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Journal of Structural Geology xx (xxxx) 1–19
JOURNAL OF STRUCTURAL GEOLOGY
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Partitioned transtension: an alternative to basin inversion models

N. De Paola[a,b,*], R.E. Holdsworth[a], K.J.W. McCaffrey[a], M.R. Barchi[b]

[a]*Reactivation Research Group, Department of Earth Sciences, University of Durham, Durham DH1 3LE, UK*
[b]*Gruppo di Geologia Strutturale e Geofisica, Dipartimento di Scienze della Terra, University of Perugia, Perugia 06100, Italy*

Received 17 July 2004; received in revised form 17 January 2005; accepted 25 January 2005

Abstract

'Inversion structures' (e.g. folds, reverse faults) spatially associated with basin-bounding faults are very widely recognised in rift basins in both onshore and offshore settings worldwide. The great majority of such structures are attributed to local or regional crustal shortening events. There is, however, an alternative, which is investigated in this paper: inversion could reflect a horizontal shortening component of deformation formed during progressive and partitioned transtension. A case study from the Carboniferous Northumberland Basin shows that shortening structures can also form in obliquely divergent rifts if the bulk strain undergoes kinematic partitioning into distinct regions of wrench- and extension-dominated transtension. Such strain partitioning appears to be particularly favoured in basins where fault localisation is strongly influenced by pre-existing basement structures. This may occur because the pre-existing anisotropies are zones of long-lived weakness that lie in an orientation particularly favourable to the preferential accommodation of either strike-slip or dip-slip displacements. Our strain analysis applied to the Northumberland Basin, traditionally considered as a classic example of a Variscan inverted basin, reduces the deformation history to a single kinematically partitioned phase of dextral transtension during the late Carboniferous–early Permian. Our findings have profound implications for the interpretation of inversion structures in any rift basin where the direction of extension may be significantly oblique to the basin margins.

Keywords: Transtension; Basin tectonics; Inversion; Strain partitioning; Carboniferous

1. Introduction

It has long been recognised that many regions of rift-related deformation will experience directions of divergence that are significantly oblique to the main basin-bounding faults, i.e. bulk transtensional strain (Fig. 1) (Harland, 1971; Withjack and Jamison, 1986; Woodcock, 1986; Smith and Durney, 1992; Dewey et al., 1998; Dewey, 2002). Such 3-D (non-plane strain) non-coaxial strains can arise when the causative plate separation is oblique to the plate boundary and/or when basin-bounding or intrabasinal faults reactivate pre-existing structures that lie at an oblique angle to the regional direction of extension. The first case is adequately described using a homogeneous transtension model (Sanderson and Marchini, 1984; Dewey et al., 1998) (Fig. 1a). In contrast, the second scenario can give rise to a partitioned transtension where the bulk strain is split up into kinematically distinct and subparallel structural domains whose location and orientation is controlled by pre-existing anisotropies in the crustal basement such as lithological contacts, faults and shear zones (Tikoff and Teyssier, 1994; Jones and Tanner, 1995; Jones et al., 2004) (Fig. 1b). Thus, components of wrench simple shear (Jones and Tanner, 1995) or dip-slip extension (De Paola et al., 2005) may be preferentially taken up along pre-existing planar structures, or within narrow zones, leaving residual components of strain to be accommodated within the adjacent country rock domains (e.g. Fig. 1b).

Transtensional (and transpressional) strains are characterised by complex relationships between finite and infinitesimal strain (≡stress) axes. In zones with low to high angles of divergence ($20° < \alpha < 90°$), where α is the angle between regional displacement and boundary faults (assuming an ideal incompressible material with a Poisson's ratio $\nu = 0.5$; McCoss, 1986; Dewey et al., 1998; De Paola et al., 2005), the axes of infinitesimal (z) and finite shortening (Z') should always be coincident and vertical

* Corresponding author
E-mail addresses: depaola@unipg.it (N. De Paola), R.E.Holdsworth@durham.ac.uk (R.E. Holdsworth).

0191-8141/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.jsg.2005.01.006

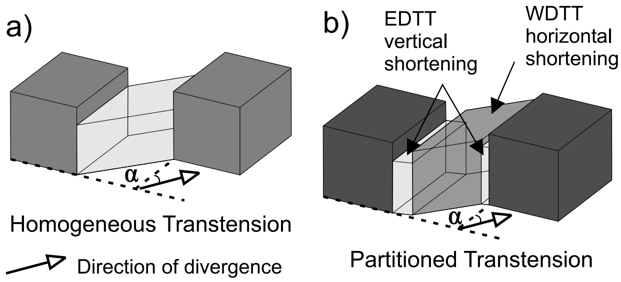

Fig. 1. (a) Homogeneous transtension. (b) Partitioned transtension, with a central wrench-dominated domain (WDTT; horizontal infinitesimal shortening) and adjacent extension-dominated domains (EDTT; vertical infinitesimal shortening). Other domain configurations are possible provided their boundaries are parallel to the regional boundaries of the deformation zone.

('extension-dominated transtension' (EDTT); Figs. 1b and 2a–c). However, at low angles of divergence ($\alpha<20°$), the infinitesimal axis z is horizontal, with the finite axis (Z') eventually swapping orientation with the vertical intermediate finite axis Y' with increasing amounts of finite strain ('wrench-dominated transtension' (WDTT); Figs. 1b and 2a, b and d). It has been demonstrated, both theoretically (McCoss, 1986; Teyssier and Tikoff, 1999; Dewey, 2002) and in analogue modelling studies (Withjack and Jamison, 1986; Smith and Durney, 1992; Ramani and Tikoff, 2002), that the horizontal shortening arising from WDTT should be sufficient to generate structures such as thrusts, conjugate strike-slip faults and folds (Fig. 2d). The development of such structures could easily be incorrectly attributed to localised or regional-scale episodes of crustal shortening due to basin inversion. In this paper, we illustrate this problem using observations and data collected from late-Carboniferous–early Permian structures developed across the Upper Palaeozoic Northumberland Basin, NE England (Fig. 3a and b). We demonstrate that structures previously interpreted as resulting from successive phases of extension and compression are more readily explained using a single protracted phase of partitioned dextral transtension.

2. Regional geological setting

In Northern Britain, the early Carboniferous foreland region of the Variscan orogenic belt is characterised by a system of fault-bounded structural highs, cored by relatively buoyant Caledonian granites and overlain by a thin cover of Carboniferous sediments (Fig. 3a). These are separated by intervening subsided basinal regions with much thicker Lower Carboniferous infills. In the present paper, the 'Northumberland Basin' refers to two deeper basins, the Tweed sub-basin to the north and the Northumberland Trough to the south, which are separated by a fault-bounded central high with a relatively thin Lower Carboniferous cover—the Cheviot Block (Fig. 3a) (Fraser et al., 1990). Importantly, the Northumberland Trough overlies the northward dipping Iapetus Suture zone buried at depth (Fig. 3a) (Bott et al., 1985; Chadwick and Holliday, 1991; Soper et al., 1992). This earlier Palaeozoic suture zone formed during closure of the Iapetus Ocean and collision of the Avalonian microcontinent with Laurentia during the Caledonian Orogeny (e.g. Woodcock and Strachan, 2000 and references therein; Dewey and Strachan, 2003).

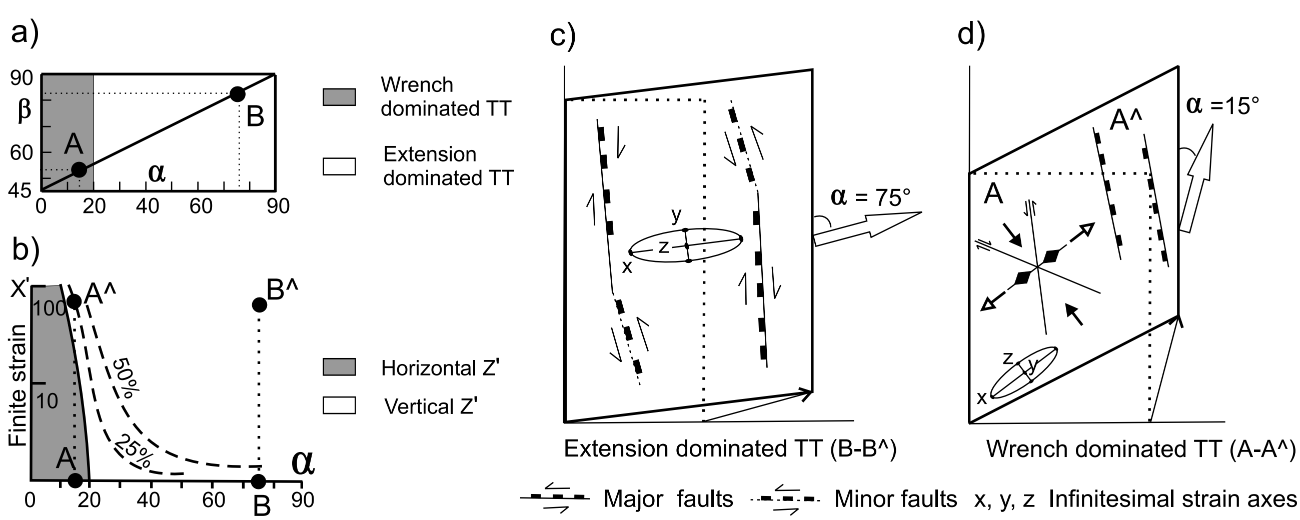

Fig. 2. (a) The fields of wrench-dominated transtension (horizontal infinitesimal maximum shortening) and extension-dominated transtension (vertical infinitesimal maximum shortening) represented on an α vs. β diagram. β and α are the angle between the boundary fault and the infinitesimal maximum extension axis and the transport direction, respectively. (b) α vs. X' (here expressed as finite strain intensity) diagram illustrating that the swap from wrench- to extension-dominated transtension is a function of the angle α and of the amount of finite strain. Note that X' is always in the horizontal plane for transtensional deformation. The dashed curves show how the boundary between wrench- and extension-dominated transtension changes with different amounts of volume increase during transtensional deformation (Teyssier and Tikoff, 1999). The field of stability of wrench-dominated transtension is expanded when volume increase occurs. (c) and (d) Plan views of structural styles and geometries of associated minor structures are shown for homogeneous transtension zones with divergence angles of $\alpha=75°$ (EDTT, (c)) and $\alpha=15°$ (WDTT, (d)).

