Chaotic breccia zones on the Pembroke Peninsula, South Wales: evidence for collapse into voids along dilational faults

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Abstract

Chaotic breccias and megabreccias – locally called gash breccias – hosted within the Pembroke Limestone Group (Visean, Mississippian, lower Carboniferous) of southwest Wales are re-mapped along with spatially-related crackle and mosaic breccias. Of thirteen studied megabreccia bodies, seven lie along steep, NNW- or NNE-striking strike-slip faults originating during north-south Variscan (late Carboniferous) shortening, though reactivated during later extension. Four bodies are conformable with E-W striking, steeply-dipping bedding, and two have irregular or indeterminate margins. The bedding-parallel zones are interpreted as the dilational tips of listric normal faults, and the cross-strike faults as transtensional transfer zones. Sub-horizontal clast fabrics suggest brecciation by gravitational collapse into opening fissures rather than by cataclasis along the faults. Most fissures have geometrically matched margins produced by this dilational faulting, and only locally have the indented margins indicating solutional processes. The most likely age for the main fissure extension and fill is late Triassic, based on analogous dated fills at the eastern end of the

Bristol Channel Basin. The Pembroke megabreccias blur the distinction between fault rocks formed by deformation and those formed by redeposition along fault zones.

Keywords: megabreccia, fault rocks, dilational fault, Bristol Channel Basin.

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1. Introduction

Breccias, rocks made of coarse angular fragments, form by a range of sedimentary, magmatic and deformational processes (e.g. Laznicka, 1988). They commonly have a high porosity and permeability, and are therefore economically important as hosts and conduits for groundwater, hydrocarbons or mineralization. The origin of some breccias can be deduced from their texture, composition and context but the origin, or even the three-dimensional geometry, of other breccias is uncertain.

One problematic breccia formation mechanism is gravitational collapse into voids formed by solution (Loucks, 1999) or by mismatch of fault walls (e.g. Woodcock et al., 2006; Ferrill et al., 2011; Walker et al., 2011). This collapse mechanism grades into other processes: confined implosion at pressure-release zones along faults (e.g. Sibson, 1986) and phreato-magmatic explosion in igneous and hydrothermal settings. One area where all these mechanisms have been proposed for the same suite of breccias is the Pembroke Peninsula, south Wales (review by Walsh et al., 2008) where chaotic megabreccias (e.g. Fig. 4d, e), locally called gash breccias, are hosted within lower Carboniferous (Mississippian) limestones. This paper reports new work on the megabreccias and on spatially related fault breccias that clarifies the origin of many of the occurrences.

2. Geological setting of the studied breccias

The Pembroke Peninsula, west Wales, lies close to the northern limit of strong Variscan (late Carboniferous) deformation in Britain (Fig. 1b; British Geological Survey, 1996). The mid-Ordovician to late Carboniferous sequence is deformed into E-W trending upright folds with kilometric wavelengths (Fig. 1a). The studied breccias occur in the Pembroke Limestone Group (Tournaisian and Visean), which crops out in three major synclines: the St Florence, Pembroke and Bullslaughter Bay Synclines. The folds are cut by two conjugate sets of strike-slip faults striking NNW and NNE (Fig. 1a). The peninsula is geologically bounded to the north by the steeply S-dipping Ritec Fault, with a reverse throw of 0.5 to 1 kilometre.

[Figure 1 about here]

Thirty localities have been studied, all but two of them coastal. Most are accessible either at shore level or at the top of the 50 metre high cliffs, although some can only be reached or viewed from the sea.

The stratigraphic distribution of breccias within the Pembroke Group reflects its lithological contrasts (Fig. 2). No megabreccias occur in the lower units, which are dominantly shale-prone thin- or medium-bedded limestone. Megabreccias are common where mechanically strong thick-bedded limestone dominates: particularly in the High Tor and Cornelly formations (Arundian to Holkerian) of the northern areas and the Stackpole and Oxwich Head formations (Holkerian to Asbian) of the southern area. However, overlying thinner-bedded units are also brecciated: the Stormy Limestone Formation (Holkerian) in the north and the Oystermouth Formation (Brigantian) in the south.

[Figure 2 about here]

3. Previous work and hypotheses

The history of research on the Pembrokeshire megabreccias has been reviewed by Walsh et al. (2008). Early research produced two genetic hypotheses. Dixon (1921) envisaged karstic solution of limestone, producing large voids into which wall and roof rocks progressively collapsed (Fig. 3a). By contrast, Hancock (1964) and Thomas (1970, 1971) proposed formation by tectonic fragmentation along faults (Fig. 3b). Walsh et al. (2008) concluded that the megabreccias were formed by more than one mechanism, and suggested a third: phreatic explosion due to upward escape of thermally-driven superheated fluids (Fig. 3d). Rowberry et al. (2014) and Błażejowski and Walsh (2013) showed that, at Bullslaughter Bay (localities 3 and 4), chemically aggressive fluids, either deep or meteoric, have produced substantial residual deposits, which apparently overprint chaotic breccias and bedded sequences.

[Figure 3 about here]

Recent studies on chaotic breccia hosted within Carboniferous limestone elsewhere in the UK provide analogues for the Pembrokeshire examples. Woodcock et al. (2006) attributed megabreccia along the Dent Fault, northwest England, to collapse of voids produced by dilational fault displacement (Fig. 3c). Wright et al. (2009) studied strike-slip cross faults in the Pembroke Group of the Gower Peninsula, there contain void-filling veins and breccias produced during active faulting rather than by solution. One of the westernmost faults contains megabreccia identical to the Pembrokeshire examples. Eastward from Gower, sediment-filled extensional fissures cut the Pembroke Group in the Mendip Hills (Wall and Jenkyns, 2004). Rather than megabreccia, these fills are dominated by Triassic and Early Jurassic sediment infiltrated from the contemporary land surface.

4. Breccia zone lithologies

4.1 Terminology

The studied zones contain a range of breccias, particularly some with very large clasts (over 1 metre in diameter) referred to informally as *megabreccias*. Sedimentologically, such large-clast breccias would be termed *boulder breccia.* The genetic term *gash breccia* is avoided, as pre-supposing that the breccias formed in an open void.

The breccias are classified using the non-genetic scheme developed for cave-collapse zones (e.g. Loucks, 1999) as modified for fault zones (Mort and Woodcock, 2008; Woodcock and Mort, 2008). The spectrum from *crackle breccia* through *mosaic breccia* to *chaotic breccia* simply reflects increasing disaggregation of the protolith, and therefore decreasing percentage of large (>2 mm) clasts in the overall rock volume. Breccias can either contain a fine-grained matrix or carbonate cement. This classification is suitable for any breccia and its use here does not pre-judge whether or not the Pembrokeshire breccias were formed along faults.

4.2 Crackle and mosaic breccia

Crackle and mosaic breccia has angular clasts with a fitted-fabric texture and only limited separation and rotation of clasts. In crackle breccia (Fig. 4a) the porosity between large (>2 mm) clasts is less than 25% of the rock volume, whereas in mosaic breccia (Fig. 4b) it is about 25-40%. The porosity is filled either by crystalline carbonate cement or by fine (<2 mm) matrix, both detailed below (section 4.5, 4.6). Crackle and mosaic breccia typically occur at the gradational margins to chaotic breccia zones, with calcite cement between the clasts. Pods of crackle and mosaic breccia may be interleaved on a scale too fine to distinguish separately on the maps of individual fault zones (sections 6 to 9).

[Figure 4 about here]

4.3 Chaotic breccia and megabreccia

Chaotic breccia and megabreccia (Fig. 4c) has angular to sub angular clasts that lack a fitted-fabric texture. Clasts have been rotated and translated enough to obscure any match with each other. Nevertheless, all the chaotic breccias zones are monomict; that is their large clasts are entirely derived from the Pembroke Group. Indeed, in all but one zone, the clasts derive from the same limestone formation that hosts the breccia. The exception is at Trevallen (locality 7) where a breccia hosted in thickly-bedded Stackpole and Oxwich Head limestones also contains clasts from the overlying thinner-bedded Oystermouth Formation. Very large (1 to 10 metre) clasts in megabreccia may be equidimensional, or more typically bedded slabs with their long dimension parallel to their bedding (Figs 4d, e). As in mosaic breccia, the porosity in chaotic breccia can be filled either by carbonate cement or by fine-grained matrix, both detailed below (section 4.5, 4.6), or remain unfilled.

4.4 Cataclasite

The cores of some faults have thin (<1 metre) zones of cataclasite or fine matrix-rich chaotic breccia (Fig. 4f). On the fault-rock scheme of Woodcock and Mort (2008), the boundary between these two rocks types is at 2 mm average clast size, although other authors have used a smaller clast size, for instance Higgins (1971) at 0.2 mm and the North American Geologic-map Data Model (2004) at 0.1 mm. These fault rocks lack a foliation, although they may be cut by anastomosing principal slip surfaces within the fault core.

4.5 Carbonate cement

The dominant cement is calcite, occurring in two growth forms. *Blocky calcite* (Fig. 5a) comprises equidimensional crystals about 1 cm in diameter. *Elongate blocky calcite* (Fig. 5a, b) forms acicular crystals up to 5 cm long. Both forms have euhedral crystal terminations, showing that they grew into fluid-filled voids. Both calcite types nucleate on clasts and void walls, with the elongate calcite forming conspicuous radiating crystal masses. In places, clasts in 2D view are completely surrounded by radiating cement, forming *spar balls* (Fig 5b), although the possibility that such clasts are supported by other clasts in the third dimension cannot be ruled out. If not, the formation of these structures is problematic (Genna et al., 1996; Frenzel and Woodcock, in press).

Growth of equant, rather than elongate, crystals reflects high nucleation rates from hydrothermal fluids, probably due to fluid supersaturation (Oliver and Bons, 2001), arising from arrest of a rising mass of fluid (Bons, 2001) or by a rapid drop in fluid pressure during hydraulic fracture (Phillips, 1972). Because cements are void-filling rather than keeping pace with void opening, opening rates must have exceeded precipitation rates.

Although most carbonate cement is non-ferroan, small volumes of ferroan calcite fill late-stage porosity or form thin cross-cutting veins. Ferroan dolomite nodules occur (Walsh et al., 2008) in the breccia zones at Draught (locality 13, Fig. 2). The nodules are brecciated and recemented by calcite.

[Figure 5 about here]

4.6 Sediment matrix and laminated infill

Where breccia clasts have a matrix (<2 mm) infill, this typically comprises calcitic particles between silt and medium sand grade (Fig. 5c). Most sediment is coloured red by hematite or brown by limonite. Lamination is typically visible wherever voids are wider than a few centimetres. It has a concave-up catenary form (Fig. 5c) consistent with lamina-by-lamina deposition within each void. Where sediment and cement occur together within a void, the sediment is the earlier fill. The sediment occupies the lower part of voids or has accumulated above tabular clasts (Fig. 5d), and the contact of the sediment and overlying cement forms a geopetal indicator. All geopetal and way-up evidence suggests that the host breccia zones have not been significantly rotated since they were formed.

Several laminated sediment fills are of particular significance.

Laminated and thinly-bedded crinoidal grainstone occurs at Draught (locality 13). The crinoids cannot be dated. Their articulated and non-corroded shapes might question reworking from local well-cemented Carboniferous rocks although Rowberry et al. (2014)

record crinoid ossicles and Brigantian conodonts (Błażejowski and Walsh, 2013) in karstic weathering residues at Bullslaughter south (locality 4). Alternatively, Mesozoic crinoids are a conspicuous component of the Mendips fissure fills (Wall and Jenkyns, 2004), where they infiltrated in sediment from the Mesozoic sea floor.

Well-cemented laminated micrite forms prominent catenary-bedded sheets at some localities (e.g. Draught), where it is more resistant to weathering than wall rocks (Fig. 5e). In thin section it is seen to comprise calcite debris cemented by ferroan calcite and dolomite. This is the lithology confusingly termed 'stalagmite' by Dixon (1921) and also by Thomas (1971) and Walsh et al. (2008). However, the latter authors consider that the deposits are not phreatic zone speleothem but rather a form of hot-water travertine. By contrast, we do not attach any special significance to these sediments: they are merely well-cemented examples of normal sediment infill.

