passes to the west of Entrance Wood [SW 880 534], where changes in gradient of the topography appear to be related to variation of underlying rock-type: steeper slopes associated with sandstone or siltstone dominated beds, and more gentle slopes underlain by mudstone-dominated sequences. Southwest of Nantillio [SW 866 538], grey siltstone forms the crest of a ridge, and dark grey mudstone with quartz vein lenses is evident on the side of the hill.

The orientation of the boundary between the Trendrean and Grampound formations varies along strike; it dips approximately 50° to the north where it cuts across steep topography without deflection at SW 882 532, and further west it dips approximately 16° north/north-east along an appreciable part of its length (around SW 872 534). This suggests that at least part of the boundary has been reactivated by normal faults approximately parallel to the boundary, and/or that the boundary has been deformed by ductile folding which has generated variations of dip along its length.

Brittle faulting

The following pattern of brittle faulting has been established from cross-cutting relationships (Table 1). Some indication of the time at which some of the faults were active is provided by field relations east of Retyn Farm: the Trendrean Mudstone/Meadfoot Group boundary is displaced by a NNW-SSE trending fault at SW 892 589 which, to the south [SW 893 585] is cut by a quartz porphyry dyke without displacement. This indicates that this NW-trending fault experienced final movement before the end of the quartz porphyry dyke emplacement. In the southern part of the district, Alexander and Shail (1995) suggest that brittle listric faults dipping to the NNW (striking ENE-WSW) were coeval with granite emplacement, followed by successive phases of ENE-WSW shortening, NNW-SSE extension and ENE-WSW extension.

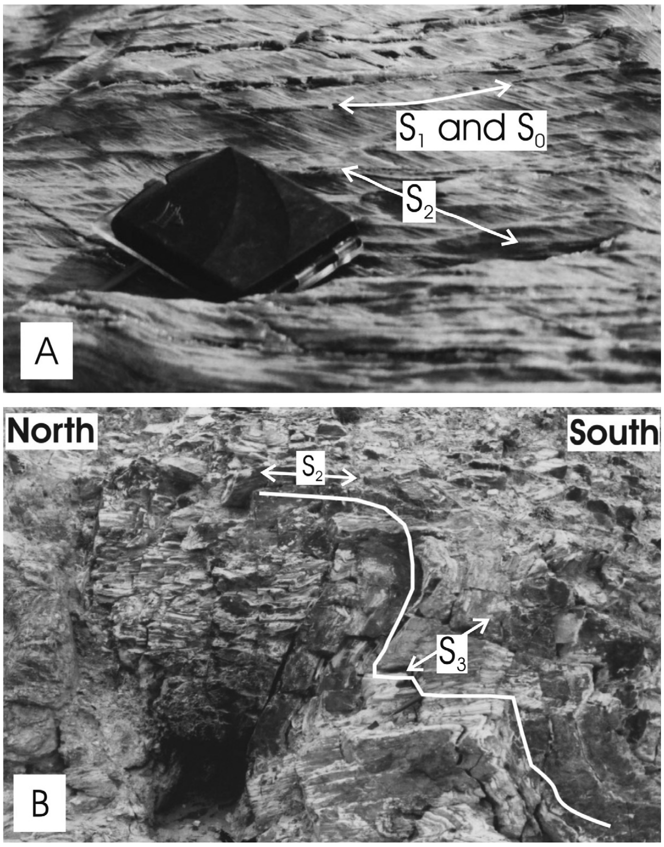

Figure 4. ***A.*** *Second cleavage (S_2) cross cuts S_0 and S_1 fabrics (which here are parallel) in the Trendrean Mudstone Formation at Porth Joke [SW 7690 6070], compass-clinometer for scale.* ***B.*** *Second cleavage (S_2) folded by the D_3 phase of deformation; here, the S_3 fabric is only locally developed in fold hinges. Hammer for scale (parallel to S_3 fabric) – length of shaft is 30 cm.*

Phase	Direction	Description and example
3	N-NE	Some regional-scale structures; offset lithological boundaries e.g. fault which displaces Porthtowan/Grampound boundary [SW 8525 5035]
2	NW	Purely brittle, with some Reidel faults trending NE e.g. fault which truncates siltstone bodies in Trendrean Formation [SW 8914 5423]
1	ESE-WSW to E-W	Probably associated with D_2 phase of ductile folding e.g. fault to west of Grampound Road [SW 9107 5127]

Table 1. *Summary of the brittle faulting phases identified in the Newquay district. Oldest event indicated at base of table; most recent event at the top.*

DISCUSSION AND SYNTHESIS

The recent resurvey of the Newquay district has yielded evidence that confirms the Devonian sedimentary rocks in the northern two-thirds of the district were deposited in the westwards continuation of the Looe Basin (e.g. Leveridge *et al.*, 2002; Leveridge and Hartley, 2006). The sedimentary rocks in the southern third of the district were deposited in northern part of the Gramscatho Basin (Leveridge *et al.*, 2000; Leveridge and Hartley, 2006). Collectively, the successions from these two areas record rifting and the development of the southern segment of the Devonian SW England passive margin. The successions were juxtaposed by Variscan thrusting and the boundary zone also preserves evidence of late- and post-Variscan reactivation.