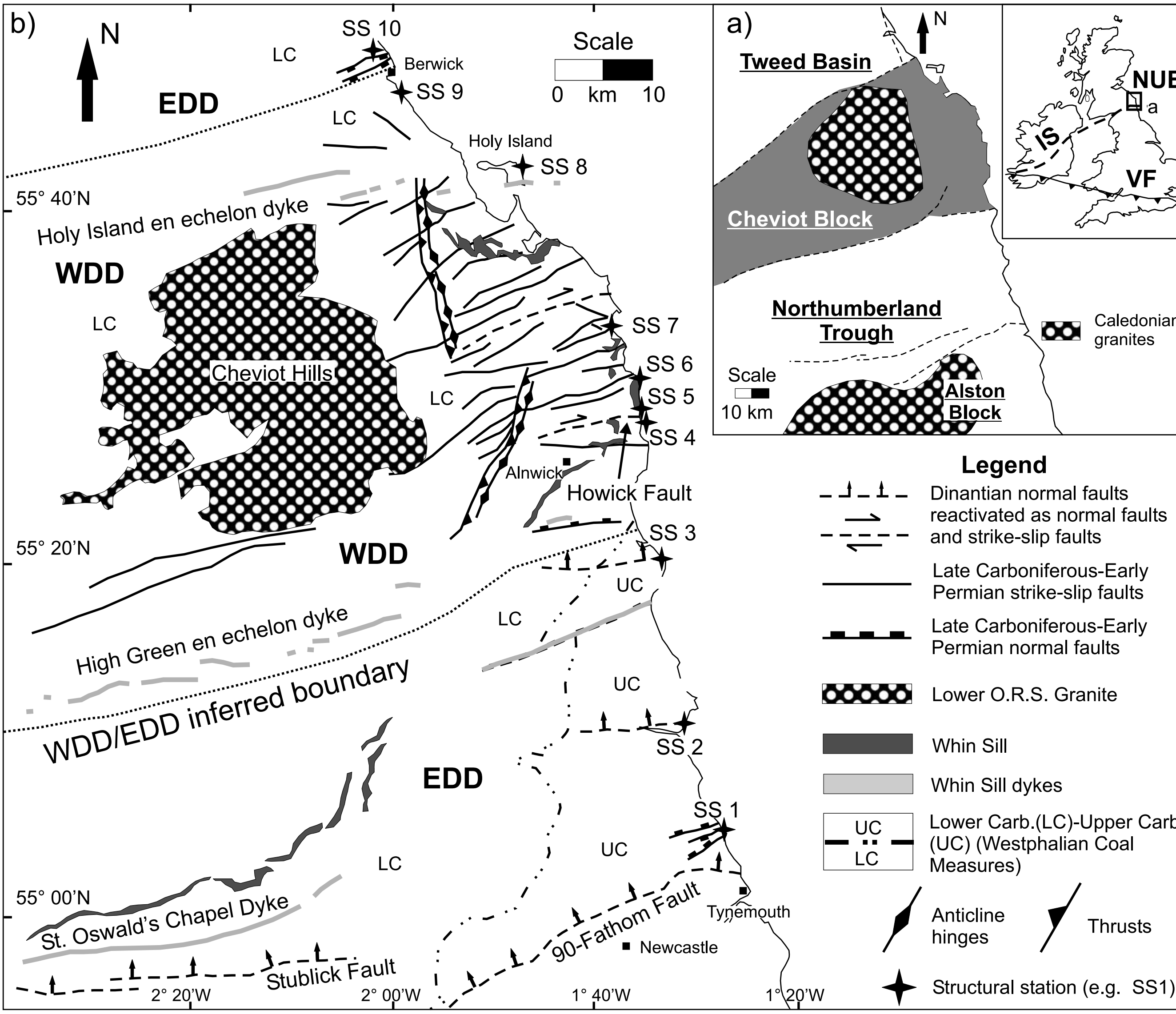

Fig. 3. (a) Internal sub-basins and blocks of the Northumberland Basin showing main Dinantian faults and locations of Caledonian plutons at depth. Inset shows location of Northumberland Basin (NUB) relative to Iapetus suture (IS) and Variscan front (VF). (b) Structural map of the Northumberland Basin showing location of key localities (SS1–SS10), and late Carboniferous extension-dominated domains (EDD) and wrench-dominated domains (WDD).

2.1. Lower Carboniferous (Dinantian) extension

Regional N–S to NNW–SSE extension is widely recognised in Northern Britain during Dinantian times (Fraser and Gawthorpe, 2003) The regional structure of the Northumberland Basin is well understood based on geological and geophysical studies (Bott, 1961, 1967; Bott et al., 1984; Johnson, 1984; Kimbell et al., 1989; Leeder et al., 1989; Fraser and Gawthorpe, 2003). The preserved Lower Carboniferous basin-fill is thickest adjacent to its southern margin defined by the Stublick-90 Fathom fault system (Kimbell et al., 1989) where up to 4000 m of Dinantian sediments accumulated. The thickening of this sequence against this faulted margin is generally taken as evidence of syndepositional faulting (Fig. 3b) (Kimbell et al., 1989). The Dinantian fill thins to ca 500 m over the Cheviot Block, thickening once again to the north to 1500 m within the Tweed sub-basin (Fig. 3a) (Johnson, 1984; Leeder et al., 1989). Dinantian rifting was superseded by a regional phase of thermal subsidence at uniform rates during the late Carboniferous (Westphalian) (Bott et al., 1984; Leeder and McMahon, 1988; Kimbell et al., 1989).

2.2. Late Carboniferous shortening (‘Variscan inversion’)

The Northumberland Basin is considered a classic example of an inverted basin (Collier, 1989; Leeder et al., 1989). Shiells (1964) and Bower (1990) identified a characteristic association of three main types of shortening structures: N- to NE-trending folds, reverse faults (thrusts) and conjugate strike-slip faults trending ENE–WSW (dextral) and ESE–WNW (sinistral). All authors relate this shortening event to the far-field effects of the Variscan Orogeny in late Carboniferous–early Permian times.

2.3. Late Carboniferous–early Permian magmatism: the Whin Sill complex

The Whin Sill complex intrusions in Northumberland (Dunham and Strasser-King, 1982; Francis, 1982; Johnson and Dunham, 2001; Liss et al., 2004) cross-cut Westphalian Coal Measures strata but not the unconformably overlying Permian rocks (Robson, 1980). Hydrothermal activity is associated with the later stages of intrusion, forming quartz, calcite and pyrite-filled veins and joints (Frost and Holliday, 1980). K–Ar dating of several samples from the igneous complex by Fitch and Miller (1967) yielded a mean age of 295 ± 6 Ma. This age is generally believed to date intrusion, while a U–Pb baddelyite age from the southern part of the Whin Sill has yielded an age of ca. 297 Ma (Hamilton and Pearson, pers. comm., 2004). Recent studies of palaeomagnetic data confirm the latest Carboniferous emplacement ages, but additionally suggest that the Whin Sill complex comprises three or four separate sills and associated feeder dykes (Liss et al., 2004). The dykes were emplaced during N–S extension, showing a regional ENE trend, with locally well-developed en-échelon geometries (Robson, 1980) (Fig. 3b).

The timing of supposed Variscan inversion in the Northumberland Basin relative to the intrusion of the Whin Sill complex has long been uncertain. Some authors view the events as broadly contemporaneous (e.g. Shiells, 1964; Johnson, 1995), whilst others (e.g. Collier, 1989; Leeder et al., 1989; Bower, 1990) have argued that the Whin Sill intrusions post-date inversion. In the latter view, the timing of inversion is confined to a 14 Ma period between the deposition of the youngest preserved Carboniferous sediments in NE Northumberland (ca. 311 Ma) and intrusion of the Whin Sill Complex (ca. 297 Ma) (Collier, 1989). On a regional scale, the Whin Sill complex is thought to be associated with a major suite of magmatic intrusions recognised across NW Europe and formed during lithospheric extension (Neumann, 1994; Sundvoll and Larsen, 1994; Smythe et al., 1995; Ernst and Buchan, 1997, 2001; Timmerman, 2004).

2.4. Post-basal Permian deformation

Late-stage, mostly minor fault arrays have long been recognised cross-cutting the Whin Sill complex intrusions (e.g. Shiells, 1964). On a larger scale, structures such as the 90-Fathom Fault offset Upper Carboniferous rocks (Coal Measures) and overlying Permian strata suggesting that reactivation of pre-existing faults occurred during Permian to Mesozoic times, probably associated with NE–SW extension during the early stages of rifting in the North Sea basin (Collier, 1989; De Paola et al., 2005).

2.5. Summary of existing models and key problems

The accepted model for the late Carboniferous–early Permian evolution of the Northumberland Basin suggests that an early phase of Dinantian N–S extension was post-dated by Variscan inversion, which was in turn superseded—or perhaps overlapped—by renewed N–S extension related to emplacement of the Whin Sill complex ca. 294–297 Ma. Two significant problems exist with this model: (1) the approximately E–W shortening direction in the Northumberland Basin is markedly non-parallel to the NNW direction of Variscan convergence in Southern Britain (e.g. Sanderson, 1984) and in NW England (Woodcock and Rickards, 2003); and (2) the timing of E–W shortening relative to the emplacement of the Whin Sill complex is uncertain. Furthermore, the emplacement of a tholeiitic suite of intrusions is typically related to lithospheric extension (e.g. Timmerman, 2004) and seems to be at odds with the occurrence of a crustal shortening episode in this part of northern Britain.

3. Regional structural patterns

In Carboniferous outcrops, post-Dinantian, pre-Permian (hereafter referred to as ‘late Carboniferous’) ages of movement can be inferred based on four criteria: (i) the structures cross-cut Westphalian Coal Measures sedimentary sequences deposited during post-Dinantian thermal subsidence; (ii) the faults are not associated with features indicative of syn-sedimentary activity; (iii) faulting is synchronous with quartz–calcite–pyrite mineralization similar to the hydrothermal activity broadly associated with intrusion of the Whin Sill complex (Frost and Holliday, 1980); (iv) the structures pre-date geometrically and kinematically distinct sets of faults inferred to be Permian–Mesozoic (see below).

Late Carboniferous extensional movements dominate south of Alnwick and in a smaller region immediately N of Berwick (labelled ‘extension-dominated domain’ (EDD) in Fig. 3b). This domain is characterised by a simple bimodal pattern of E–W- to ENE–WSW-trending conjugate normal faults with dip-slip kinematics (Fig. 4a), i.e. the classical Andersonian geometry. A contrasting pattern of late Carboniferous deformation is seen in the region to the north of Alnwick, east of the Cheviot Hills along the coast to Berwick (labelled ‘wrench-dominated domain’ (WDD) in Fig. 3b). Here, a more complicated pattern of deformation consistent with E–W shortening occurs, with the dominant structures being quadrimodal, conjugate strike-slip faults, with dextral and sinistral sets trending ENE and ESE, respectively (Fig. 4b).

The E–W shortening domain is located within the Carboniferous rocks that overlie the Cheviot block and its boundaries appear to broadly coincide with the locations of two major ENE–WSW dykes related to the Whin Sill

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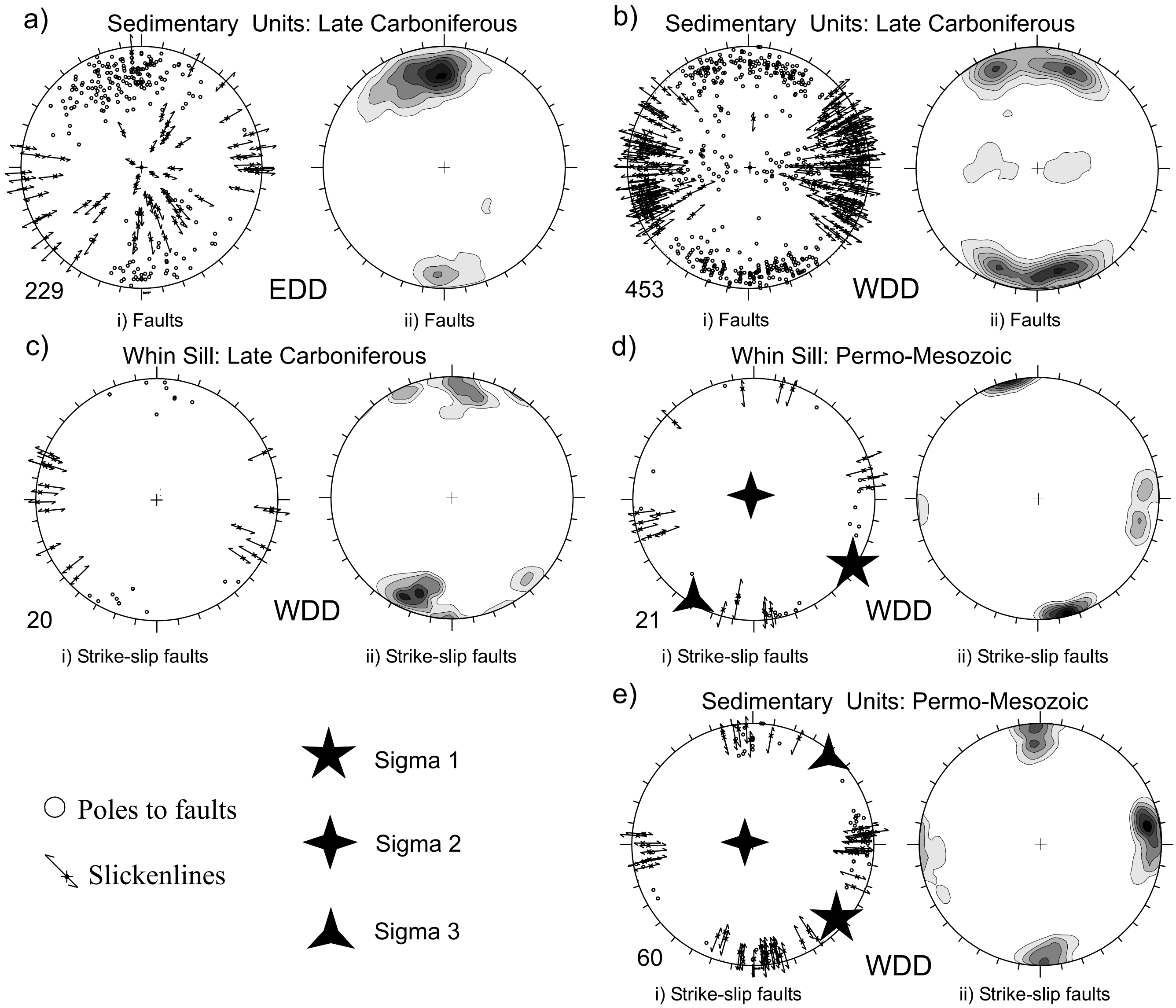