4.7 Residual deposits from weathering overprint

At Bullslaughter Bay, a deep weathering episode has converted both bedrock and breccias into residual deposits (Błażejowski and Walsh, 2013; Rowberry et al., 2014). Mudstones assigned to the late Visean Aberkenfig Formation (Błażejowski and Walsh, 2013) or the Namurian Bishopton Mudstone Formation (Walsh et al., 2008) have been kaolinised and were termed *saprolite* by Walsh et al. (2008). Chert interbeds have been brecciated but define relict bedding. Whether the brecciation results from *in situ* weathering (Rowberry et al., 2014) or involves phreatic explosive disruption (Błażejowski and Walsh, 2013) is debated. It is similarly unclear to what extent brecciation in the underlying Oystermouth Formation predated or accompanied deep weathering. For instance, one interpretation of a breccia at

Bullslaughter south (locality 4, Fig. 5f) is as a laminated sand deposited in a void, and punctured by limestone ‘dropstones’ from the hanging wall. An alternative explanation (Błażejowski and Walsh, 2013; Rowberry et al., 2014) is that the lamination is inherited from decalcified limestone, with the blocks as less weathered relicts. Such textures are termed *ghost karst* (Dubois et al., 2014). The context of the residual deposits at Bullslaughter Bay is discussed later (Sections 6.2, 9).

5. Distribution and context of breccia bodies

Figure 6 shows which lithologies are important at each locality, grouped according to its structural setting. Most lithologies occur in every setting, but chaotic megabreccias do not occur along thrusts, and cataclasites do not occur in irregular breccia bodies. The tabulated widths of zones vary from 5 to 200 metres, and do not correlate closely with structural setting.

[Figure 6 about here]

Three end-member structural settings can be recognised (Fig. 7):
a) zones that strike parallel to bedding (roughly east-west), either parallel also to bedding dip or to cross-cutting thrust faults;
b) zones along steep NNW or NNE-striking faults that cut across bedding strike; and
c) zones with irregular margins that parallel neither faults nor bedding.

A triangular diagram (Fig. 7) shows semiquantitatively the range of geometry between the three end members. Three breccia zones have geometries too uncertain to plot but, of the

27 plotted examples, over half (15) are closely related to cross-strike faults, 5 parallel bedding and 3 parallel thrust-faults. The remaining 4 have mostly irregular margins. These groupings provide a framework for detailing the structural geometry of representative breccia zones (sections 6 to 9).

[Figure 7 about here]

6. Breccias associated with cross-strike faults

6.1. Cross-fault zones with simple geometry

Nine vertical cross-strike fault zones have simple geometries and cluster at the top corner of Figure 7. Maps of three examples (Fig. 8a-d and 9a) show that one or both margins grade inwards from crackle through mosaic breccia into a fault core of chaotic breccia or megabreccia. Typically one principal slip surface cut through or bounds this central fault core. Fine-grained cataclasite occurs in the core in one only case (Stackpole, Fig. 8c, d).

[Figure 8 about here]

Six steeply-dipping cross-strike fault zones have complex geometries, with greater outcrop widths and more than one mappable fault core. The example at Flimston Bay (loc. 1, Fig. 8e, f) occurs along a NNW-striking fault with at least 500 m of dextral strike-slip offset of the Bullslaughter Bay Syncline. The example at Bullslaughter east (loc. 3, Fig. 10a, c) has three principal slip surfaces marked by chaotic breccia and megabreccia, separated by screens of intact limestone. Draught Cove (loc. 14, not illustrated) contains at least nine principal slip surfaces, seven chaotic breccias zones, three cataclasite zones and two zones of chaotic megabreccia.

In general then, the cross-strike faults host the thickest and most complex breccia zones (Fig. 6). They coincide with cross-faults mapped in the detailed survey by Dixon (1921). Independent evidence of strike-slip displacement is available where the faults laterally displace fold axial planes, for instance at localities 1, 2, 3, 4 and 12, and on about ten other faults detailed by Dixon (1921, 181-185). The sense of displacement is dextral on the NNW faults and sinistral on the NNE faults. This pattern is so well defined that it was the main example cited by Anderson (1951) for his classic stress interpretation of conjugate sets of strike-slip faults. The faults formed in response to north-south directed maximum principal stress during the Variscan event. These faults would have been transpressional during Variscan shortening, and not natural hosts for chaotic breccias that require dilation of the fault zone. An extensional phase during latest Variscan or later time is implied by regional evidence (Section 12.5).

Sub-horizontal slickensides and slickencrysts are additional evidence that the breccia zones coincide with strike-slip faults. Examples have been observed at localities 1, 5 and 14, and Dixon (1921, p. 182) states that “all the slickensiding that has been examined along the faults shows either horizontality or only a gentle inclination in the striae or fluting produced by the movement.” It might still be argued that some of the chaotic breccias are a later infill to karstic solution cavities along the faults. However, examples such as the low displacement splay fault at Stackpole Quay (loc. 12, Fig. 8c, d) argue against solution as a general genetic model. The fault walls and enclosed fragments fit back together perfectly, in contrast to the irregular, sculpted and mismatching fissure walls that would be produced by solution of the limestone.

7. Breccias associated with thrust faults

Breccia zones that parallel bedding strike (Fig. 7, bottom left) fall into two types. Three zones, described in this section, are clearly associated with faults, in that they cut across the dip of bedding, show stratigraphic displacement, host cataclasite zones, or contain slickensided surfaces. A further five zones, (section 8) lack these four criteria and are conformable with bedding dip as well as strike.

The best example of a strike-parallel thrust zone is at Tenby east (loc. 25, Fig. 9a), where the 19 km long Ritec Fault meets the coast. It dips steeply southward, with a reverse throw of about 450 m in the east of Pembrokeshire and 900 m in the west (Dixon, 1921). At Tenby a zone of crackle and mosaic breccia contains two 10-30 m wide thrust zones of cataclasite. Other possible thrust faults have lower displacements. At Barafundle Bay (loc. 11), a small south-dipping fault with chaotic and crackle breccia may be a minor limb thrust near a fold hinge (Dixon, 1921, p. 180).

The relative rarity of chaotic breccia and absence of megabreccia, along thrust faults is notable. It suggests that a dilational component to faults is necessary for megabreccia formation.

[Figure 9 about here]

8. Bedding sub-parallel breccias

By contrast with its absence in thrust zones, megabreccia is hosted in four out of five zones with contacts that parallel bedding dip as well as strike (Fig. 7). A typical zone at Nanna's Cave (loc. 29, Fig. 9b, c) has a central zone of chaotic megabreccia bordered by several metres of chaotic breccia. The flanking limestone beds, which dip about 80°, are scarcely brecciated, with just a 3m wide zone of crackle breccia within the northern wall, hosts an open angular kink fold of bedding (Fig. 9c).

Lydstep Point (loc. 16, Fig. 9d, g) and Whitesheet (loc. 15, Fig. 9d, e, f) are wider zones with the same basic geometry, including non-brecciated, but kinked wall rock south of the Whitesheet mass (Fig. 9e). The two breccia bodies do not appear to join up along strike, but are terminated by cross faults. The Whitesheet breccia is itself cut by later cross-strike faults, one hosting cataclasite. Although most margins of the five breccias zones in this category precisely parallel bedding, those at Trevallen (loc. 7, not illustrated) weakly transgress the bedding, particularly in the hangingwall. This is probably related to the lower bedding dips (40° to 70°) in this example.

The sharp planar contacts and the lack of brecciation in the adjacent limestones to the bedding-parallel breccia zones suggest that they formed by extension perpendicular to bedding rather than by shear parallel to it or solution within it. The angular kink folds at the margins of several zones indicate one way in which bedded limestone beds collapsed during extension. The amount of extension was small enough that it could dissipate in a short distance along strike or at a synchronous cross fault.

9. Irregular breccia masses

Four breccia zones have irregular margins, not obviously concordant with either bedding or faults (Fig. 7, bottom right). Incomplete exposure leaves open the possibility that some of their margins are more regular.

The largest such zone, at Bullslaughter west (loc. 2, Fig. 10a, b), maps out as an equidimensional pod of chaotic megabreccia, grading laterally into chaotic breccia. The southern and eastern margins are faulted, but with different fault strikes. Three separate breccia bodies are designated as Bullslaughter south (loc. 4, Fig. 10a). The northernmost body is an E-W matrix-rich megabreccia zone with a faulted northern margin. The central body comprises the crackle-brecciated, kaolinised cherty mudstones, termed saprolite by Walsh et al. (2008). The consensus is now that these are deeply weathered late Visean mudstones in the hinge zone of the Bullslaughter Bay Syncline (Dixon, 1921; Thomas, 1971; Walsh et al., 2008; Błażejowski and Walsh, 2013; Rowberry et al., 2014), with bedding obliterated by kaolinisation and brecciation. The southern breccia zone is of chaotic breccia and hematitic sand (Fig. 5f). The body has irregular contacts with the host limestones, transecting an anticline-syncline pair. This is the deposit already discussed (Section 4.7) in which the structures could either be interpreted as due to sedimentation and collapse into a void or as *in situ* weathering to give ghost karst .

[Figure 10 about here]

It is difficult to generalise from the breccia bodies with irregular margins, and it is possible that each of the examples at Bullslaughter Bay has contrasting origins. Irregular margins are characteristic of solutional processes, whether to form voids for subsequent breccia infill, to generate in situ brecciation by heterogeneous weathering, or to overprint earlier structures and textures. The good examples of solutional processes at Bullslaughter Bay contrast with the general paucity of such processes in other breccia zones in Pembrokeshire.

10. Geometric clues to megabreccia formation

Dixon (1921 p.158) and Walsh et al. (2008 p.139) regarded the clast fabric in the chaotic breccias as random. However, we observe a weak tendency for bedded slabs to have low dips, as for instance at St Margaret's Island (loc. 26, Fig. 4e), rather than the typical high dips of host bedrock sequences. This tendency has been tested at eight localities by plotting poles to slab bedding (Fig. 11) and computing the three eigenvectors of the orientation tensor, effectively the axes of maximum, minimum and intermediate concentration of the bedding poles. The distributions have not been rotated in any way, given the evidence that a) the conjugate subvertical cross-faults remain in the orientation in which they were formed, with their mutual intersection vertical and b) geopetal indicators in the breccias are still horizontal.

Using the test of Woodcock and Naylor (1983), all the distributions of poles are significantly non-random at the 99% confidence level, except Draught and Bullslaughter west, which are significant at the 95% level. The mean bedding poles mostly lie within 30° of vertical (Fig. 11d), indicating that the bedded slabs themselves lie within 30° of horizontal. Bullslaughter east and Giltar east show slightly higher mean dips, though with confidence areas that allow for 30° mean dips or less. Only at Draught, with a small sample size, do slabs show significantly higher dips.

If slabs had been aligned by shear strains parallel to the host fault or bedding plane, then the slabs would tend to align parallel to this controlling shear zone (Fig. 3b), indicated by the great circle on the stereoplots (Figs 11a, b, c). Actually, slabs tend to be oriented more perpendicular than parallel to the controlling zone. The tendency for the slabs to have low dips strongly suggests accumulation under gravity, by collapse of wall rock slabs into an open void formed by karstic solution (Fig. 3a) or, as suggested in this paper, by dilational faulting (Fig. 3c).

[Figure 11 about here]

11. Discussion

11.1. Karstic solution and collapse origin for chaotic breccias and megabreccias?

This discussion first compares the new observations from the Pembrokeshire breccia zones against the three main formation hypotheses (Walsh et al., 2008). The first comparison is with the original hypothesis of Dixon (1921) that the chaotic breccias and megabreccias represent collapse of the roof and walls of fissures formed by groundwater dissolution of Carboniferous limestone in the Triassic.

The present study has certainly found small (0.1 to 1 metre scale) irregular sediment-filled cavities within some breccia zones – for instance at Frank’s Shore (loc. 18) and Valleyfield East (loc. 20) – that can be ascribed to phreatic solution. However, our mapping has confirmed the observations of Thomas (1971) and Walsh et al. (2008) that the margins of the breccia zones lack fluted and scalloped solution surfaces. Instead they are either smooth bedding or fault planes, or grade out through mosaic and crackle breccia into intact limestone. Slickensided clasts are found within some breccias, but derived fluted surfaces are not.

Although karstic solution alone is an unlikely origin for the breccia-filled fissures, our measured sub-horizontal clast fabrics (Section 10, Fig. 11) are strong evidence for the second component of Dixon's (1921) hypothesis: gravitational collapse of blocks and slabs into an open void. We merely prefer a dilational tectonic origin for those voids. However, given the increased solubility of fractured limestone in acidic groundwater, such fault zones might naturally suffer localised solution.