Rifting and passive margin development

Looe Basin. The oldest sedimentary rocks in the district are those assigned to the Dartmouth Group. They provide evidence of a (probable) non-marine depositional setting during the Lochkovian-Pragian. A conformable contact with the succeeding Bovisand Formation (Meadfoot Group) indicates that marine conditions had been established across the district by late Pragian times and continued into the Emsian; thin beds of tuff intercalated with the sandstone, siltstone, mudstone and limestone indicate syn-depositional volcanism. Palynological evidence indicates a Mid-Emsian or younger age for the Trendrean Mudstone Formation (Meadfoot Group), perhaps indicating that if the Bovisand Formation in this district is also of Emsian age (as seen to the east), then the contact between these formations may be tectonic. However, no dates for the Bovisand Formation have yet been obtained from the Newquay district, so the nature of this contact – tectonic or essentially stratigraphic – is not determined.

Overall, the progression from Dartmouth Group through Bovisand Formation to Trendrean Mudstone Formation is consistent with a progressive deepening of depositional environment that was probably achieved by rift-related thinning of the lithosphere (e.g. Leveridge *et al.*, 2002). The Trendrean Mudstone Formation is likely to represent deposition in an outer shelf (sub storm wave base) or slope environment.

Gramscatho Basin. Around and to the south of Perranporth, mudstone, siltstone and fine-grained sandstone of the Grampound Formation, extends along the coast to just north of Trevellas Porth. Bodies of laterally discontinuous coarse-grained sandstone within this formation are referred to as the Treworgans Sandstone Member, thought to represent channel deposits cutting through the finer-grained outer shelf or slope components of the formation. No precise palynological dating has been obtained for these rocks, but sparse evidence indicates an early Devonian age (Dean, *pers. comm.*), suggesting deposition was broadly coeval with the Meadfoot Group, but evidently in a separate marine basin.

The boundary between the Grampound and Porthtowan formations to the south appears to be transitional. The Porthtowan Formation comprises dark grey slaty mudstone with some thinly bedded fine-grained sandstone that includes packets of sandstone. Deposition was entirely deep marine. South of the sheet boundary, the Porthtowan Formation has yielded a Frasnian palynomorph assemblage (Leveridge *et al.*, 1990).

Structural geology

Structural evolution during the Variscan orogeny was polyphase and spatially complex. All sedimentary rocks in the district experienced D_1 regional ductile deformation, which formed isoclinal folds and penetrative axial planar cleavage (evident in the northern and southern parts of the coastal section, with S_1 parallel to S_0 in fold limbs). Large-scale thrusts also formed during D_1, such as that which forms the boundary between the Dartmouth and Meadfoot groups in Watergate Bay [SW 840 649], and the contact between the Trendrean Mudstone (deposited in the Looe Basin) and the Porthtowan Formation (deposited in the Gramscatho Basin). This latter thrust fault would seem to be the reactivation of a basin-bounding fault that had accommodated extensional movement during the Devonian. D_2 structures are developed in the Looe Basin succession to the south of Porth Joke and throughout the Gramscatho Basin succession. A structurally complex zone extends along the coast from the south side of Polly Joke to the middle of Perran Sands, and can be traced inland along an ESE-WSW strike. In this zone, the second cleavage (S_2) overprints the first (S_1), and vergence of S_2 with respect to S_1 is northwards, suggesting this deformation expresses continued Variscan convergence. Between Penhale Point and Ligger Point, S_2 is overprinted by a third (S_3) fabric in a zone up to 900 m wide; D_3 folds steepen the orientation of the S_2 foliation, forming a monoclinal structure. The south-verging relationship of S_3 with S_2 suggests that this set of fabrics may have formed as a response to extensional collapse of the Variscan Orogeny (e.g. Alexander and Shail, 1995).

The focus for the formation of both S_2 and S_3 is hypothesised to be a (now) occluded pre-Variscan ESE-WNW-trending basement feature, perhaps once a sub-basin boundary within the Looe Basin. Intensification of D_2 fabrics in this area probably reflects the NNW- directed thrusting across this feature. The steep fabrics along this zone are primarily a function of subsequent D_3 refolding of the earlier thrust-related D_2 zone rather than transpression (Holdsworth, 1989; Shail and Leveridge, 2005). The monoformal F_3 geometry in the Penhale-Ligger section is consistent with that proposed (as an F_2 structure) by Sanderson (1971). D_3 developed in response to latest Carboniferous-Early Permian NNW-SSE extensional reactivation of the strongly inverted passive margin (Alexander and Shail, 1995). Crustal thinning associated with the extensional collapse of orogens is elsewhere correlated with the onset of volcanism (e.g. Inger, 1994). Attenuation of the crust during the latest Carboniferous and Early Permian may be linked to the formation of ductile-brittle to brittle late-phase extensional normal faulting across the peninsula and the generation and emplacement of the Cornubian granite (Shail and Wilkinson, 1994; Alexander and Shail, 1995; Leveridge and Hartley, 2006).

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