Fig. 4. Summary equal-area stereoplots of structures measured within the Northumberland Basin. In each case, (i) shows poles to planes and slickenlines, while (ii) shows contoured plot of poles to planes. (a) Late Carboniferous structures, EDD Carboniferous; (b) late Carboniferous structures, WDD Carboniferous; (c) late Carboniferous structures, WDD Whin Sill dolerites; (d) Permian–Mesozoic structures, Whin Sill dolerites, with stress axes; (e) Permian–Mesozoic structures, Carboniferous country rocks, with stress axes. Note that in (a), there are minor occurrences of strike-slip faults in the EDD that are discussed in detail in Section 4.1.1.

complex (Fig. 3b). All previous workers have assumed that the distinct structural assemblages found in the EDD and WDD result from deformation events of differing age and tectonic significance. An alternative hypothesis investigated in the present paper is that they are contemporaneous, and that the observed geographic separation reflects tens-of-km-scale partitioning of a regional transtensional deformation.

In order to unravel this deformation, it is first necessary to separate out late Carboniferous from younger Permian–Mesozoic features. In their detailed study of the post-Carboniferous reactivation of the 90-Fathom Fault, De Paola et al. (2005) have demonstrated that faulting in Permian sandstones and dolostones, involved regional dextral transtension with a NE–SW direction of finite extension. To help identify the post-Carboniferous structures, data have been collected from outcrops of the Whin Sill complex in the WDD. Two sets of structures emerge (Fig. 4c and d). ENE- (dextral) and ESE- (sinistral) trending conjugate strike-slip faults, with a quadrimodal geometry, and associated N–S-trending reverse faults are similar to the pattern of deformation observed in the sedimentary units of the WDD (Figs. 3b and 4b). Later N–S-trending sinistral and ∼E–W-trending dextral conjugate strike-slip faults are here interpreted to be Permian–Mesozoic structures as stress inversions yield a stress/infinitesimal strain field compatible with that obtained by De Paola et al. (2005) for fault patterns of post-Carboniferous age (Fig. 4d). Geometrically and kinematically identical structures are found in the

Carboniferous sedimentary rock exposures (Fig. 4e) where they consistently cross-cut or reactivate late Carboniferous fractures (e.g. N–S stylolites are often reopened as veins).

4. Detailed kinematic analysis of late Carboniferous structures

Detailed measurements of the geometries, kinematics and relative overprinting relationships have been made for late Carboniferous structures at a number of well-exposed localities across the Northumberland Basin (labelled SS1–SS10 in Fig. 3b). In the following account, structures are described and interpreted from selected structural stations (SS1, SS4–SS7, SS9); other stations are documented in De Paola (2005).

4.1. The extension-dominated domains (EDD)

Late Carboniferous extension-dominated domains occur in the region south of a line coincident with the High Green Echelon Dyke–Hauxley Fault (i.e. the Northumberland Trough of Kimbell et al. (1989)) and in a smaller region immediately north of Berwick in the coastal outcrops of the east–central Tweed sub-basin. Here we present details of structural patterns typical of the EDD using SS1 (Fig. 3b).

4.1.1. SS1: St Mary's Lighthouse–Hartley section

This locality is located about 4 km north of the faulted southern margin of the basin, in coastal exposures near Hartley (Figs. 3b and 5a). The lithological units are the Coal Measures (Westphalian), comprising interbedded sandstones, silty-sandstones, shales and thin coal seams, which provide useful markers to estimate the sense and magnitude of displacements.

The dominant structures are conjugate Andersonian normal faults on cm- to tens-of-metre-scales, with E–W to ENE–WSW trends, exhibiting dip-slip slickenlines and associated subvertical veins (Fig. 5a–f). The veins are mostly filled with calcite, but a conspicuous number show pyrite mineralisation (Fig. 5f). Pyrite mineralisation also occurs on all the main fault planes shown on Fig. 5a.

A narrow belt of dextral faults, with slightly oblique-extensional displacement, is present in one fault system west of St Mary's Lighthouse (Fig. 5a and g). These faults are steeply dipping, displaying small (cm-scale) extensional offsets of the sub-horizontal bedding. The trend of these structures is E–W to ENE–WSW, subparallel to the adjacent normal faults (Fig. 5a and g). These dextral strike-slip faults carry syn-shearing calcite, hematite and pyrite mineralisation identical to that associated with the normal faults.

Stress inversion (using the inversion routine supplied with DAISY 2; Salvini, 2001), applied to the dip-slip normal faults, yields an approximately vertical σ_1, a sub-horizontal ENE–WSW-trending σ_2, and a subhorizontal NNW–SSE-trending σ_3 (Fig. 5d). There is no evidence of substantial rotation of minor structures, such as veins or synthetic and antithetic shears associated with the major faults. This implies that the calculated stress axes can, to a first approximation, be considered as direct equivalents to infinitesimal strain axes, i.e. $z \equiv \sigma_1$, $y \equiv \sigma_2$, $x \equiv \sigma_3$. Stress inversion data are in good accord with the orientation of mineralised tensile veins for an Andersonian extensional system, i.e. σ_3 corresponds to the poles to veins (Fig. 5d and e).

4.1.2. EDD: summary and structural model

The EDDs display a uniform and straightforward pattern of late Carboniferous deformation (Fig. 6a and b). The dominant structures are E–W- to ENE–WSW-trending normal faults arranged in conjugate Andersonian sets with dip-slip kinematics (Fig. 6a). Sub-vertical tensile veins have the same trend as the faults (Fig. 6b). Stress inversions suggest NNW–SSE extension (σ_3) and subvertical shortening (σ_1). Minor, subordinate sets of faults displaying wrench-transtensional kinematics occur locally, separate from, but parallel to the adjacent major normal faults within the EDD. If the faults cutting the Coal Measures strata reactivate pre-existing Dinantian structures at depth, the zones of wrench faulting could represent reactivated structures that preferentially accommodate residual wrench components following dip-slip extensional reactivation of the major faults in the section, cf. the model presented by De Paola et al. (2005) for the Permian–Mesozoic faulting along the 90-Fathom Fault.

4.2. The wrench-dominated domain (WDD)

The dominant structures in the WDD are ENE-trending dextral and ESE-trending sinistral shear zones (Fig. 3b). Two N–S- to NNE–SSW-trending regional-scale folds also occur, bounded to the west by east-dipping thrusts.

4.2.1. SS4–SS6: the Howick section

The ∼5-km-long Howick section lies on the coast east of Howick northwards to Grey Mares Rocks (SS4–SS6; Figs. 3b and 7–9). The coastal exposure from Howick (SS4) to Cullernose Point (SS5) (Figs. 3b and 7) is particularly important as it illustrates the relative age relationships between Dinantian and late Carboniferous faulting and intrusion of the Whin Sill complex. Rocks belonging to the Middle Limestone Group (Visean) and Upper Limestone Group (Namurian) are juxtaposed by the south-dipping Howick normal fault (Figs. 3b and 7). The Howick fault system is well exposed on the cliff at SS4, where a series of ∼E–W-trending Andersonian conjugate normal faults, displaying dip-slip slickenlines, are present (Fig. 8a and b). Locally, beds in fault hanging walls thicken towards the footwall (Fig. 8a). This evidence, together with the listric geometries and locally observed soft-sediment deformation associated with faulting, suggest that the Howick fault was a

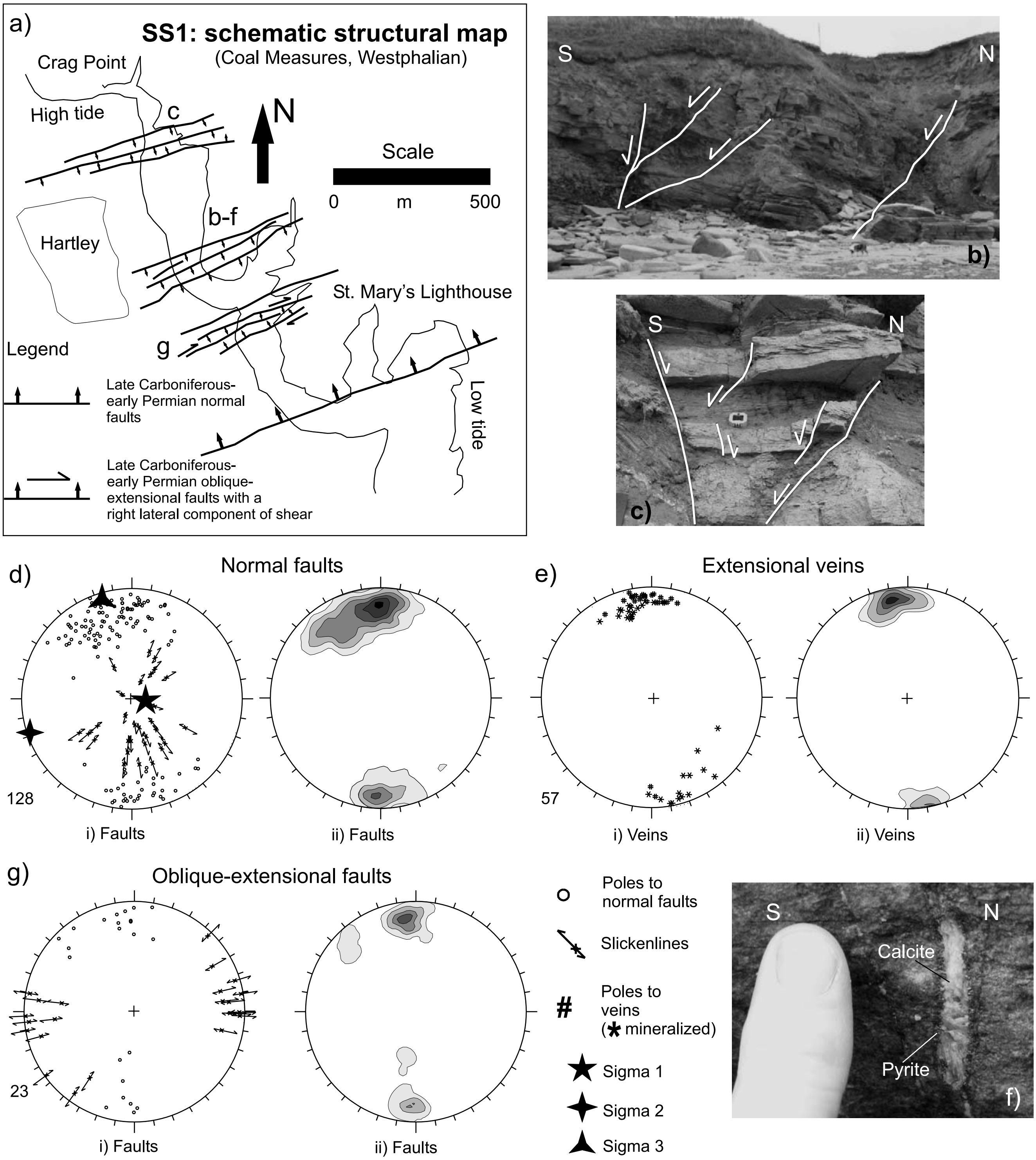

Fig. 5. (a) Schematic structural map of SS1 in Upper Carboniferous Coal Measures exposed at St Mary's Lighthouse–Hartley (for location, see Fig. 3b). (b) and (c) Large- to meso-scale dip-slip normal faults at SS1 showing classic Andersonian conjugate geometry. (d) Stereoplots of normal faults and associated slickenlines, with calculated stress axes. (e) Stereoplots of tensile mineralised veins. (f) Subvertical extensional vein, associated with normal faulting, with calcite–pyrite mineralisation. (g) Stereoplots of strike-slip-oblique extensional faults and associated slickenlines. All stereoplot formats as in Fig. 4.

syn-sedimentary feature active in Dinantian–Namurian times.