Bullslaughter Bay (locs 2, 3, 4) has received recent attention (Walsh et al., 2008; Błażejowski and Walsh, 2013; Rowberry et al., 2014) because of a solutional overprint on earlier formed breccias. It is significant that none of the eleven other sites of deep weathering recorded by Rowberry et al. (2014) are associated with chaotic breccias, but rather occur in normally bedded limestones. We therefore regard the solutional overprint at Bullslaughter Bay as affecting breccias formed in the same way as elsewhere in Pembrokeshire: by dilational tectonics followed by collapse.

11.2. Phreatic explosion origin for chaotic breccias and megabreccias?

The second hypothesis is that of Walsh et al. (2008) that brecciation was due to phreatic explosion. Phreatic activity results from the interaction of magma with external water, creating overpressure that brecciates then erupts the country rock (Tămaş and Milési, 2003). However, their diagnostic criteria for phreatic brecciation do not match well the Pembrokeshire examples:-

1. Pembroke Group breccia bodies lack the typical shape of phreatic bodies: conical pipes, narrowing downwards, with irregular finger-like contacts. Rather, most bodies are planar

(Fig. 7), with only 4 out of 27 being irregular, and none being demonstrably conical. Many have at least some planar contacts.

2. Clasts in the studied breccias are mostly angular, whereas phreatic breccias typically have some rounded fragments.
3. The studied breccias lack the pervasive siliceous cementation and alteration characteristic of phreatic breccias.
4. The matrix in phreatic breccias is the fine-grained fraction from rock brecciation, necessarily deposited at the same time as the larger fragments. By contrast, much of the interclast matrix in the studied breccias is laminated (e.g. Fig. 5c, d) and therefore introduced after the clasts.

This evidence, together with the absence of the requisite magmatic heat source in this area, argues against the phreatic brecciation model.

11.3. Dilational faulting and collapse origin for chaotic breccias and megabreccias?

"Tectonic" hypotheses for Pembroke Group breccia formation were initiated by Thomas (1971) although he was unspecific about the process involved. We suggest that the chaotic breccias and megabreccias resulted from collapse of the walls and roofs of voids formed along dilational faults during regional extension. Minor solutional widening of the void is possible, but no evidence for large-volume solution has been observed. The collapse could have been at the same time as fault displacement, or could have happened between fault episodes. Evidence of polyphase brecciation and cementation is consistent with repeated displacement on some fault zones. Most interclast matrix infiltrated later from above, and residual void space was then filled by carbonate cement.

An important factor in the collapse hypothesis is that the final width of the breccia zone is predicted to be over three times the width of the primary fissure (Loucks, 1999). If the wall rocks have zero initial porosity and collapse into a planar void of width W_v, the final width of the breccia body W_b is given by $W_b = W_v/\Phi_b$, where Φ_b is the porosity of the collapse breccia. With a breccia porosity $\Phi_b = 0.3$, a 1 m aperture void would generate a 3.3 m thickness of chaotic breccia. Even a 1 metre wide void exceeds the likely average fault displacement in this area. Using an empirical determined fault displacement/length factor of 6.5×10^{-5} (Sibson, 1989; Scholz, 2002) Pembrokeshire faults of the order of 5 km would have a maximum displacement of 0.325 m. Wide zones of collapse breccia would require repeated fault displacements, evidenced by the observed polyphase brecciation and cementation.

Evidence for collapse into fault-induced voids is:-

1. Most of the breccia zones are related to cross-strike faults, marked by dilational crackle and mosaic breccias and by principal slip surfaces, some with low-plunge slickensides.
2. Clasts of crackle and mosaic breccia are common in the chaotic breccias, representing fragments of faulted wall rock collapsed into the fault void.
3. Slickensided clasts from the fault walls occur in the chaotic breccias.
4. The bedded slabs in the megabreccias tend to lie at low dips rather than parallel to margins of the breccia zone, precluding alignment due to zone-parallel fault shear.
5. Kinked bedding bordering some breccia zones shows one way in which wall rock collapsed into voids.

Dilational faulting is less compatible with megabreccia formation during Variscan shortening than during later regional extension. In Section 12.5 Below (section 12.5) we suggest a Triassic or later extension age, coeval with formation of the Bristol Channel Basin.

We deduce that dilation occurred on two main types of fault in response to north-south extension. *Dilational strike-slip faults* reactivated the conjugate Variscan faults striking NNE and NNW (Fig. 12a) (Thomas, 1971). For a 60° dihedral angle between faults, every metre of north-south extension across one of these faults would resolve into cos 30° = 0.87 metres of strike-slip and sin 30° = 0.5 metres of dilation. The east-west bedding-parallel breccia zones are seen as the steep segments of *dilational normal faults* opening perpendicular to regional north-south extension (Fig. 12b). We envisage them having listric geometry (Fig. 12c), so dipping less steeply at depth and maybe rooting into reactivated Variscan thrusts. Dilational normal faults are well understood (e.g. Ferrill and Morris, 2003) and have been postulated for sediment-filled fissures in the Pembroke Group of the Mendip Hills, 200 kilometres to the east (Wall and Jenkyns, 2004).

[Figure 12 about here]

Most examples of breccia-filled dilational normal faults (localities 15, 16, 26, 29) occur along the steep southern limb of the Pembroke Syncline. Clearly, bed-normal north-south extension will be greatest in these steeply-dipping beds. In moderately-dipping panels of stratigraphy, deep-seated normal faults probably propagated by bedding-plane slip, with less bed-normal dilation.

11.4. Objections to a "tectonic" origin for the megabreccia voids?

Walsh et al. (2008) have raised a number of objections to the tectonic origin of breccia-filled voids, which we now address.

1. A solutional origin for the voids explains why studied megabreccias are restricted to the Pembroke Limestone Group. Walsh et al. (2008) ask *why, if the voids are produced by faulting, are they "absent in the equally brittle rocks and complicated Variscan structures in the adjacent Old Red Sandstone outcrop?"* The same question can be extended to include the later Carboniferous Marros and Coal Measures groups. An answer is that, although all these units suffered the same Variscan deformation, they are not equally "brittle". The units above and below the Pembroke Limestone Group are dominated by sandstone and shale. Sandstones tend to be less well cemented than limestones, and therefore to have lower compressive strengths (70 rather than 100 Mpa), tensile strengths (5 rather than 10 MPa) and shear strengths (15 rather than 30 Mpa) (Waltham, 2002). The lower strength of the sandstones means that they tend to creep ductilely, that brittle fractures nucleate at closer spacings, and that any one fracture is less likely to produce a large void. The greater proportion of shale in the Old Red Sandstone and upper Carboniferous units further weakens them. The concentration of breccias within the the strong shale-poor lithologies in the Pembroke Group (Fig. 2) is predicted from other studies of fault rock control by mechanical stratigraphy (e.g. Ferrill and Morris, 2008; Woodcock et al., 2008)
2. *"Why are [megabreccia-filled voids] also absent in the Carboniferous Limestone outcrops west of the Flimston Fault, in SE Ireland and in the Gower Peninsula?"* In section 12.5, we argue that the void-forming event was the Triassic or later extension that formed the Bristol Channel Basin. Southeast Ireland is more remote from such Mesozoic basins, and the western end of the Pembroke Peninsula seems to have been just outside the zone of basin extension. The Gower Peninsula does have one megabreccia zone at Mewslade (Wright et al., 2009) and many other sediment- and vein-filled dilational faults.

3. *Why, if the breccia bodies "are largely controlled by the main-phase Variscan fold geometry" do the breccias not "follow the cross-faults and fold axes as sheet-like or wall-like bodies?"* We have shown that about 23 out of 30 mapped zones are indeed planar sheets. However some geometries are problematic, particularly the relationship of the Whitesheet and Lydstep Point breccia bodies (Fig. 9d) cited by Walsh et al. (2008). These masses involve collapse of two slightly different stratigraphic horizons, which we envisage as overlapping (Fig. 12b) or being separated by cross-strike transfer faults (Fig. 9c), like that cutting the Whitesheet mass.
4. We agree with Walsh et al. that the size and arrangement of the blocks in a megabreccia body such as Trevallen "implies a lodgement from free-fall conditions into a large pre-existing cavity and, as such, is incompatible with Thomas's origin by "rock-bursting in compressional zones". We differ from Thomas (1971) in proposing breccia formation during regional extension.

11.5. Regional pattern of dilational faulting

The conclusion that the chaotic breccias were due to fissure collapse during north-south extension begs the question of the age of this event. The geopetal matrix/cement contacts (Fig. 5c) show that fault fissure formation post-dated Variscan (late Carboniferous) folding, and predated a truncating Mid-Miocene planation surface (Walsh et al., 2008). Within this time window, evidence for polyphase breccia formation includes clasts of earlier breccia and their calcite cement, and successive cements of contrasting composition. However regional correlations with analogous extensional fracture systems consistently suggest a late Triassic to early Jurassic age.

[Figure 13 about here]

A map of southwest England and south Wales (Fig. 13) plots the location of extensional fracture systems associated with breccias, finer sediments or hydrothermal cements analogous to the Pembroke examples. All but the three southern sites are hosted in Pembroke Group, from Pembrokeshire to the Mendip Hills. The sites border or lie within the Mesozoic Bristol Channel Basin in four main groups.

The Gower Peninsula, about 30-50 km east of the Pembroke Peninsula, is crossed by the same conjugate strike-slip Variscan cross faults (George, 1940). These faults have also been reactivated in the Pembroke Group with a dilational component, and filled mostly with hematite-calcite veins and laminated red sediment (Wright et al., 2009). One locality (Mewslade, Fig. 14a) has a megabreccia similar to those of the Pembroke Peninsula. The age of the Gower fault fissures is unproven. Wright et al.(2009) suggested a late Variscan age, but we favour the Triassic age suggested by Strahan (1907) on the basis of supposedly Triassic red sandstones unconformably overlying the Pembroke Group at Port Eynon. A later age cannot be ruled out.

[Figure 14 about here]

The Vale of Glamorgan, about 20-60 km further east again, has a well-dated Triassic to Jurassic cover (Waters and Lawrence, 1987; Wilson et al., 1990) and underlying fissures in the Pembroke Group filled with red sandstone and mudstone (Fig. 13). Some fissures are notable for their vertebrate remains (Benton and Spencer, 1995). Whiteside and Marshall (2008) conclude that most of these fills and analogous examples around Bristol and the

Mendips are Rhaetian (latest Triassic). The tectonic setting of the Glamorgan examples is poorly understood, though most seem to be associated with dilational faults (Wilson et al., 1990; Wall and Jenkyns, 2004) with the same Variscan template as further west. No megabreccia has been described. Faults cutting Early Jurassic units are consistent with extension of the Bristol Channel Basin continuing at least till Late Jurassic (Glen et al., 2005) or Early Cretaceous (Holford et al., 2005) time.

The Mendip Hills lie 15-60 km ESE of Glamorgan, where the Bristol Channel Basin merges with the Wessex Basin (Fig. 13). The eastern Mendips contain sedimentary fissure fills descended from the contemporary land surface or sea bed, or derived from collapse of the fissure walls (Wall and Jenkyns, 2004). There are some chaotic breccias, but no megabreccias. The fills range through late Triassic and early Jurassic. Wall and Jenkyns make a strong case that the fissures are the steep segments of dilational normal faults rather than solution cavities. They deduce a roughly NE-SW maximum extension direction from the spread of late Triassic fissure directions. However, reactivated Variscan strike-slip cross faults have not been distinguished from east-west dip-slip faults, and the kinematic pattern may be simpler than Wall and Jenkyns suggest. Where the Mendip Hills meet the coast (Fig. 13, locations Bre, Wor & San), we have observed fault fissures with fills that include calcite-cemented crackle to chaotic breccia, bedded red sandstone, and bedded chaotic breccia (Fig. 14b). The fissures comprise both north-south cross faults and east-west dilational normal faults apparently reactivating north-dipping Variscan thrusts. Fissure sediments in boreholes south of the Mendips (Fig. 13, locations Can, Dar & Bru) are undated (e.g. Holloway and Chadwick, 1984).

The Bristol area, to the north of the Mendips, has sediment-filled fissures containing vertebrate remains (review by Whiteside and Marshall, 2008) at localities such as Tytherington, Cromhall and Durdham Down (Fig. 13). Whiteside and Marshall prefer a solutional origin for these fissures and a late Triassic age for the faunas. The fissures have more irregular margins than the Mendips examples, although some do follow E-W or NW-SE fractures. Boreholes at Beachley and Filton have red marl fissure fill below the Triassic unconformity (Whittard, 1947). A blue clay fissure fill at Lulsgate has a lower Sinemurian (Jurassic) fauna (Donovan, 1958).

In addition to the probable late Triassic fissure-fill sites associated with the Bristol Channel Basin, a fifth group, around *Torbay* occurs on the south-western fringe of the Wessex Basin (Fig. 13). These fills are hosted in Middle Devonian Torquay and Brixham Limestone formations. However, the fills include similar red sediment, sparry calcite and cemented or matrix-rich breccias (Fig. 14c) to those in the Pembroke Group. The Shoalstone example was studied in detail by Richter (1966). Matching fissure margins imply an origin as dilational fractures, and cross-cutting relationships between predominant ENE-striking and N-striking sets preclude a solutional origin. Our observations at the other two localities confirm these conclusions, though the main extensional fractures strike more ESE at Hope's Nose. The Triassic age for the sediment fill is based only on a lithological match with the unconformably overlying cover.

The conclusion from this regional survey is that dilational fractures at most localities on Figure 13, including Pembrokeshire, formed during Mesozoic extension of the Bristol Channel and Wessex basins. A latest Triassic (Rhaetian) age is favoured for the main extension and sediment fill, though extension probably continued at least till Early Cretaceous. Sand and mud from the Mesozoic land surface infiltrated down the extensional fractures and formed laminated fissure fills or matrix to limestone breccias derived by collapse of the fissure walls. Calcite and hematite were deposited from circulating fluids, probably sourced both hydrothermally and from groundwater.

12. Conclusions

1. The studied breccia zones each contain several of the following lithologies: crackle and mosaic breccia, chaotic breccia and megabreccia, laminated sediment and matrix, and carbonate cement.
2. Of the 30 localities described, 21 have significant bodies of chaotic breccia and 13 of megabreccia.
3. Of the 27 breccia examples with clear contacts, over half are related to cross-strike faults that originated as Variscan strike-slip faults. Five breccia zones parallel moderately to steeply dipping bedding, three zones parallel east-west thrust-faults, and the remaining four zones have irregular margins.
4. The margins of some of the fault-hosted chaotic breccias and of all the bedding-parallel breccias are sharp and match across the breccia zone, arguing for dilational faulting rather than a solutional origin.
5. Slickensides within cross-strike breccia zones and polyphase brecciation and cementation also favour the fault-related origin.
6. Megabreccia slabs tend to have low dips rather than to parallel the host-rock bedding or the breccia-zone margins. This geometry suggests collapse of the walls of open voids along the dilational faults.
7. Episodes of karstic weathering that overprint breccias at Bullslaughter Bay are not observed in other breccia zones, and are not the primary reason for their formation.
8. The structural template for the breccia zones was the Variscan (late Carboniferous) east-west folds and thrust faults and the strike-slip cross faults, all due to north-south shortening. The dilational faulting resulted from later north-south extension, reactivating

the cross-faults in transtension, and using the folded bedding for the steep dilational segments of listric normal faults.

9. The Pembroke Peninsula fissures have geometric analogues along-strike to the east, in Gower, Glamorgan, the Mendips and around Bristol. The eastern examples are due to late Triassic north-south extension of the Bristol Channel Basin, and this is proposed as the most likely age for the Pembrokeshire fissures.

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Figure captions

Fig. 1. a) Geological map of the Pembroke Peninsula, southwest Wales, with breccia localities discussed in the text. Map based on British Geological Survey (1977) but with the Flimston Bay Fault modified to join to the NNW with the easternmost Castlemartin Fault rather than the Freshwater West Fault. b) Location and geological context of main map

Fig. 2. Stratigraphic distribution of breccia in a) the St Florence and Pembroke Synclines and b) the Bullslaughter Bay Syncline. Key and scale (inset bottom right) applies to both areas.

Fig. 3. Schematic diagram of four types of breccia formation mechanism.

Fig. 4. Examples of breccia zone lithologies. a) crackle breccia, Proud Giltar (loc. 17); b) mosaic breccia, Giltar West (loc. 21); c) chaotic breccia, Bullslaughter east (loc. 3); d) chaotic megabreccia, Trevallen (loc. 7); e) chaotic megabreccia, St Margaret's Island (loc. 26); f) cataclasite, Stackpole Quay (loc. 12).

Fig. 5. Examples of cement and matrix infill to breccia bodies. a) blocky calcite(left) and elongate calcite (right), Valleyfield East (loc. 20); b) calcite spar ball, Whitesheet (loc. 15); c) laminated (catenary) sand/silt infill to breccia, Bullslaughter south (loc. 4); d) geopetal sediment and cement infill to breccia, Trevallen (loc. 7); e) catenary-bedded micrite, Draught Cove (loc. 14); f) either 'ghost karst' or bedded sediment with dropstones (see text), Bullslaughter south (loc. 4).

Fig. 6. Breccia zone characteristics and infill lithologies at each of the studied localities (numbered on Fig. 1), arranged by structural setting (see text).

Fig. 7. Triangular diagram of contact relations of the studied breccia bodies, as numbered on Fig. 1. End member geometries are illustrated by thumbnail geological maps.

Fig. 8. Maps and photographs of representative breccia zones related to vertical cross faults. a) and b) Raming Hole (loc. 10); c) and d) Stackpole Quay (loc 12); e) and f) Flimston (loc. 1). All photos taken looking north. Photos (b) and (f) were taken by Sid Howells.

Fig. 9. Maps and photos of strike-parallel breccia zones: a) Tenby east (loc. 25) (with the Tenby west, loc. 24, simple strike-slip zone); b) and c) Nanna's Cave (loc. 29); d-g) Whitesheet (loc. 15) and Lydstep Point (loc 16). Photos (c), (d) and (g) were taken looking west and photo (f) looking east. Photo (g) was taken by Sid Howells.

Fig. 10. a) Map of the breccia zones at Bullslaughter Bay west, east and south (locs 2, 3 & 4). b) and c) Photo-montages of Bullslaughter Bay west (b) and east (c). Photos were taken by Sid Howells.

Fig. 11. Lower hemisphere equal-area plots of poles to bedded slabs in a) cross-strike fault zones b) irregular zones, and c) bedding sub-parallel zones. Mean bedding poles and their 95% confidence areas are shown for each distribution, and d) aggregated on one comparison plot. e) The shape and strength of each distribution shown on a plot of the ratios of their eigenvalues (Woodcock, 1977).

Fig. 12. a) Diagrammatic map of folds and conjugate strike-slip faults formed by north-south Variscan shortening. b) Map of postulated post-Variscan north-south extensional reactivation of Variscan faults and steepened bedding. c) Cross-section across a dilational normal fault that steepens to parallel bedding at shallow depths.

Fig. 13. Map of the depositional limits and faults of the Mesozoic Bristol Channel Basin and the western end of the Wessex Basin, with localities of probable late Triassic fissure fills. Faults are from British Geological Survey (1996), and fissure localities mainly from Wall and Jenkyns (2004), Whiteside and Marshall (2008) and Wright et al. (2009).

Fig. 14. Field photographs of probable late Triassic fissure fills from other areas around the Bristol Channel and Wessex Basins (Fig. 13). a) Chaotic megabreccia, Mewslade, Gower Peninsula; b) Bedded chaotic breccia in dilational fault, Worlebury shore, Somerset; d) Sediment fills and calcite-hematite veins in Devonian limestone, Berry Head Quarry, Devon.

Figure 1

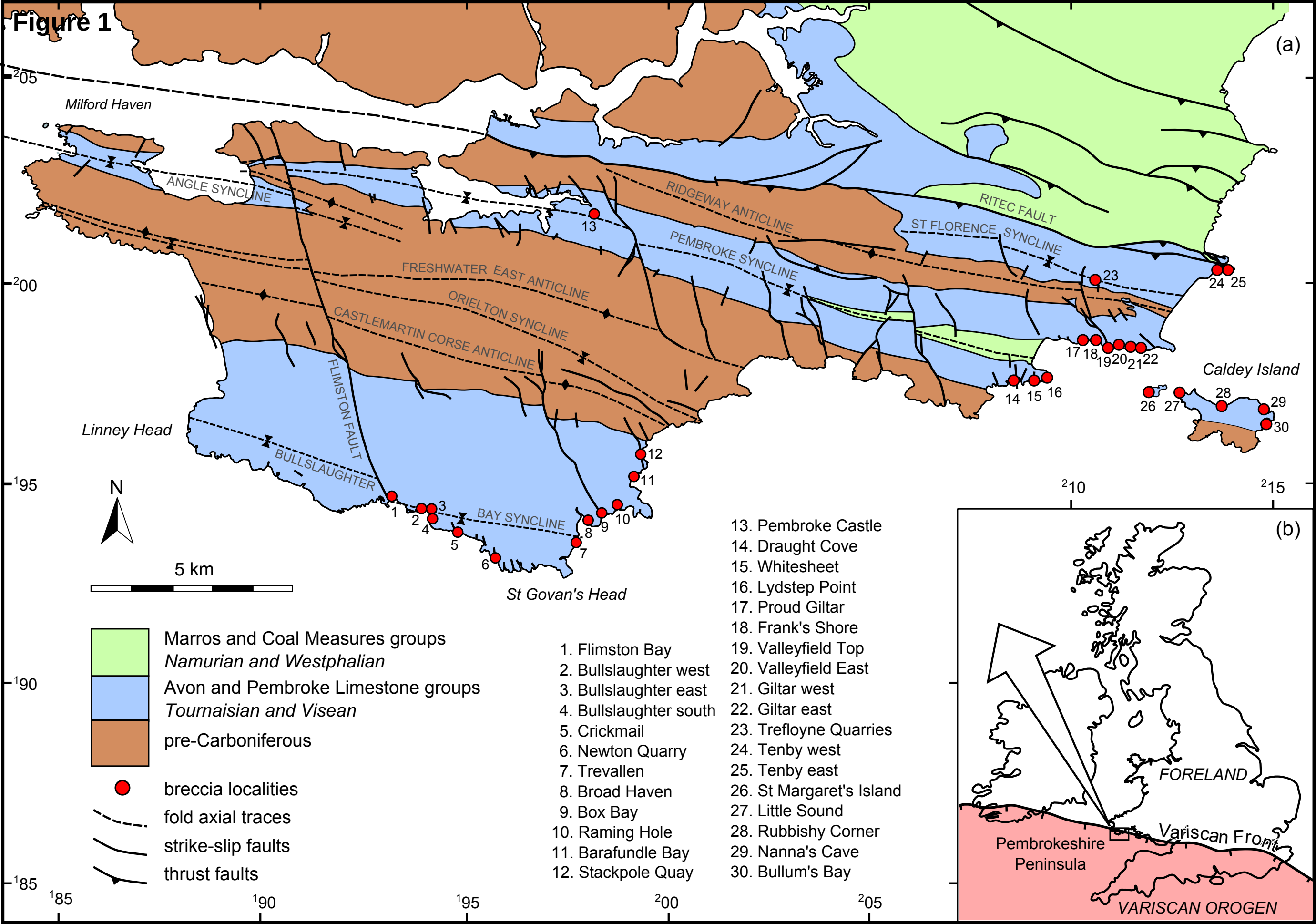

(a)
Milford Haven
ANGLE SYNCLINE
RIDGEWAY ANTICLINE
RITEC FAULT
ST FLORENCE SYNCLINE
PEMBROKE SYNCLINE
FRESHWATER EAST ANTICLINE
ORIELTON SYNCLINE
CASTLEMARTIN CORSE ANTICLINE
FLIMSTON FAULT
BULLSLAUGHTER
BAY SYNCLINE
Linney Head
St Govan's Head
Caldey Island
N
5 km
205
200
195
190
185
185
190
195
200
205
210
215
Marros and Coal Measures groups
Namurian and Westphalian
Avon and Pembroke Limestone groups
Tournaisian and Visean
pre-Carboniferous
breccia localities
fold axial traces
strike-slip faults
thrust faults
1. Flimston Bay
2. Bullslaughter west
3. Bullslaughter east
4. Bullslaughter south
5. Crickmail
6. Newton Quarry
7. Trevallen
8. Broad Haven
9. Box Bay
10. Raming Hole
11. Barafundle Bay
12. Stackpole Quay
13. Pembroke Castle
14. Draught Cove
15. Whitesheet
16. Lydstep Point
17. Proud Giltar
18. Frank's Shore
19. Valleyfield Top
20. Valleyfield East
21. Giltar west
22. Giltar east
23. Trefloyne Quarries
24. Tenby west
25. Tenby east
26. St Margaret's Island
27. Little Sound
28. Rubbishy Corner
29. Nanna's Cave
30. Bullum's Bay
(b)
FORELAND
Variscan Front
Pembrokeshire
Peninsula
VARISCAN OROGEN