The geometries of faulting change as one moves eastward out onto the foreshore along the strike of the faults; fault planes are more steeply dipping with subhorizontal slickenlines (Fig. 8c–e). Dextral offsets occur along the main E–W-trending faults (Fig. 8c–e), which are linked by sub-vertical, synthetic, NE–SW-trending dextral faults

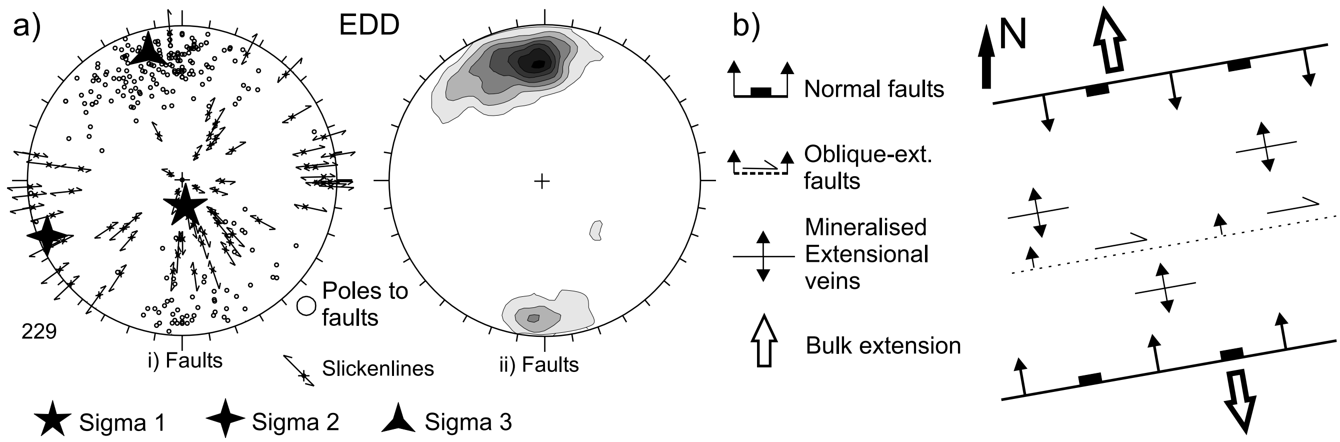

Fig. 6. (a) Stereoplots of all late Carboniferous faults and associated slickenlines in the EDD, with calculated stress axes. All stereoplot formats as in Fig. 4. (b) Summary plan-view structural model for the EDD in the late Carboniferous.

consistent with a strike-slip duplex structure (Fig. 7). E–W-trending vertical veins and bedding-parallel shear along N–S-trending, east-dipping beds have also been observed (Fig. 8f). This strain is consistent with the development of a dextral restraining bend, with extension and shortening,

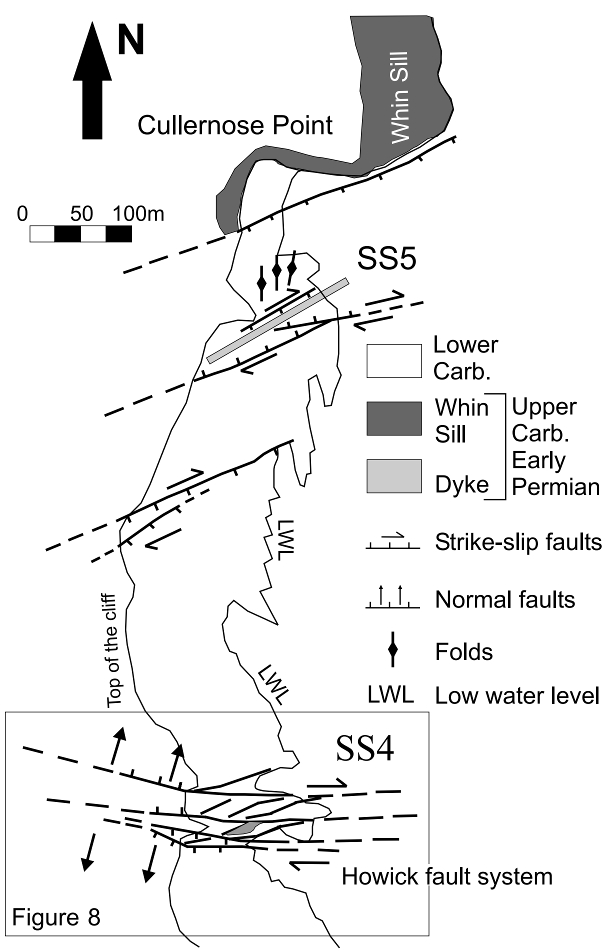

Fig. 7. Simplified structural map of the Lower Carboniferous rocks of the Howick–Cullernose Point area (SS4–SS5; for location see Fig. 3b). The box shows location of Fig. 8.

respectively, orthogonal and parallel to faults (Woodcock and Fischer, 1986; Walsh et al., 1999). An approximately bedding-parallel intrusion of Whin Sill complex dolerite up to 3 m thick occurs here within the Howick fault zone (Fig. 8c). The intrusion is bounded by two strike-slip faults, but is not brecciated or cross-cut by faulting, suggesting that emplacement may be contemporaneous with the strike-slip fault movements.

The change in the geometry and kinematics of faulting observed along the strike of the Howick fault system suggests that the Dinantian (Lower Carboniferous) synsedimentary normal faults have been reactivated as dextral strike-slip faults (Fig. 7). The latter event appears to be contemporaneous with emplacement of at least some parts of the Late Carboniferous Whin Sill ca. 297 Ma.

North of the Howick fault system, E–W to ENE–WSW dextral strike-slip faults are dominant (e.g. SS5–SS6, Figs. 3b, 7 and 9). The mesoscale structures associated with these faults include: strike-slip faults, shear arrays and associated veins, parallel-bedding thrusts, folds and stylolites (Fig. 9a). The mesoscale strike-slip faults can be divided into four groups based on their orientation representing two conjugate sets with opposed dips (i.e. quadrimodal faults; Fig. 9a–c); faults trending E–W to ENE–WSW and E–W to ESE are dextral and sinistral, respectively. The angle between the two sets of conjugate faults is 40–50°. All faults display shallowly-plunging slickenlines and horizontal offsets of bedding (Fig. 9b and c). Sets of N–S-trending structures observed in these outcrops (Fig. 9a) cross-cut and therefore post-date all other structures and are thought to be Permian–Mesozoic features.

Shortening structures such as folds, bedding-parallel thrusts and stylolites are widespread at localities SS5 and SS6. Folds are open to tight structures with NNE- to NNW-trending sub-horizontal hinges, while stylolites are subvertical and lie in an approximately axial planar orientation relative to the folds (Fig. 9d). Top-to-the-east and -west reverse shear planes are mostly at low

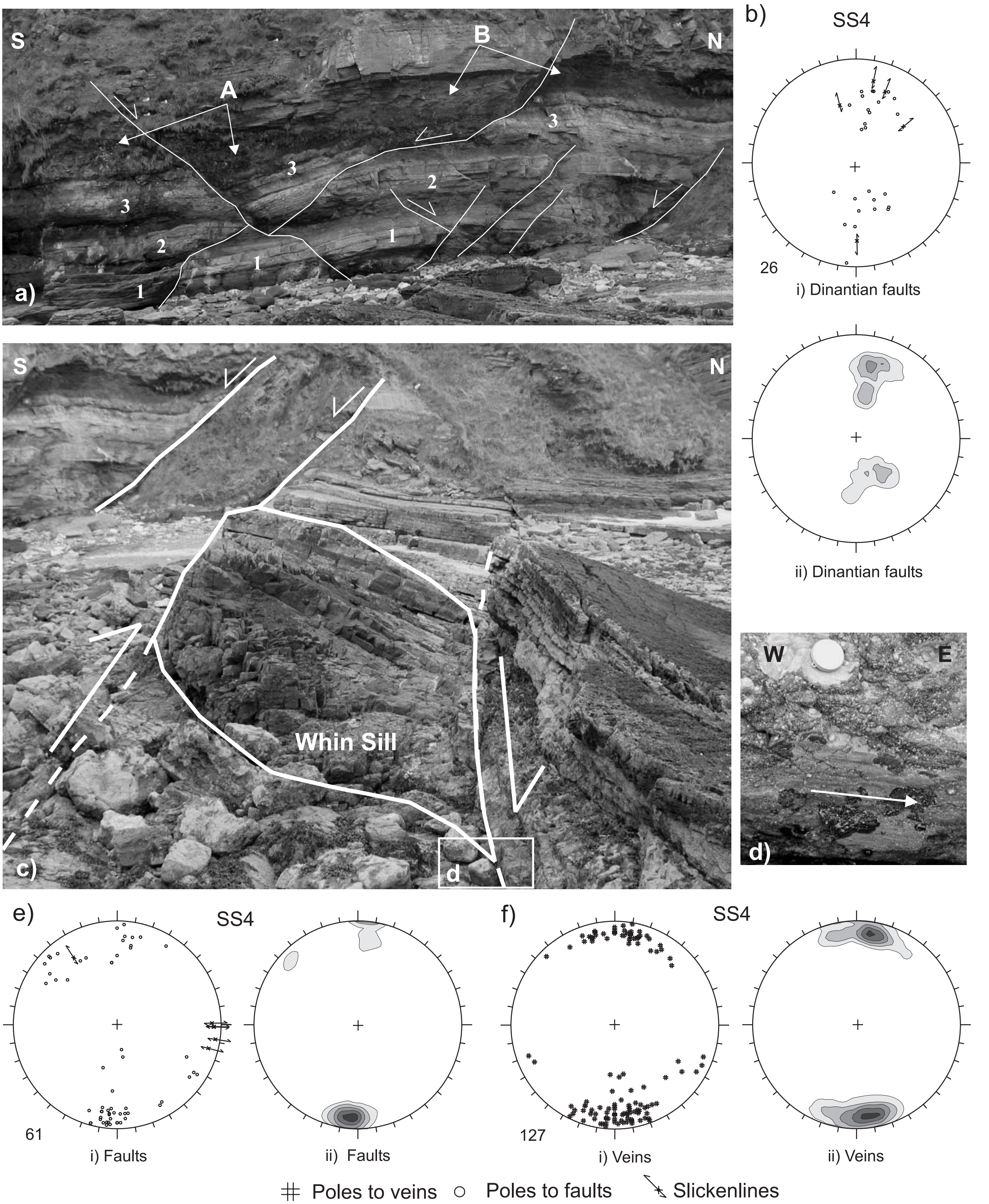

Fig. 8. (a) The Howick fault system (SS4; for location see Fig. 7) exposed on the cliff just east of Howick. Syn-sedimentary (Dinantian/Namurian) normal faults displaying hanging wall thickening (A–B), listric geometry and soft sediment deformation. (b) Stereoplots of the syn-sedimentary normal faults. (c) Whin Sill intrusion between two segments of strike-slip reactivated normal faults (in background cliff) as dextral strike-slip faults. (d) Subhorizontal slickenlines observed on early Carboniferous (Dinantian/Namurian?) normal fault planes reactivated as strike slip faults during the Whin Sill intrusion (late Carboniferous–early Permian). (e) Stereoplots of strike-slip faults. (f) Stereoplots of tensile veins in Howick fault duplex. All stereoplot formats as in Fig. 4.

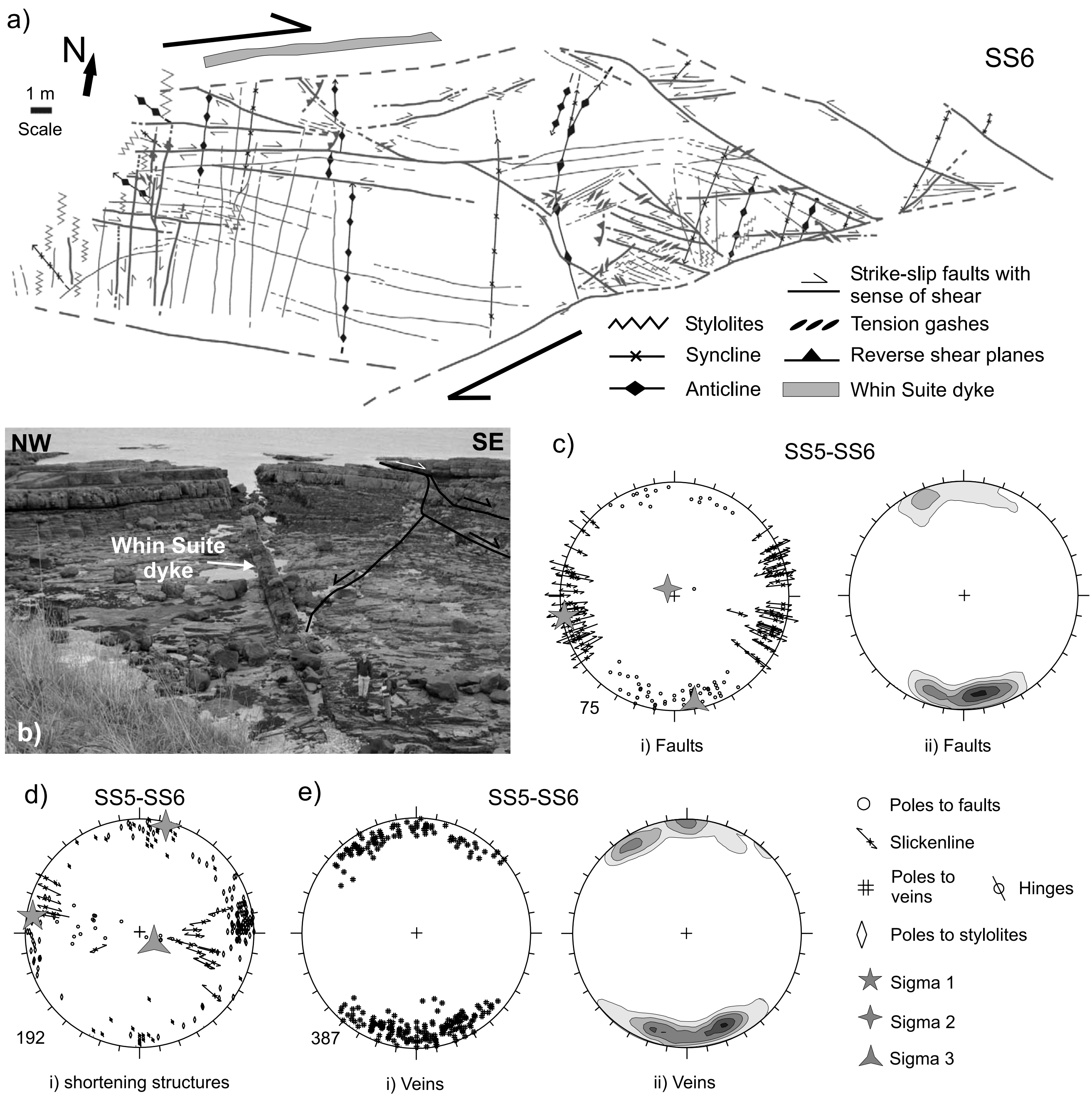

Fig. 9. (a) Detailed structural map of SS6 in Lower Carboniferous rocks exposed at Grey Mares Rocks just north of Dunstanburgh Castle (for location see Fig. 3b). (b) Plan view of SS5 (for location see Fig. 7) with the major faults shown in the top-right corner. Note how the dyke is subparallel to the main dextral faults. (c)–(e) Stereoplots of faults with calculated stress axes (c), shortening structures with calculated stress axes (d) and veins (e), respectively, measured at SS5–SS6. All stereoplot formats as in Fig. 4.

angles or sub-parallel to bedding, with N–S strikes and slickenlines oriented approximately orthogonal to local fold hinges (Fig. 9d). Flexural slip was an efficient folding mechanism as testified by the abundance of sheared bedding surfaces with opposing senses of shear on opposite fold limbs. As first recognised by Shiells (1964), these shortening structures are often compartmentalised between mesoscale dextral strike-slip faults and appear to have formed in response to horizontal shortening related to strike-slip displacements along these faults (Fig. 9a and b).

Stress inversions applied to both strike-slip fault sets and reverse shear planes yield different but coaxial stress/infinitesimal strain fields (Fig. 9c and d). These have a common ∼E–W oriented shortening axis z (σ_1) and a ∼N–S oriented horizontal extension axis x (σ_3) for the strike-slip faults, which becomes vertical for the reverse faults. Stress inversion data are in good accord with the orientation of minor structures such as veins, fold hinges and stylolites (Fig. 9c–e).

The observed pattern of conjugate strike-slip faulting and stylolite development also occurs in the absence of folds where the beds are subhorizontal and strain is small (Fig. 7; between SS4 and SS5). Folding appears to be associated with localised high strains along larger-scale strike-slip fault zones.

E–W- to ENE–WSW-trending dykes of the Whin Sill complex are oriented parallel to the major dextral strike-slip fault zones (Figs. 7, 8b and 9a and b). Some ENE-trending dextral faults and associated fractures are deflected when approaching the dyke (Figs. 7 and 9b; SS5), suggesting that the dyke had been already intruded at the time of faulting or that intrusion and faulting were synchronous. The intensity of brecciation and quartz–carbonate mineralisation of the country rocks in the fault zones seems to correlate with the local thickness of the dykes. Once again, this may suggest a link between faulting and emplacement of the Whin Sill complex.

A characteristic association occurs between the strike-slip faults and tensile veins (Fig. 10a and b), which are typically arranged in en-échelon arrays adjacent to faults and fault tip zones. Most veins are tabular in shape, with sigmoidal forms rarely preserved (Fig. 10a and b). ENE and ESE sub-vertical vein orientations are dominant (Fig. 9e). The trends of individual veins and of each tension gash can be plotted vs. fault and shear-array trends (Fig. 10c) (McCoss, 1986; Kelly et al., 1998). The geometric relationship between the shear arrays and the associated tension gashes is expressed by the angle θ. This angle can be used to characterise the bulk strain field operating at the time when they formed (e.g. extension $\theta=0°$, transtension $0°<\theta<45°$, wrench simple shear $\theta=45°$, transpression $45°<\theta<90°$, shortening $\theta=90°$). Tension gash arrays and veins associated with shear arrays and faults from SS5 to SS6 (and other localities in the WDD), mostly cluster in the fields of transtensional strain with sinistral and dextral kinematics (Fig. 10).

4.2.2. SS7: Beadnell

The SS7 is located on the coast (Fig. 3b) where the Middle Limestone Group (Visean) crops out close to the small town of Beadnell. The outcrop is characterised by a 5-m-thick, E–W-trending vertical dyke, belonging to the Whin Sill complex and by conjugate strike-slip faults trending ENE (dextral) and ESE (sinistral) (Fig. 11a).

The deformation is heterogeneous and is localised within the country rocks adjacent to the dyke. The dominant structures are ENE-trending dextral strike-slip faults and ESE-trending sinistral strike-slip faults, both with sub-horizontal slickenlines (Fig. 11b). Minor structures associated with the major fault zones include tensile veins and shortening structures such as reverse faults, folds and stylolites (Fig. 11c–e). The tensile veins are vertical, E–W-trending and calcite-filled, with orientations similar to the dyke (Fig. 11a and e). They are associated with strike-slip faults and shear arrays as tension gashes and once again plot in the fields of transtension for sinistral and dextral faults as shown by Kelly et al. (1998) at this locality.

Shortening structures are particularly associated with the main faults. N–S striking folds and reverse faults, with

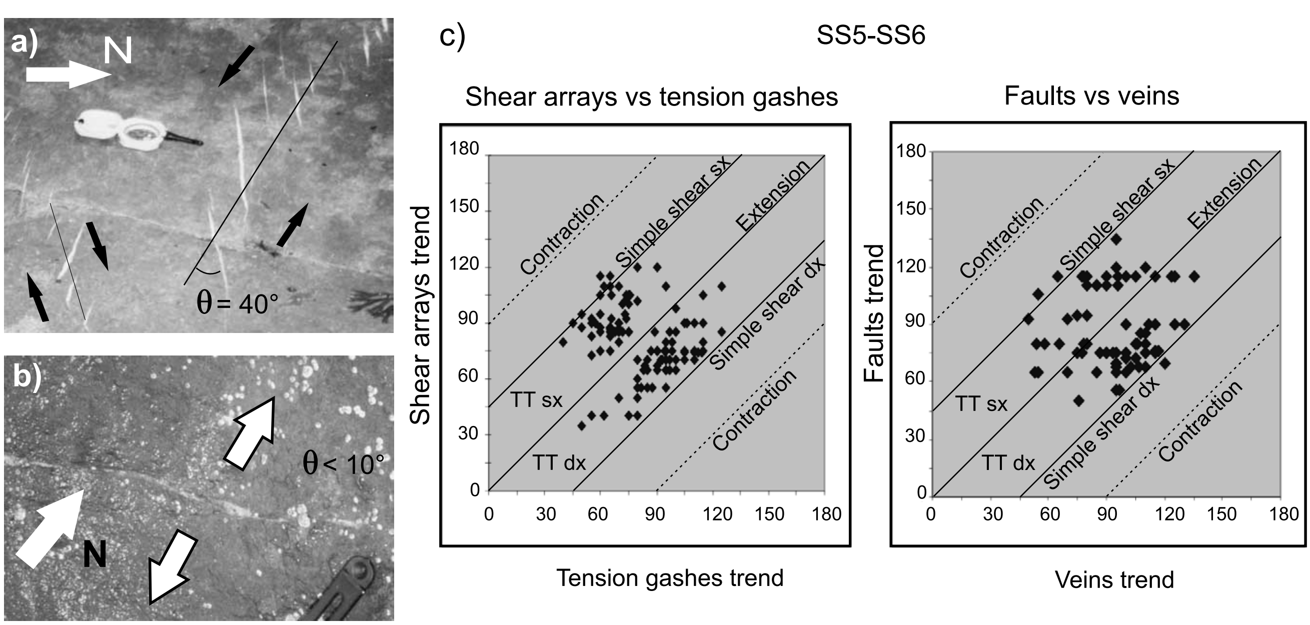

Fig. 10. (a) Shear arrays (thin dark line) and associated tension gashes (white veins) displaying dextral and sinistral senses of shear at SS5 and SS6. Note the angle $\theta\approx 40°$ between the inferred arrays and the tension gashes. (b) Extension array and associated tension gashes display ∼NNE extension with an angle $\theta<10°$. (c) Cartesian diagrams, displaying the fields of all tectonic regimes (McCoss, 1986), where shear arrays vs. tension gashes trends and faults vs. vein trends (Kelly et al., 1998), measured at SS5–SS6, are plotted. Note how most of the data plot in the transtensional strain field (i.e. $0°<\theta<45°$), dextral (TTdx) and sinistral (TTsx), respectively.