Figure 2

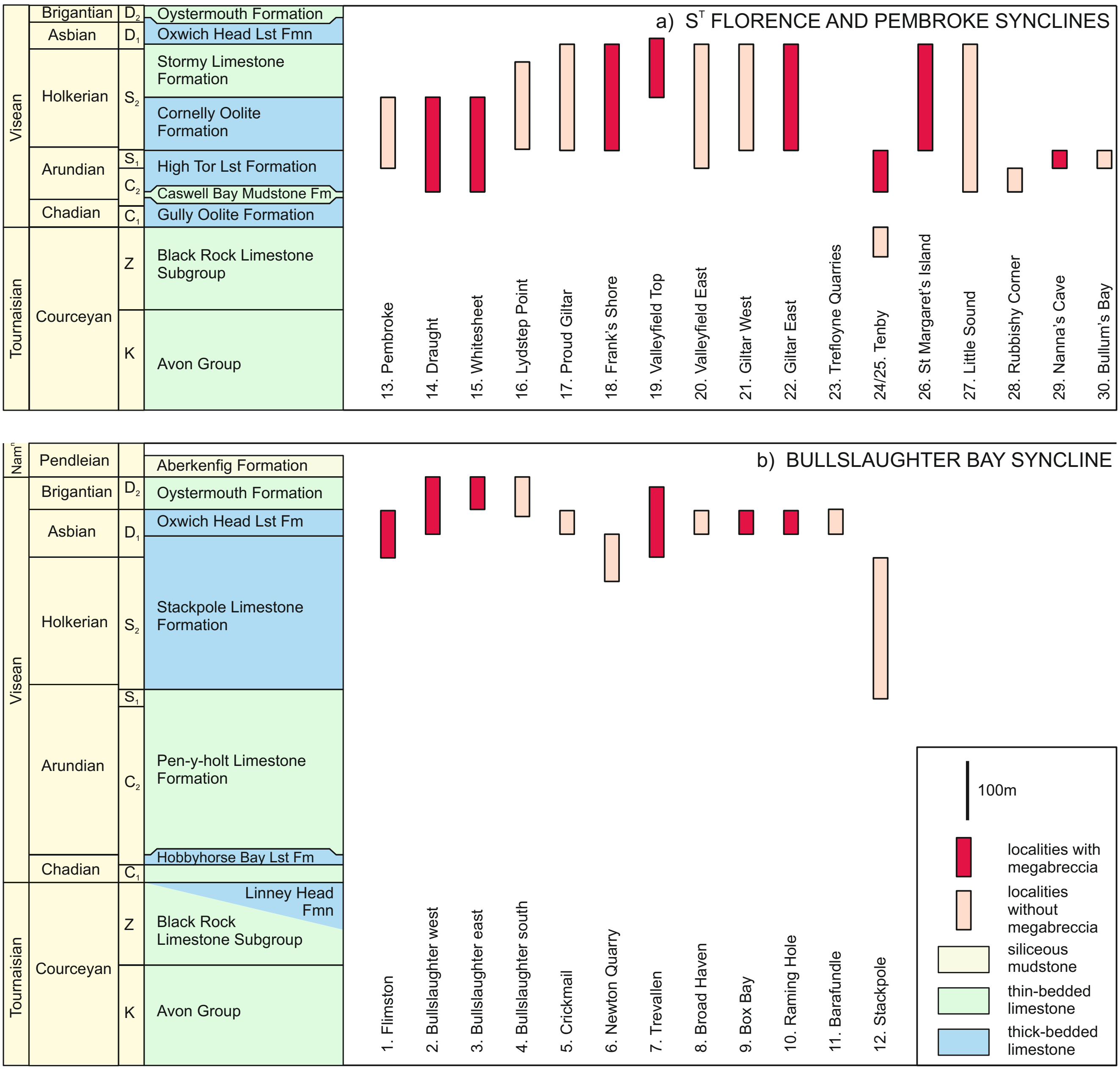
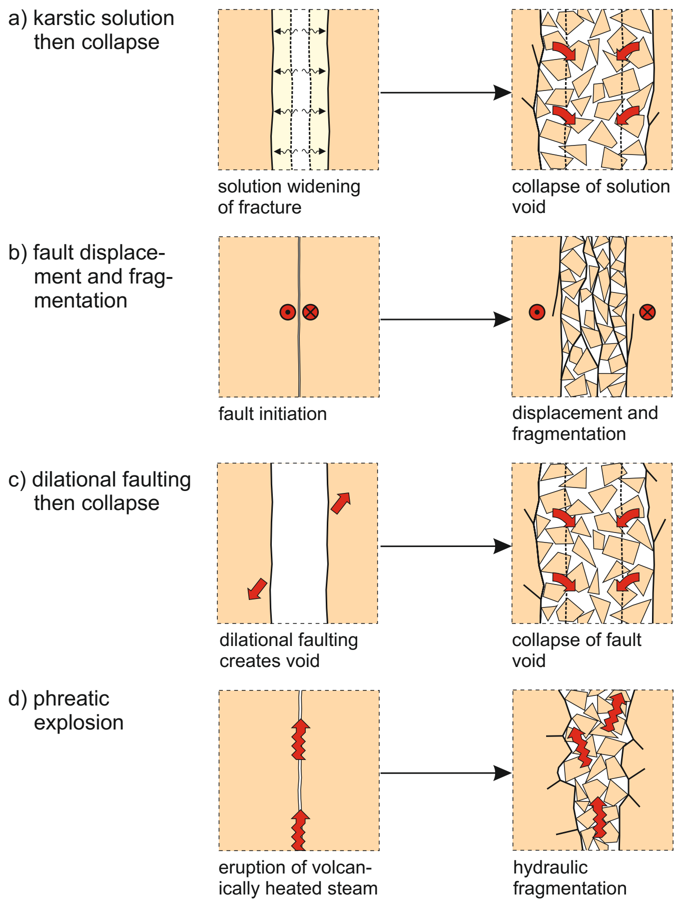

a) S^T FLORENCE AND PEMBROKE SYNCLINES
Visean
Tournaisian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan
D2
D1
S2
S1
C2
C1
Z
K
Oystermouth Formation
Oxwich Head Lst Fmn
Stormy Limestone Formation
Cornelly Oolite Formation
High Tor Lst Formation
Caswell Bay Mudstone Fm
Gully Oolite Formation
Black Rock Limestone Subgroup
Avon Group
13. Pembroke
14. Draught
15. Whitesheet
16. Lydstep Point
17. Proud Giltar
18. Frank's Shore
19. Valleyfield Top
20. Valleyfield East
21. Giltar West
22. Giltar East
23. Trefloyne Quarries
24/25. Tenby
26. St Margaret's Island
27. Little Sound
28. Rubbishy Corner
29. Nanna's Cave
30. Bullum's Bay
b) BULLSLAUGHTER BAY SYNCLINE
Nam^n
Visean
Tournaisian
Pendleian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan
D2
D1
S2
S1
C2
C1
Z
K
Aberkenfig Formation
Oystermouth Formation
Oxwich Head Lst Fm
Stackpole Limestone Formation
Pen-y-holt Limestone Formation
Hobbyhorse Bay Lst Fm
Linney Head Fmn
Black Rock Limestone Subgroup
Avon Group
1. Flimston
2. Bullslaughter west
3. Bullslaughter east
4. Bullslaughter south
5. Crickmail
6. Newton Quarry
7. Trevallen
8. Broad Haven
9. Box Bay
10. Raming Hole
11. Barafundle
12. Stackpole
100m
localities with megabreccia
localities without megabreccia
siliceous mudstone
thin-bedded limestone
thick-bedded limestone

Figure 3



a) karstic solution
then collapse
solution widening
of fracture
collapse of solution
void
b) fault displace-
ment and frag-
mentation
fault initiation
displacement and
fragmentation
c) dilational faulting
then collapse
dilational faulting
creates void
collapse of fault
void
d) phreatic
explosion
eruption of volcan-
ically heated steam
hydraulic
fragmentation

Figure 4

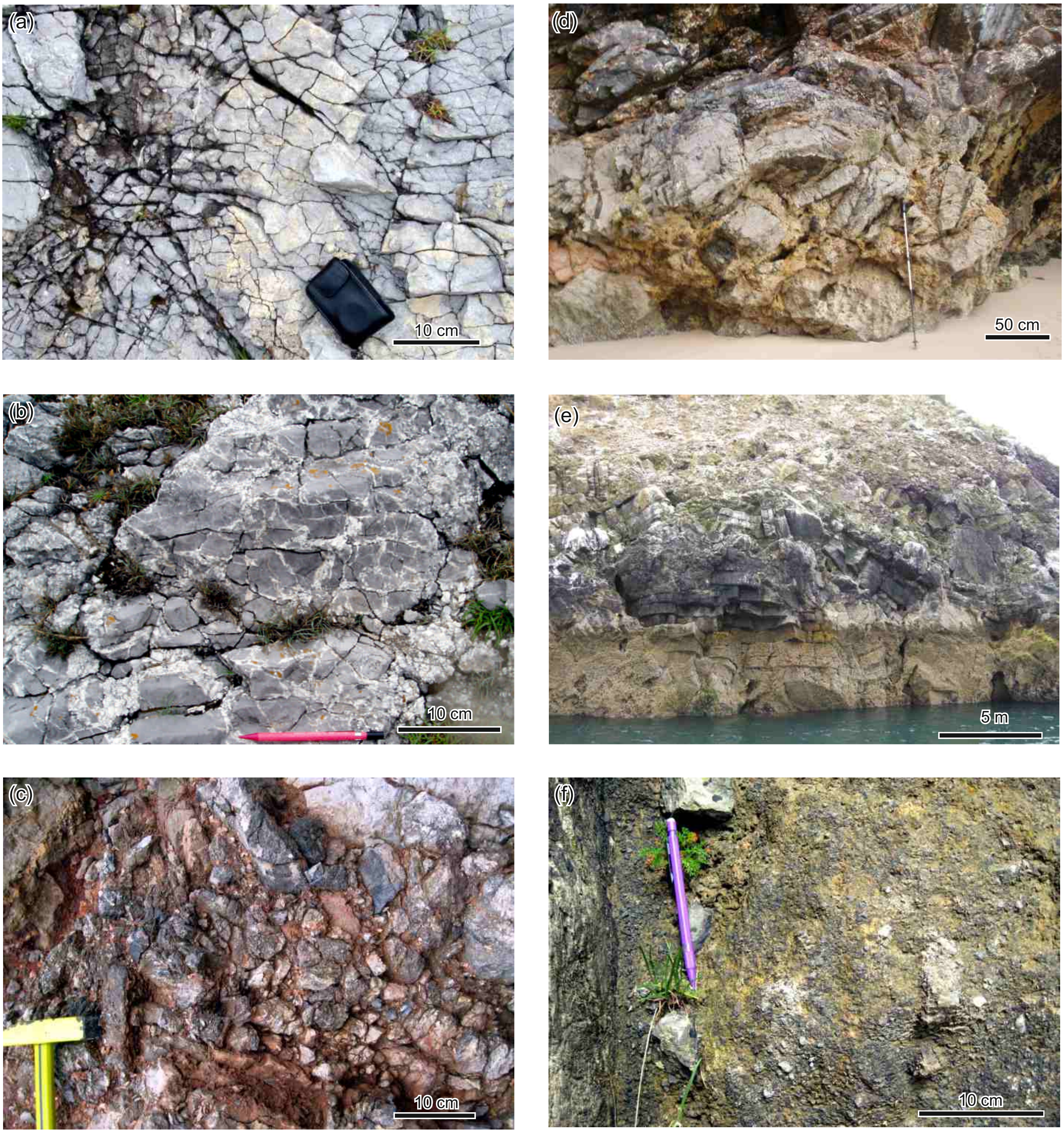


Figure 5

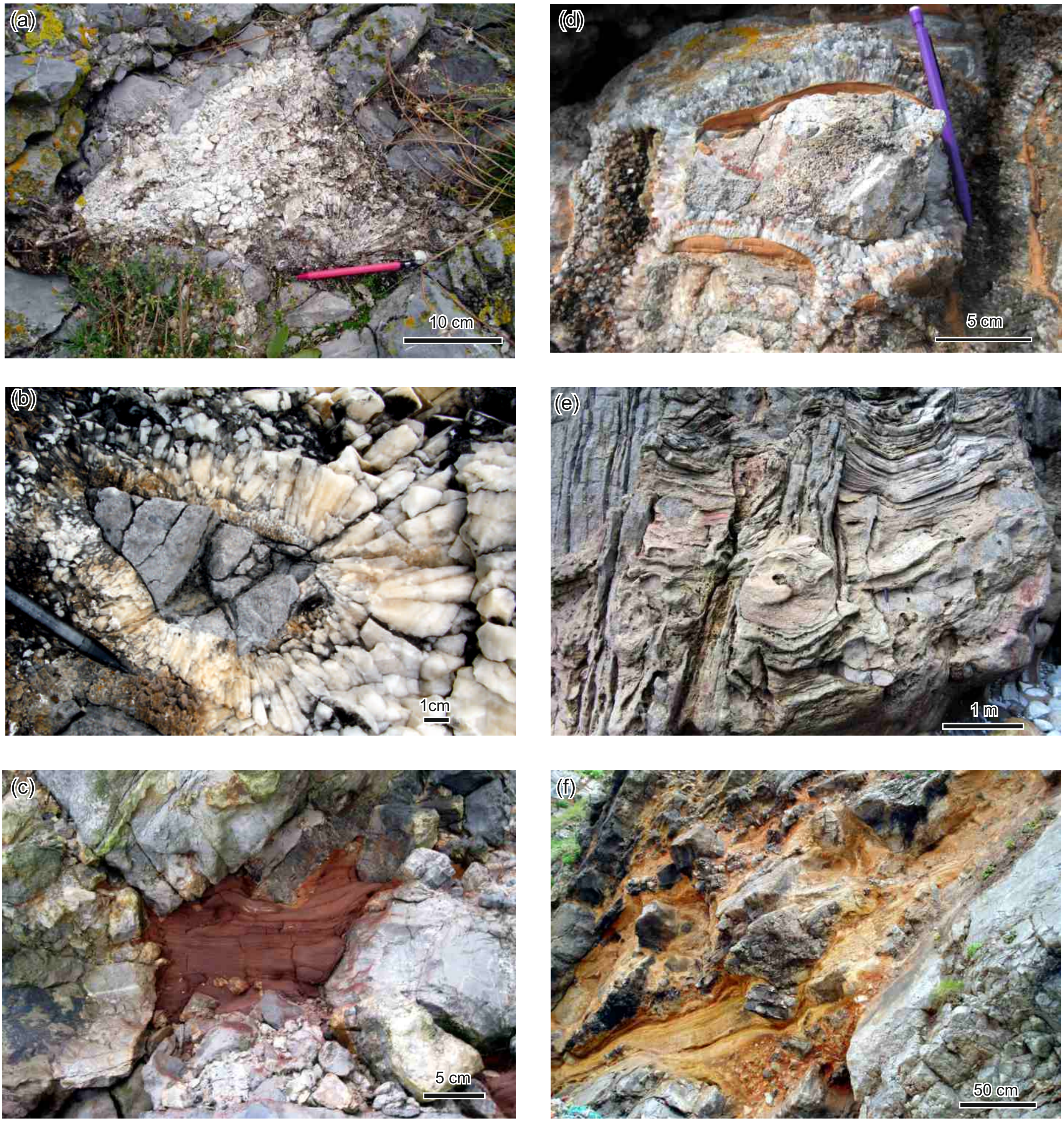


Figure 6

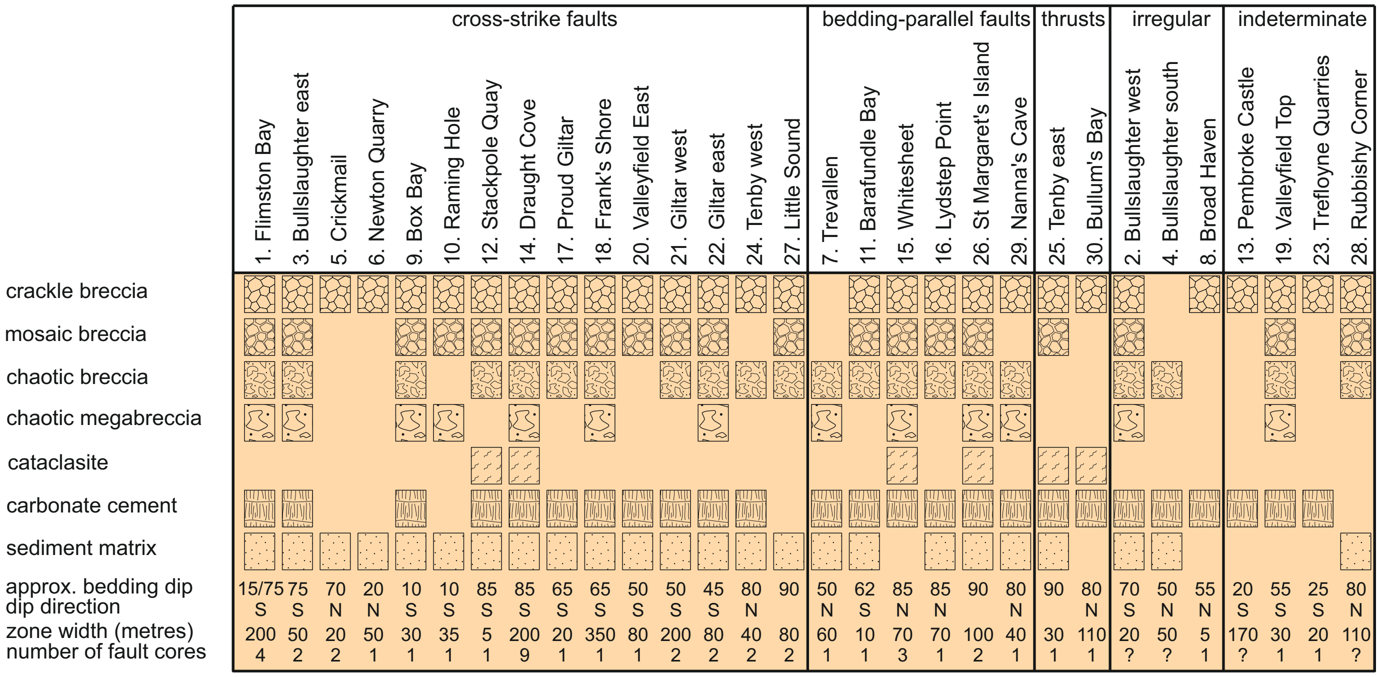
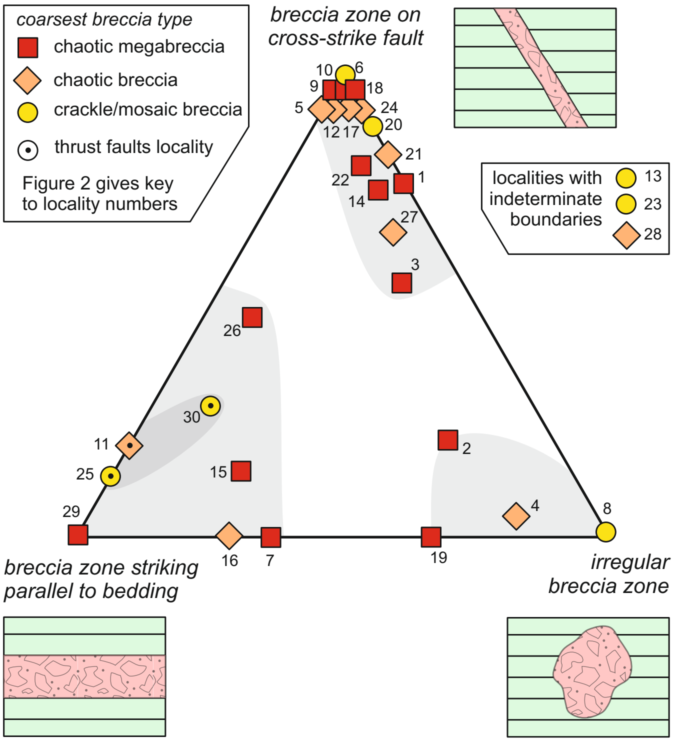

cross-strike faults
bedding-parallel faults
thrusts
irregular
indeterminate
1. Flimston Bay
3. Bullslaughter east
5. Crickmail
6. Newton Quarry
9. Box Bay
10. Raming Hole
12. Stackpole Quay
14. Draught Cove
17. Proud Giltar
18. Frank's Shore
20. Valleyfield East
21. Giltar west
22. Giltar east
24. Tenby west
27. Little Sound
7. Trevallen
11. Barafundle Bay
15. Whitesheet
16. Lydstep Point
26. St Margaret's Island
29. Nanna's Cave
25. Tenby east
30. Bullum's Bay
2. Bullslaughter west
4. Bullslaughter south
8. Broad Haven
13. Pembroke Castle
19. Valleyfield Top
23. Trefloyne Quarries
28. Rubbishy Corner
crackle breccia
mosaic breccia
chaotic breccia
chaotic megabreccia
cataclasite
carbonate cement
sediment matrix
approx. bedding dip
dip direction
zone width (metres)
number of fault cores
15/75 75 70 20 10 10 85 85 65 65 50 50 45 80 90 50 62 85 85 90 80 90 80 70 50 55 20 55 25 80
S S N N S S S S S S S S S N N S N N N N S N N S S S N
200 50 20 50 30 35 5 200 20 350 80 200 80 40 80 60 10 70 70 100 40 30 110 20 50 5 170 30 20 110
4 2 2 1 1 1 1 9 1 1 1 2 2 2 2 1 1 3 1 2 1 1 1 ? ? 1 ? 1 1 ?

Figure 7


coarsest breccia type
chaotic megabreccia
chaotic breccia
crackle/mosaic breccia
thrust faults locality
Figure 2 gives key to locality numbers
breccia zone on cross-strike fault
localities with indeterminate boundaries
13
23
28
breccia zone striking parallel to bedding
irregular breccia zone
10
6
9
18
5
24
12
17
20
21
22
1
14
27
3
26
30
11
25
15
2
4
8
29
16
7
19