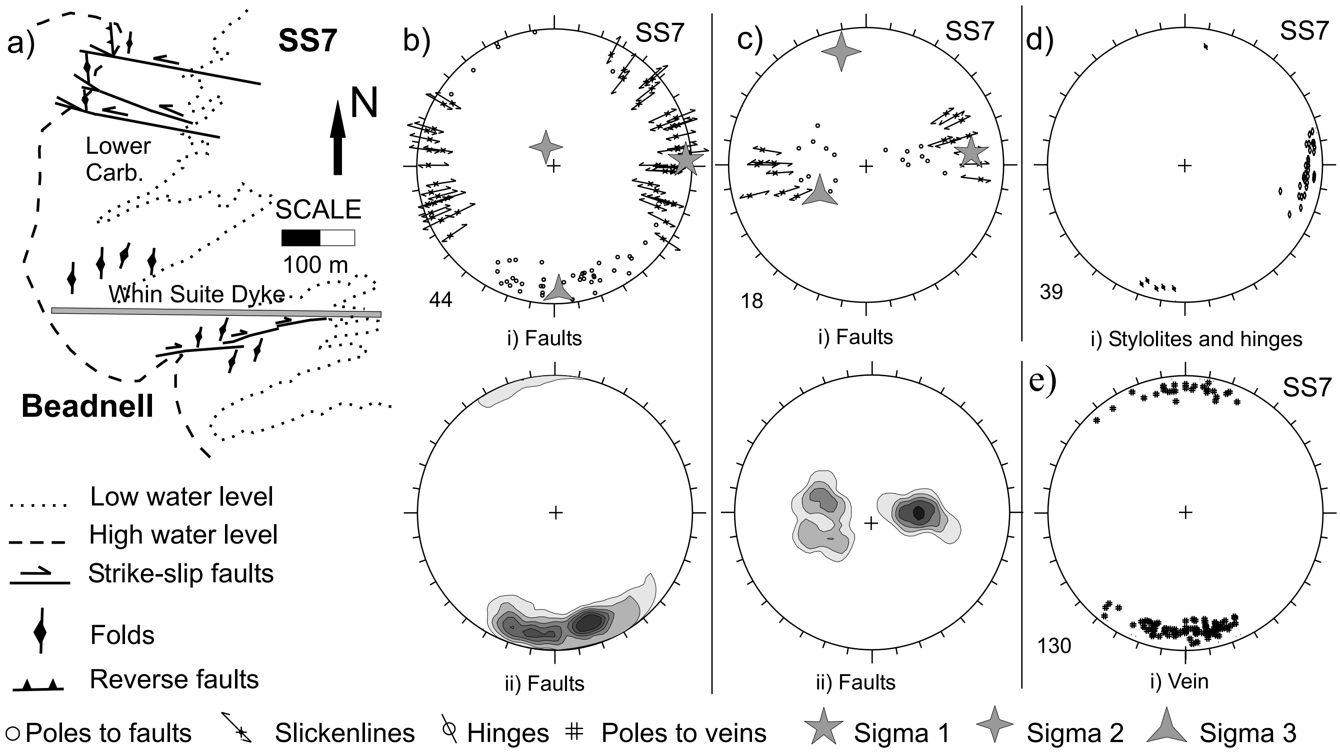

Fig. 11. (a) Schematic structural map of SS7 in Lower Carboniferous rocks at Beadnell (for location see Fig. 3b). (b) and (c) Stereoplots of strike-slip faults with calculated stress axes (b) and reverse faults with calculated stress axes (c). (d) and (e) Stereoplots of minor structures as stylolites and hinges (d) and veins (e). All stereoplot formats as in Fig. 4.

dip-slip slickenlines form conjugate push-up structures between compressionally overlapping segments of adjacent en-échelon strike-slip faults. Stylolites are steeply-dipping, N–S-trending and lie in an approximately axial planar orientation relative to adjacent folds (Fig. 11d).

Stress inversions applied to the strike-slip faults and associated slickenlines yield a stress field with a horizontal, E–W-trending σ_1, a vertical σ_2 and a horizontal N–S-trending σ_3. Stress inversions obtained from minor shortening structures show a coaxial stress field in which the σ_2 and σ_3 have swapped positions so that they are now horizontal and vertical, respectively. Significantly, the Whin Sill complex dyke has been intruded in a vertical plane parallel to the σ_1–σ_2 plane and orthogonal to σ_3. Once again, this is consistent with emplacement synchronous with faulting.

4.2.3. SS9: the Spittal section

The Spittal section is located on the coast approximately 2 km south of Berwick (Fig. 3b). Rocks belonging to the Dinantian Scremerston Coal Group and Lower Limestone Group (Robson, 1980) are cross-cut by two families of conjugate faults trending ENE (dextral) and ESE (sinistral). Slickenline orientations and offsets of bedding planes indicate mainly strike-slip to obliquely extensional stratigraphic displacements (Fig. 12a–c).

Minor structures such as veins, folds and thrust faults are once again closely associated with the major strike-slip faults (Fig. 12c). Veins are less abundant compared with other sections, often occurring at the tips of fault as tension gash arrays; they are subvertical and NNE-trending (Fig. 12c). Folds are restricted mainly to the limestone beds with generally NNE-trending subhorizontal hinges. They are gently periclinal in form and are mainly open to tight disharmonic buckles (Fig. 12c and d). Top-to-the-east and -west thrusts lie at low angles or subparallel to bedding planes, with dip-slip slickenlines oriented orthogonal to local fold hinges (see also Shiells, 1964). Stress inversion of the fault data sets yields a stress field with a horizontal ~E–W-trending σ_1, a horizontal ~N–S-trending σ_3 and a vertical σ_2 (Fig. 12c).

4.2.4. WDD: summary and structural model

The dominant structures are ENE-trending dextral faults, with a subordinate set of associated ESE-trending sinistral faults. The geometry and kinematics of associated small-scale structures are related to the deformation accommodated along these major strike-slip faults (Fig. 13a and b). The stress–infinitesimal strain analyses carried out using the small-scale structures allow us to reconstruct the orientation of the bulk (infinitesimal) strain ellipsoid in the areas between the mesoscale faults (Fig. 13a and b). In all cases, we are able to assume that stress and infinitesimal strain axes are *approximately* parallel as finite strains are generally low (e.g. shortening strains <5%, very locally rising to

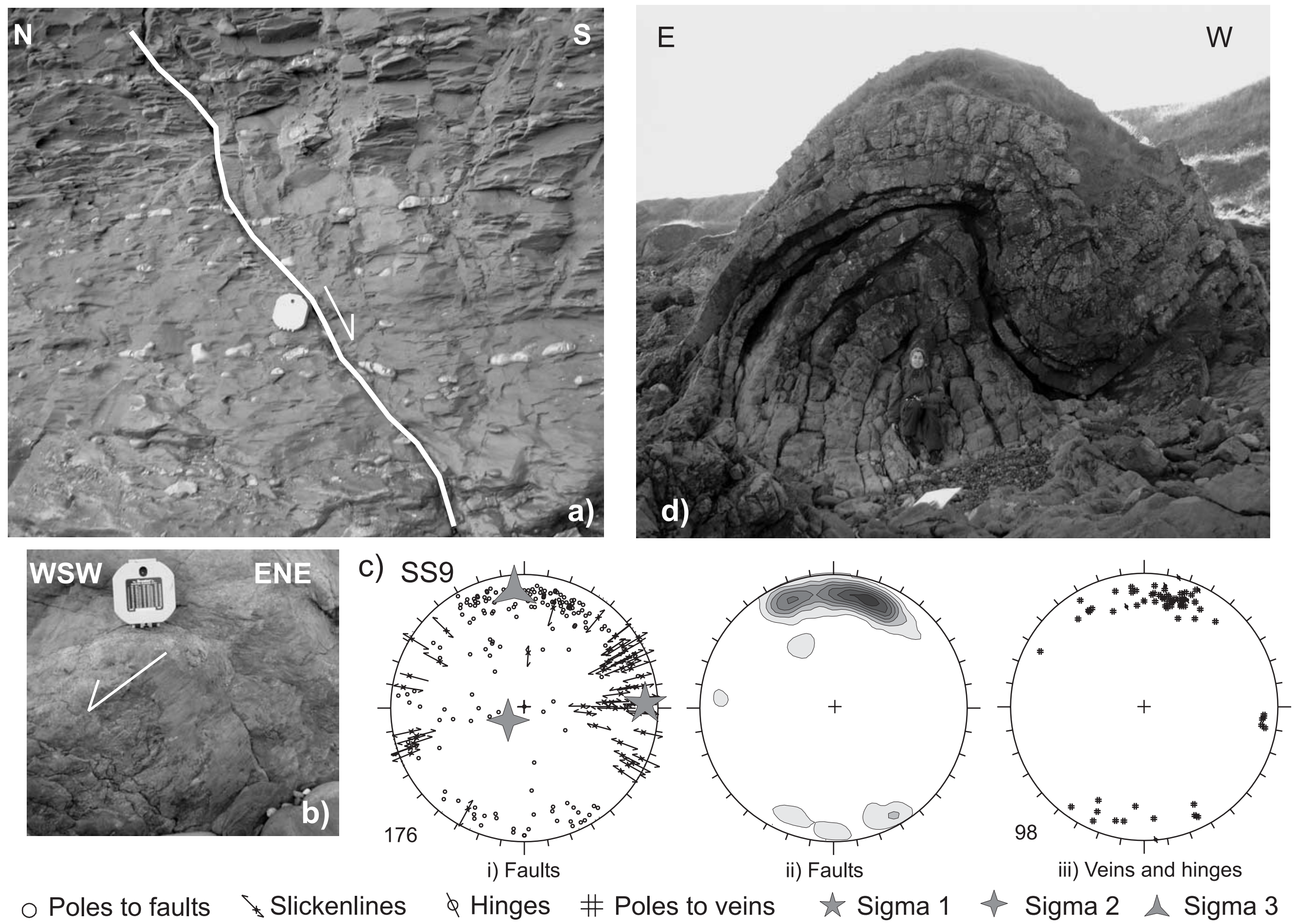

Fig. 12. Late Carboniferous structures developed in Lower Carboniferous rocks at SS9 (for location see Fig. 3b). (a) Oblique-slip extensional fault. (b) Oblique shallow dipping slickenlines on slightly oblique extensional faults. (c) Stereoplots of structures, faults and veins, respectively, with calculated stress axes. All stereoplot formats as in Fig. 4. (d) Spectacular folds displaying a western overturned limb at SS9.

25%); there is also little evidence to suggest that substantial fault block rotations have occurred.

The geometry of the conjugate quadrimodal strike-slip fault system and associated minor structures is everywhere consistent with a sub-horizontal E–W-trending infinitesimal shortening axis (z) bisecting the acute angle between the conjugate fault sets. The orientation of the other axes depends on their local kinematic setting. Thus the conjugate strike-slip faults and associated vein arrays are consistent with a subhorizontal N–S-trending infinitesimal extension axis (x) and sub-vertical intermediate infinitesimal strain axis (y). These axes swap orientations for local folds and associated shortening structures. Stress inversions applied to fault and slickenline data sets yield stress fields consistent with the infinitesimal strain fields inferred from the geometry of the structures observed in the field (Fig. 13a–d). The results obtained for the entire WDD region are everywhere consistent with the results obtained from individual localities—this reinforces the view that it is valid to treat stress and infinitesimal strain axes as being approximately equivalent.

Assuming a geologically reasonable value for Poisson's ratio for the lithologies cropping out in the WDD ($\nu = 0.3$; see De Paola et al., 2005), we can calculate the angle α between the bulk displacement direction and the regionally recognised basin- and domain-bounding faults trending approximately 060° (Fig. 13a–e). The calculated angle $\beta = 60°$, between the infinitesimal horizontal extension x and the boundary zone, indicates a value for $\alpha \approx 30°$ (Fig. 13a–e). This means that the bulk infinitesimal strain in the WDD is a wrench-dominated transtension (Fig. 13a–e). This proposal is confirmed by the independent geometric analysis of the fault and associated tension gash arrays (Fig. 13f) (see also Kelly et al., 1998).

4.3. Summary and synthesis of strain data

The late Carboniferous deformation patterns of the EDD and WDD in the Northumberland Basin are significantly different. Reconstructions of palaeostress/infinitesimal strain axes suggest that both domains are associated with regional sub-horizontal extensional displacements, which are NNW- and NNE-directed in the EDD and WDD, respectively (Fig. 14). We can find no compelling evidence

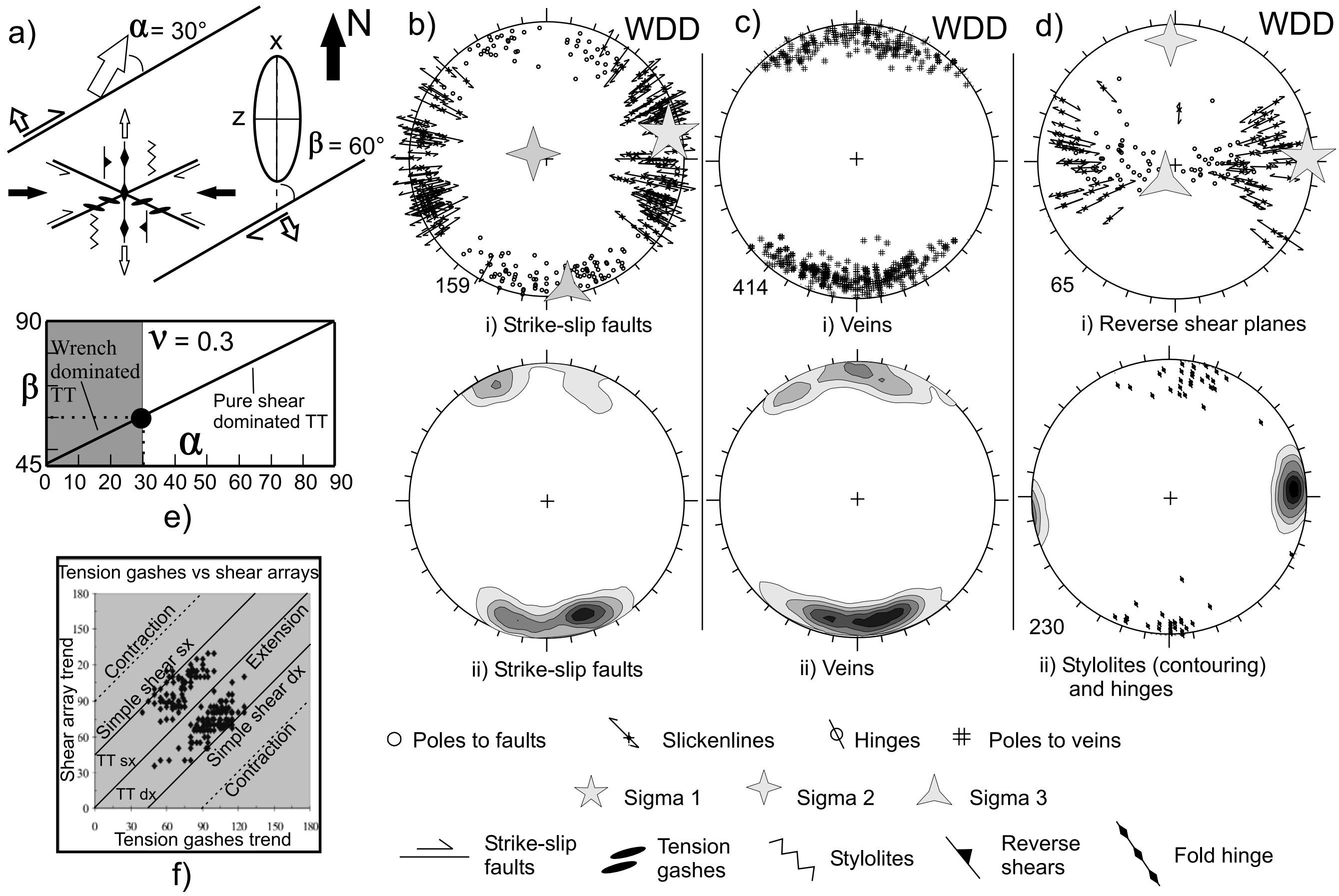

Fig. 13. (a) Simplified plan-view structural model of the WDD in the late Carboniferous, with the geometry of major shear zones and associated minor structures shown. (b)–(d) Stereoplots of strike-slip faults with calculated stress axes (b), veins (c) and shortening structures with calculated stress axes (d). All stereoplot formats as in Fig. 4. (e) α vs. β diagram reconstructing the transport direction $\alpha \approx 30°$, for the WDD, using the calculated (strain analysis + stress inversion (b)) angle $\beta \approx 60°$ between the infinitesimal horizontal extension axis x and the boundary shear zone. (f) Tension gashes vs. shear arrays trends diagram plotted for the overall data in the WDD. In both cases the data plot in the transtensional strain field, sinistral (TTsx) and dextral (TTdx).

to suggest that the late Carboniferous structural assemblages have different ages and we therefore propose that they are contemporaneous and result from partitioning of a regional bulk strain. The mismatch in extension directions suggests an approximately N–S-trending, sub-horizontal regional bulk extension (Fig. 14).

5. Discussion

5.1. Relative age of structures: the emplacement of the Whin Sill complex

No clear examples of overprinting relationships between the late Carboniferous structures recognised in the EDD and WDD have been recognised in the Northumberland Basin. The timing of emplacement of the Whin Sill complex intrusions potentially represents a relative time marker for the deformation events. Some intrusions clearly cross-cut structures such as folds, but many authors have argued that emplacement of the Whin Sill complex occurred contemporaneously with the latter stages of E–W shortening (e.g. Holmes and Harwood, 1928; Shiells, 1964; Robson, 1980; Johnson, 1995). These authors highlight the en-échelon geometries of the ENE–WSW-trending Holy Island and High Green dykes (Fig. 3b), which are thought to indicate the operation of strike-slip shear and E–W shortening, synchronous with N–S extension and emplacement; both lie within or close to the margins of the WDD. The ENE–WSW dykes further to the south in the EDD show a more linear geometry consistent with simple NNW–SSE extension (Robson, 1980). Liss et al. (2004) have used palaeomagnetic analyses to show that the Whin Sill complex can be subdivided into three geographically separate sills, each associated with one or more palaeomagnetically indistinguishable dyke(s), that were emplaced at slightly different times during the Late Carboniferous–Early Permian. These authors suggest that the St Oswald's Chapel dyke (in the EDD), the High Green Dyke en échelon and Alnwick sill (both in the WDD) have been emplaced contemporaneously. If the intrusions are all syntectonic, this implies that the late Carboniferous deformation in the EDD and WDD is the same age.

The regional patterns seem to be confirmed by outcrop-

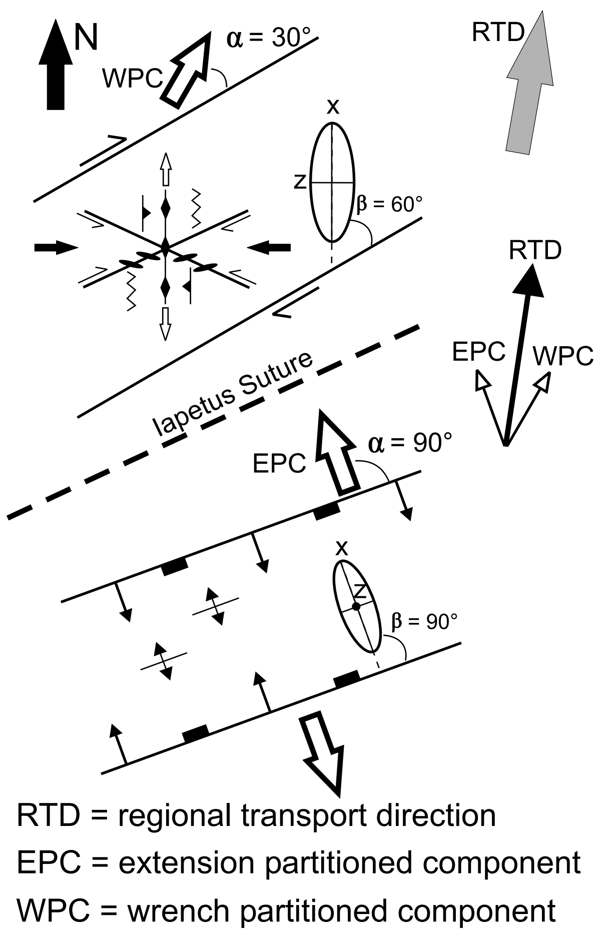

Fig. 14. Structural plan-view model of Northumberland Basin during the late Carboniferous–early Permian deformation. It is proposed that the wrench (WPC) and extension (EPC) components of deformation in the EDD and WDD arise from partitioning of a NNE-directed regional transport direction (RTD). Strain partitioning may have occurred because the RTD was at an oblique angle to pre-existing structures in the Laurentian Caledonian basement north of the Iapetus Suture.

scale observations. Quartz–calcite–pyrite mineralisation broadly contemporaneous with Whin Sill complex emplacement is also synchronous with late Carboniferous fault movements in the EDD and WDD. Local intrusions such as the small lensoid sill in the Howick Fault zone (Fig. 8) appear to be bounded, but not cut by strike-slip fault movements and in some locations (e.g. SS7 Beadnell; Fig. 11), Whin Sill complex dykes trend E–W in the correct orientation relative to the local dextrally transtensional stress/strain field. Finally, the earlier set of quadrimodal conjugate ENE-dextral and ESE-sinistral strike-slip faults cutting Whin Sill dolerites in the WDD is very similar to the late Carboniferous faulting patterns observed in the adjacent sedimentary units (compare Fig. 4b and c).