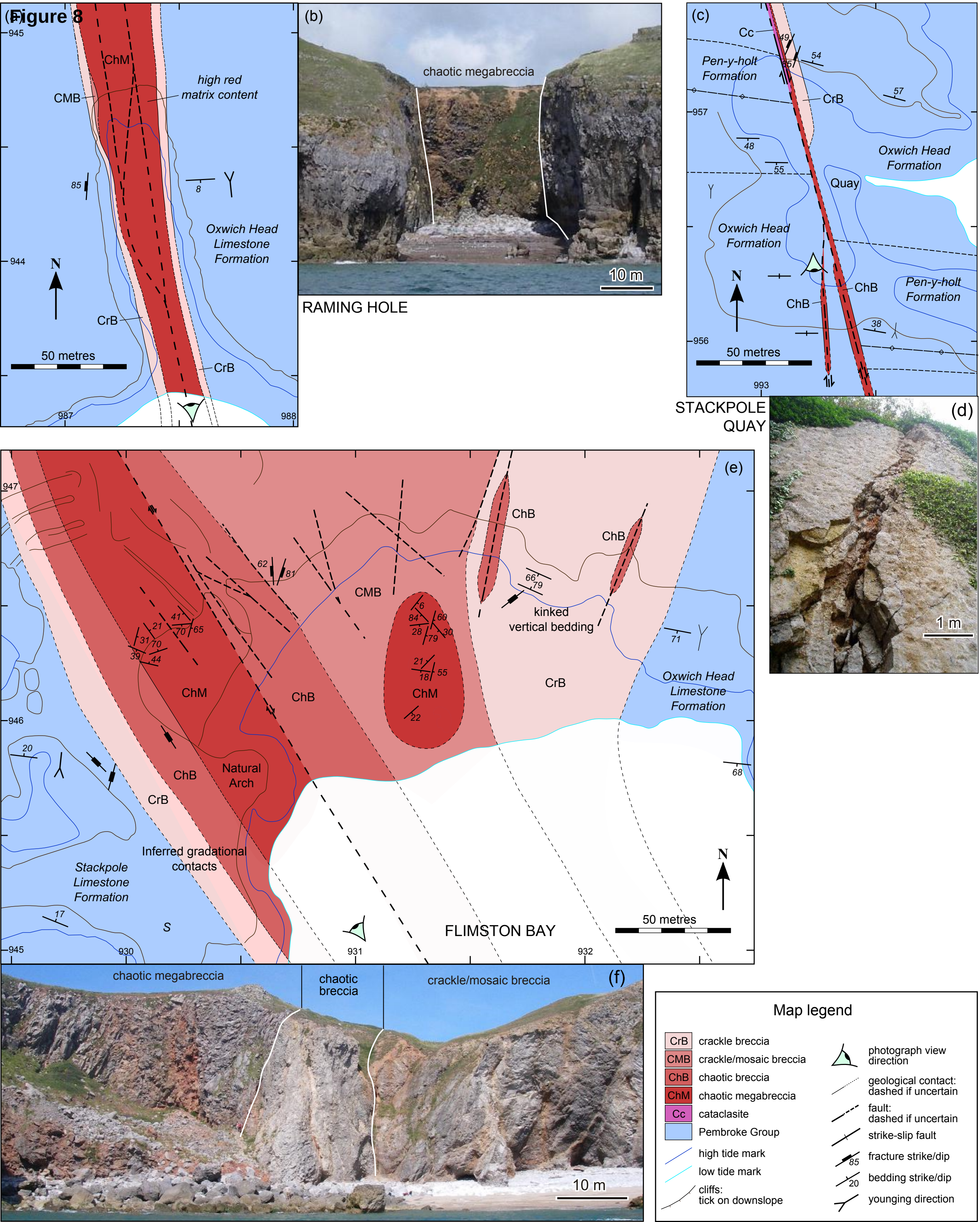


Figure 8
(a)
ChM
CMB
high red matrix content
CrB
Oxwich Head Limestone Formation
50 metres
(b)
chaotic megabreccia
10 m
RAMING HOLE
(c)
Cc
Pen-y-holt Formation
CrB
Oxwich Head Formation
Quay
ChB
50 metres
STACKPOLE QUAY
(d)
1 m
(e)
ChB
CMB
ChM
kinked vertical bedding
CrB
Oxwich Head Limestone Formation
Natural Arch
Inferred gradational contacts
Stackpole Limestone Formation
FLIMSTON BAY
50 metres
(f)
chaotic megabreccia
chaotic breccia
crackle/mosaic breccia
10 m
Map legend
CrB crackle breccia
CMB crackle/mosaic breccia
ChB chaotic breccia
ChM chaotic megabreccia
Cc cataclasite
Pembroke Group
high tide mark
low tide mark
cliffs: tick on downslope
photograph view direction
geological contact: dashed if uncertain
fault: dashed if uncertain
strike-slip fault
fracture strike/dip
bedding strike/dip
younging direction

Figure 9

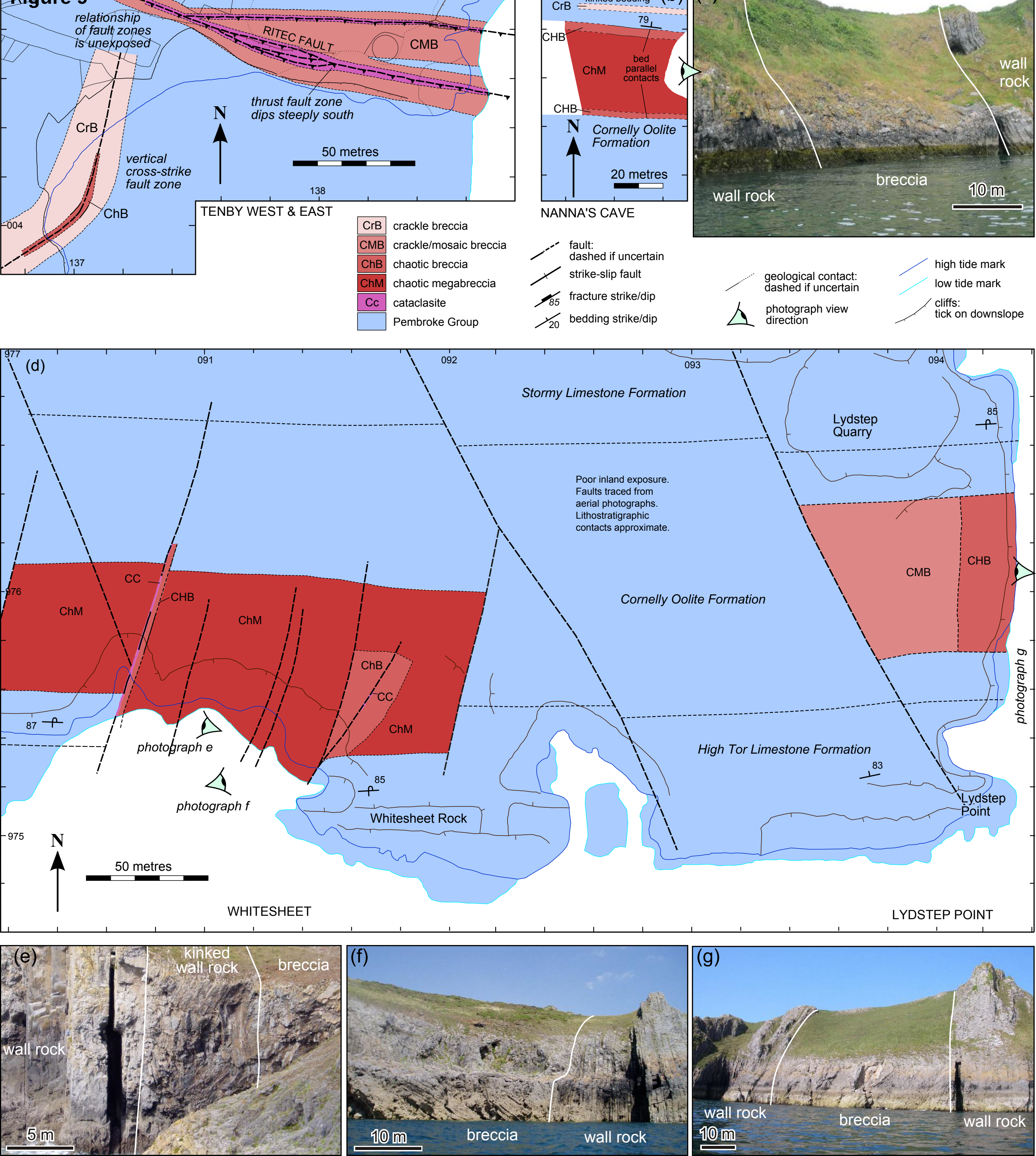
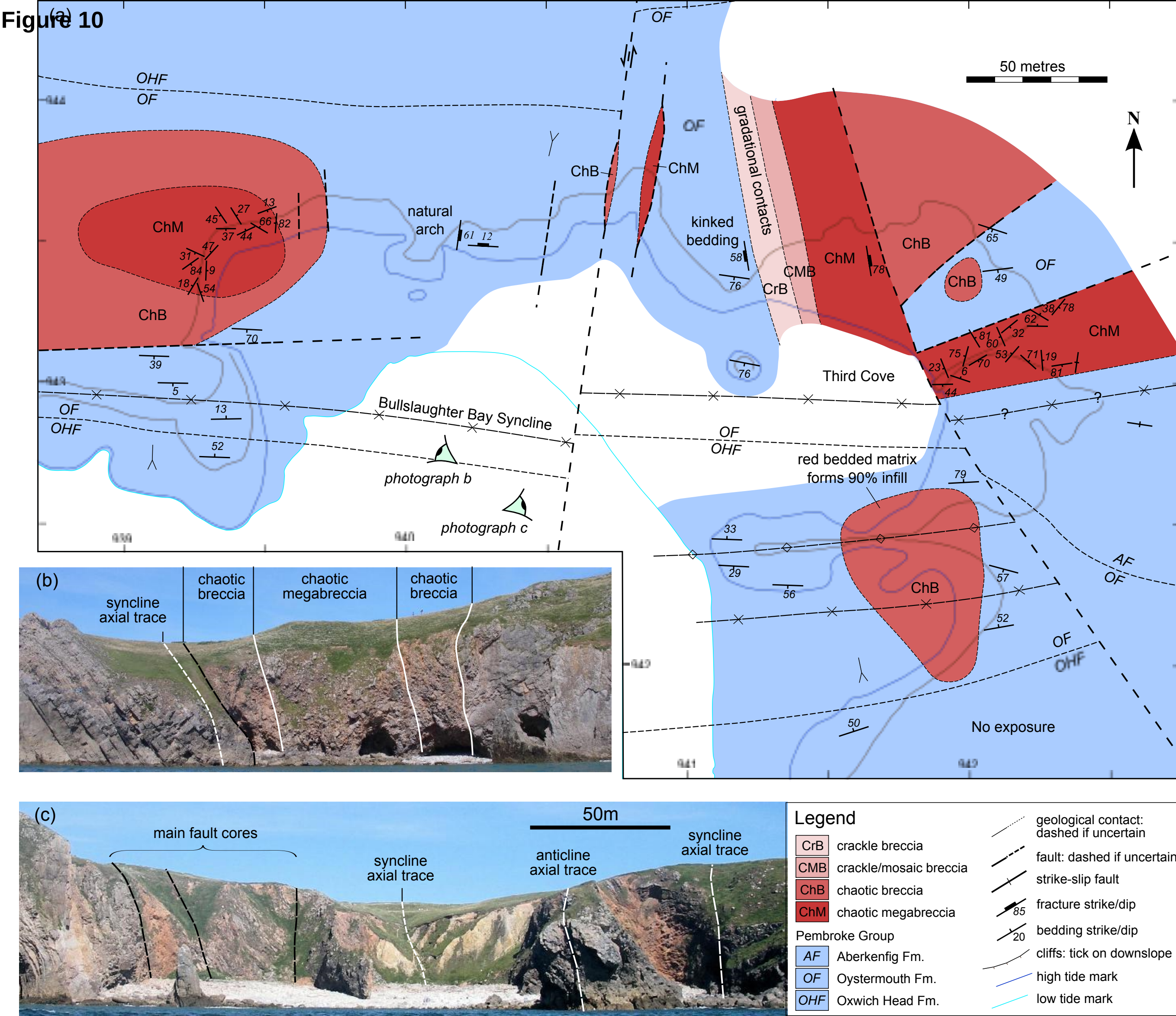

(a)
relationship of fault zones is unexposed
RITEC FAULT
CMB
thrust fault zone dips steeply south
CrB
vertical cross-strike fault zone
ChB
50 metres
TENBY WEST & EAST
(b)
146
kinked bedding
CrB
CHB
ChM
bed parallel contacts
CHB
Cornelly Oolite Formation
20 metres
NANNA'S CAVE
(c)
wall rock
breccia
wall rock
10 m
CrB crackle breccia
CMB crackle/mosaic breccia
ChB chaotic breccia
ChM chaotic megabreccia
Cc cataclasite
Pembroke Group
fault: dashed if uncertain
strike-slip fault
fracture strike/dip
bedding strike/dip
geological contact: dashed if uncertain
photograph view direction
high tide mark
low tide mark
cliffs: tick on downslope
(d)
Stormy Limestone Formation
Lydstep Quarry
Poor inland exposure. Faults traced from aerial photographs. Lithostratigraphic contacts approximate.
CMB
CHB
CC
ChM
CHB
ChB
CC
Cornelly Oolite Formation
High Tor Limestone Formation
photograph e
photograph f
photograph g
Whitesheet Rock
Lydstep Point
50 metres
WHITESHEET
LYDSTEP POINT
(e)
wall rock
kinked wall rock
breccia
5 m
(f)
10 m
breccia
wall rock
(g)
wall rock
breccia
wall rock
10 m

Figure 10



(a)
OHF
OF
50 metres
N
ChM
ChB
natural arch
kinked bedding
gradational contacts
CMB
CrB
Third Cove
Bullslaughter Bay Syncline
photograph b
photograph c
red bedded matrix forms 90% infill
No exposure
AF
(b)
syncline axial trace
chaotic breccia
chaotic megabreccia
chaotic breccia
(c)
main fault cores
syncline axial trace
anticline axial trace
50m
syncline axial trace
Legend
CrB crackle breccia
CMB crackle/mosaic breccia
ChB chaotic breccia
ChM chaotic megabreccia
Pembroke Group
AF Aberkenfig Fm.
OF Oystermouth Fm.
OHF Oxwich Head Fm.
geological contact: dashed if uncertain
fault: dashed if uncertain
strike-slip fault
fracture strike/dip
bedding strike/dip
cliffs: tick on downslope
high tide mark
low tide mark

Figure 11

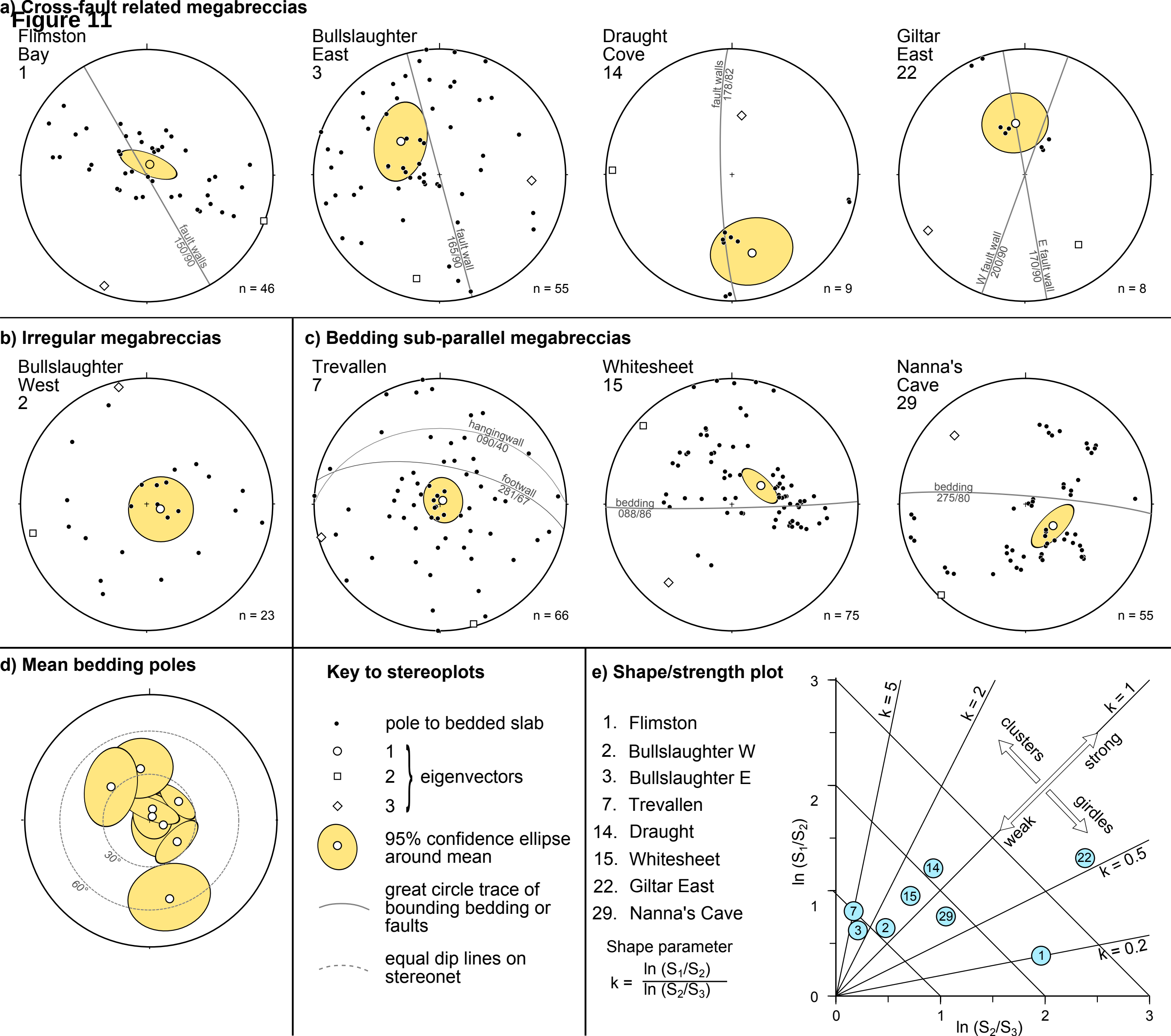

a) Cross-fault related megabreccias
Flimston Bay 1
fault walls 150/90
n = 46
Bullslaughter East 3
fault wall 165/90
n = 55
Draught Cove 14
fault walls 178/82
n = 9
Giltar East 22
W fault wall 200/90
E fault wall 170/90
n = 8
b) Irregular megabreccias
Bullslaughter West 2
n = 23
c) Bedding sub-parallel megabreccias
Trevallen 7
hangingwall 090/40
footwall 281/67
n = 66
Whitesheet 15
bedding 088/86
n = 75
Nanna's Cave 29
bedding 275/80
n = 55
d) Mean bedding poles
30°
60°
Key to stereoplots
pole to bedded slab
1
2
3
eigenvectors
95% confidence ellipse around mean
great circle trace of bounding bedding or faults
equal dip lines on stereonet
e) Shape/strength plot
1. Flimston
2. Bullslaughter W
3. Bullslaughter E
7. Trevallen
14. Draught
15. Whitesheet
22. Giltar East
29. Nanna's Cave
Shape parameter
$k = \frac{\ln(S_1/S_2)}{\ln(S_2/S_3)}$
k = 5
k = 2
k = 1
k = 0.5
k = 0.2
clusters
strong
girdles
weak
$\ln(S_1/S_2)$
$\ln(S_2/S_3)$
0
1
2
3
7
3
2
15
14
29
22
1

Figure 12

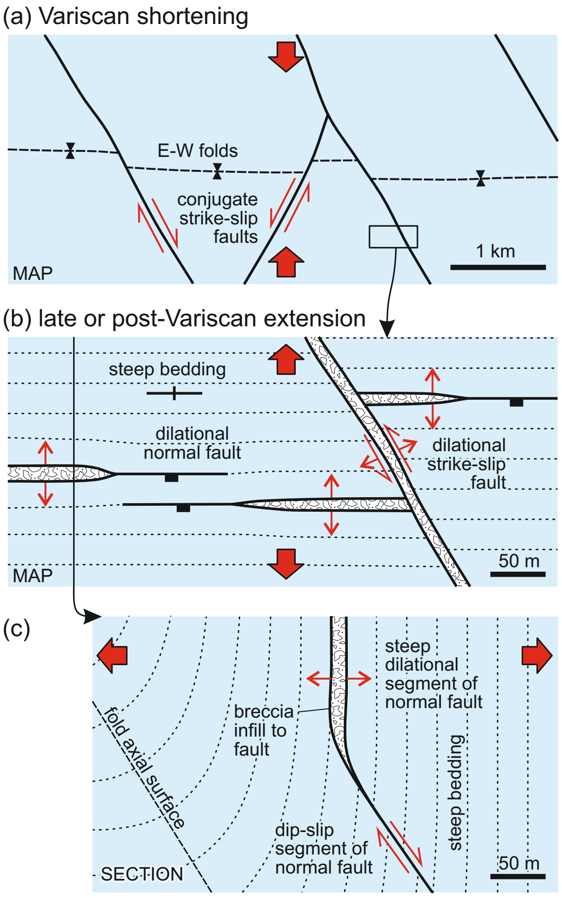
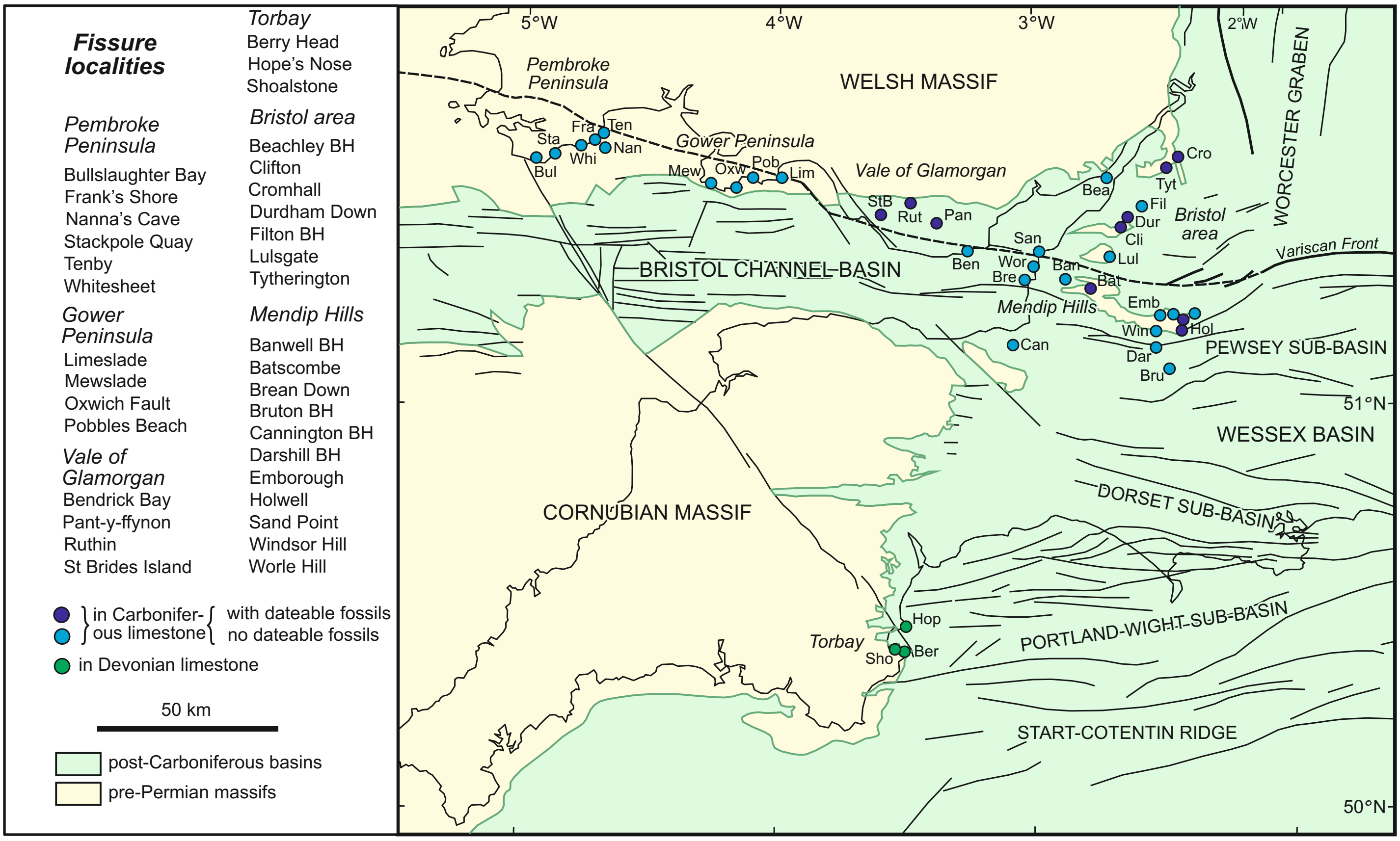

(a) Variscan shortening
E-W folds
conjugate
strike-slip
faults
MAP
1 km
(b) late or post-Variscan extension
steep bedding
dilational
normal fault
dilational
strike-slip
fault
MAP
50 m
(c)
steep
dilational
segment of
normal fault
breccia
infill to
fault
fold axial surface
steep bedding
dip-slip
segment of
normal fault
SECTION
50 m

Figure 13



Fissure localities
Pembroke Peninsula
Bullslaughter Bay
Frank's Shore
Nanna's Cave
Stackpole Quay
Tenby
Whitesheet
Gower Peninsula
Limeslade
Mewslade
Oxwich Fault
Pobbles Beach
Vale of Glamorgan
Bendrick Bay
Pant-y-ffynon
Ruthin
St Brides Island
Torbay
Berry Head
Hope's Nose
Shoalstone
Bristol area
Beachley BH
Clifton
Cromhall
Durdham Down
Filton BH
Lulsgate
Tytherington
Mendip Hills
Banwell BH
Batscombe
Brean Down
Bruton BH
Cannington BH
Darshill BH
Emborough
Holwell
Sand Point
Windsor Hill
Worle Hill
in Carboniferous limestone
with dateable fossils
no dateable fossils
in Devonian limestone
50 km
post-Carboniferous basins
pre-Permian massifs
5°W
4°W
3°W
2°W
51°N
50°N
WELSH MASSIF
CORNUBIAN MASSIF
BRISTOL CHANNEL BASIN
WESSEX BASIN
PEWSEY SUB-BASIN
DORSET SUB-BASIN
PORTLAND-WIGHT SUB-BASIN
START-COTENTIN RIDGE
WORCESTER GRABEN
Variscan Front
Pembroke Peninsula
Gower Peninsula
Vale of Glamorgan
Bristol area
Mendip Hills
Torbay
Sta
Fra
Ten
Whi
Nan
Bul
Mew
Oxw
Pob
Lim
StB
Rut
Pan
Ben
San
Wor
Bre
Ban
Bat
Bea
Cro
Tyt
Fil
Dur
Cli
Lul
Emb
Win
Hol
Dar
Bru
Can
Hop
Sho
Ber

Figure 14