One puzzling association occurs repeatedly in many locations. Zones of N–S-trending minor folds and strike-slip faults are often localised in regions adjacent to dykes (e.g. Figs. 7, 9 and 11). One possible explanation for this may be that the strike-slip faults are unable to accommodate all of the imposed oblique extension, leading to strain partitioning with a residual component of (orthogonal) extensional strain developing in the wall rock regions immediately adjacent to active faults (Fig. 15a). These regions would then conceivably be favoured sites for dyke emplacement. This in turn would lead to local volume increases, which will lead to an expansion of the field of the wrench-dominated transtensional strain, inhibiting the development of dip- or oblique-slip normal faults and potentially promoting a component of sub-horizontal E–W shortening, leading to the development of N–S folds, thrusts and stylolites (Fig. 15a). As dyke intrusion accommodates the orthogonal extensional component of strain the vertical infinitesimal strain axis would probably lie close to zero (Ramsey and Huber, 1987). This accords well with the lack of vertical displacement observed in any of the strike-slip faults adjacent to the dykes at SS4–SS7. If this model is correct, the *absence* of dykes should promote the contemporaneous development of dip- or oblique-slip extensional faults to

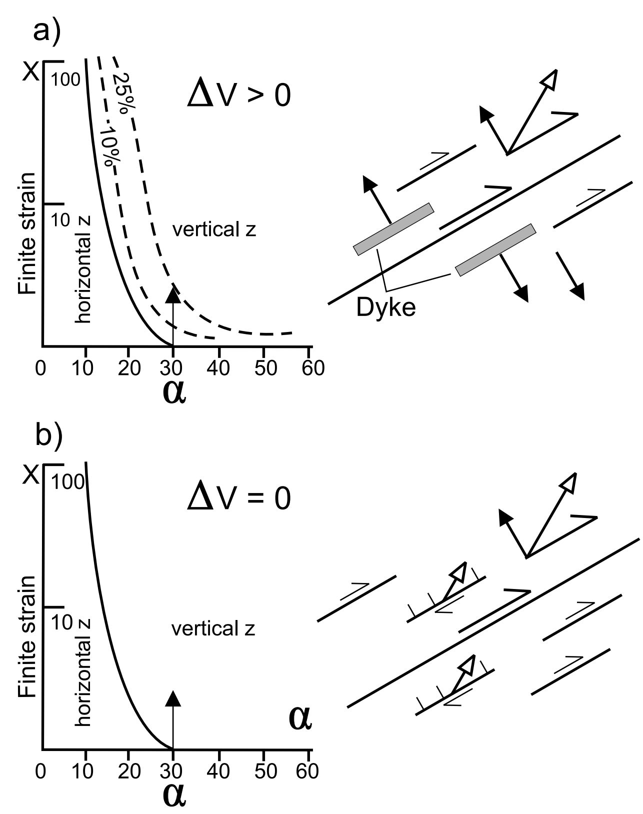

Fig. 15. (a) The fields of WDTT (horizontal *z*) and EDTT (vertical *z*) plotted on a transport direction (α) vs. finite horizontal extension strain axis (X) diagram. The dashed curves (from Teyssier and Tikoff, 1999) represent the effect of different amounts of volume increase during transtensional deformation. The sketch to the right shows the proposed structural model corresponding to the condition $\alpha=30°$ plotted on the diagram (black arrow) when positive volume change is due to dyke/sill intrusion. (b) Shows the same diagram as above, but plotted for a volume-constant transtensional deformation. The field of WDTT (horizontal *z*) is soon unstable with increasing amount of strain. The sketch to the right shows the plan-view structural model for the condition $\alpha=30°$ plotted on the diagram (black arrow).

relieve the residual component of extension that wrench faults were not able to accommodate (Fig. 15b). This is exactly the pattern of deformation observed at sites lacking intrusions (e.g. SS9; Fig. 12) where sub-parallel dip- and oblique-slip extensional faults and strike-slip faults are both present. In this case, the vertical, intermediate, infinitesimal axis *y* is negative and the strain ellipsoid will have a prolate shape typical of transtensional strains (Dewey, 2002). Very similar mixed geometric and kinematic patterns of structures have been reproduced in analogue experiments where the boundary conditions were similar to those inferred for the WDD ($\alpha < 30°$; Withjack and Jamison, 1986).

5.2. Strain partitioning: basement control?

It is widely accepted that the Northumberland Trough overlies the unexposed trace of the northward-dipping (15–25°) Iapetus suture zone at depth (Fig. 3a and b) (Bott et al., 1985; Chadwick and Holliday, 1991; Soper et al., 1992) and that the acoustically blank sequence observed in deep seismic reflection profiles within the basement overlying the suture corresponds to the southernmost part of the Laurentian crust, specifically the Southern Uplands accretionary prism (Bott et al., 1985; Beamish and Smythe, 1986).

Chadwick and Holliday (1991) have suggested that the Dinantian bounding faults of both the Northumberland Trough and possibly the Tweed sub-basin may have reactivated northerly-dipping Caledonian thrust zones at depth, some of which link into the Iapetus suture. A similar Caledonian basement control may have influenced the late Carboniferous deformation patterns. The ENE–WSW trend of the EDD–WDD boundaries, the dominant dextral strike-slip faults in the WDD and the trend of the Whin Sill complex dykes (Figs. 3b, 7, 9a and b and 11a) all correspond well with the trends of basement structures exposed in nearby regions of the Southern Uplands. The latter rocks experienced significant amounts of orogen-parallel sinistral shear from the Late Llandovery to the Devonian and carry a very well defined, moderately- to steeply-dipping ENE–WSW-trending fabric (e.g. see Holdsworth et al., 2002a,b). Reactivation of such a basement anisotropy during N–S or NE–SW extension would result in dextral transtensional bulk strains (Figs. 13 and 14).

The role of basement in controlling the *location* of the EDD and WDD is less clear. The WDD and trend of the associated en échelon dykes close to its northern and southern boundaries is clearly coincident with the position of the Cheviot block (Fig. 3b). The existence of this region as a relatively uplifted region during Dinantian rifting is likely to have been determined by the presence of the relatively buoyant Cheviot Granite at depth, a feature common to many of the uplifted horsts in the Carboniferous basins of Northern Britain (e.g. Leeder, 1982), including the Alston block immediately south of the Stublick-90 Fathom fault system (Fig. 3a and b). The partitioning of strike-slip deformation into the Carboniferous rocks overlying the Cheviot block may occur because the total thickness of basin fill is significantly reduced, making this region more susceptible to basement influence. More speculatively, it may be that the emplacement of the Cheviot granite—perhaps in a Caledonian pull-apart—has in some way made the basement fabric in this basement block more prone to strike-slip reactivation.

5.3. Inversion vs strain partitioning in the Northumberland Basin

The most commonly accepted interpretation of the tectonic evolution of the Northumberland Basin involves the initiation of an extensional basin in the Dinantian, with a subsequent phase of late Carboniferous inversion followed very closely by a phase of extension continuing into the early Permian. The latter event is generally considered synchronous with intrusion of the Whin Sill complex (e.g. Collier, 1989; Leeder et al., 1989), although others suggest that intrusion may have overlapped the inversion event (e.g. Shiells, 1964; Robson, 1980; Johnson, 1995). The late Carboniferous inversion is related, by almost all authors, to the far-field effects of the Variscan orogenic event in Southern Britain. The anomalous E–W orientation of shortening is generally attributed to the strike-slip jostling or lateral extrusion of basement-controlled fault bounded blocks in the Variscan foreland (e.g. Bower, 1990).

Our observations from the Northumberland Basin suggest an alternative and, from a regional late Carboniferous–early Permian tectonic viewpoint, much more straightforward interpretation. We propose that there was a single phase of prolonged (ca. 15 Ma) dextral oblique extension in this part of Northern Britain (Fig. 14). The differing and heterogeneous character of deformation observed across the basin results from a possibly basement-controlled partitioning of the regional transtension into geographically distinct domains of extension- and dextrally wrench-dominated strain. Importantly, analogue experiments have demonstrated that the component of horizontal shortening arising from a wrench-dominated transtensional strain (i.e. $\alpha < 30°$) is sufficient to generate conjugate wrench faults and associated folds with geometries identical to those observed in the Northumberland Basin WDD (Withjack and Jamison, 1986; Ramani and Tikoff, 2002).

The two contemporaneous strain fields can be integrated to give a bulk regional transport direction oriented ~N–S, oblique to pre-existing NE–SW-trending structures in the Laurentian basement underlying the Northumberland Basin (Fig. 14). The proposed tectonic setting fits well with the development of the tholeiitic Whin Sill complex during (oblique) lithospheric stretching, the effects of which are recognised all across NW Europe at this time (Neumann, 1994; Sundvoll and Larsen, 1994; Smythe et al., 1995; Ernst and Buchan, 1997, 2001; Timmerman, 2004). In the absence of any evidence for NNW–SSE shortening, our model also means that there is no need to invoke Variscan inversion in the Northumberland Basin, although it is likely that the events described here were contemporaneous with orogenesis further to the south.

5.4. Implications for the Carboniferous of Northern Britain

The dextral transtensional structures of the Northumberland Basin—and particularly those of the WDD—are very similar in terms of their orientation and scale to those that occur widely in the Carboniferous and older rocks of the Midland Valley in Scotland where a long history of dextral shearing is well known (e g. Read, 1988; Read et al., 2003). The widespread development of conjugate strike-slip fault arrays that compartmentalise generally N–S-trending folds and thrusts and the synchronous occurrence of tholeiitic magmatism in both regions is particularly striking. The dominance of dextral strike-slip displacements along faults with a distinctly Caledonian trend suggests that these basins are tectonically distinct from the other Carboniferous basins of Northern England, a feature almost certainly linked to the fact that they overlie Laurentian, as opposed to Avalonian, basement. On a broader scale, our findings have important implications for regional models of basin development and inversion, and how these events may be related to plate tectonic processes in Carboniferous–Permian times. The recent synthesis of Maynard et al. (1997) illustrates that tectonic models for this time period in Britain and NW Europe are becoming increasingly complex due to three inter-related factors:

(1) The importance of basement fault reactivation in controlling local tectonic patterns and evolution (e.g. Corfield et al., 1996; Woodcock and Rickards, 2003);
(2) The increasing recognition of the important role played by local and regional-scale strike-slip tectonics, partly—but not exclusively—due to reactivation of basement faults oriented obliquely to the regional plate tectonic vectors (e.g. Coward, 1993; Waters et al., 1994);
(3) The recognition of numerous, often localised 'uplift events' and unconformities within the intra-Carboniferous sedimentary record (e.g. Maynard et al., 1997).

In all these models, *an explicit link is made between inversion/uplift events and compressional or transpressional tectonic episodes*. This inevitably leads to more complex regional tectonic models. Our model of strain partitioning during a single and possibly protracted phase of regional transtension removes this unnecessary and unrealistic link between tectonic complexity on local and regional scales, whilst still emphasising the important role of basement control on deformation patterns. It allows local 'inversion' events to occur while a region experiences extension on a lithospheric scale, which can lead to widespread synchronous tholeiitic magmatism as a result.

Our findings strongly suggest that existing models of late Carboniferous–Permain inversion tectonics in the Variscan foreland of Northern Britain need to be reassessed, particularly in areas where the inferred shortening directions do not correspond well with the NNW–SSE orientation generally associated with Variscan collision (e.g. the Pennine Basin, e.g. Waters et al., 1994).

5.5. Global implications of the present study

The recognition that strain partitioning leads to local structural complexity that is not necessarily of regional (e g. plate-scale) significance is a recent theme that has received considerable attention in transpressional settings (e.g. Dewey et al., 1998; Holdsworth et al., 2002a; Clegg and Holdsworth, 2005; Jones et al., 2004). The equivalent importance of strain partitioning in transtension zones has received much less attention. Recent studies of tectonically active transtensional regimes have revealed the presence of structural domains characterised by different kinematic patterns and associated seismicity (e.g. Oldow, 2003). The domainal deformation patterns can be attributed directly to the obliquity between horizontal displacements measured using GPS velocity fields and pre-existing block-bounding faults in the crust. Oldow (2003), for example, has demonstrated that the angular relationship between incremental horizontal strain axes and horizontal displacement deviates from the typical geometry of plane strain deformation in a way that would be expected during transtensional deformation (Fig. 2a, c and d; see also McCoss, 1986; Teyssier et al., 1995; Dewey et al., 1998; Dewey, 2002). In ancient terrains, the far-field regional transport direction is generally unknown, but our study of the Northumberland Basin demonstrates that it can be reconstructed from the partitioned components of strain recognised within contemporaneously active, kinematically-different and spatially distinct structural domains (e.g. Fig. 14). These components can be calculated using the predictable geometric and kinematic relationships that exist between the orientations of the infinitesimal strain (stress) axes and the boundaries of the system in transtensional (and transpressional) systems (McCoss, 1986).

We suggest therefore that if the overall geometry, kinematics and spatial distribution of the structural domains in a basin display heterogeneous structural patterns and infinitesimal strain/stress inversions consistent with partitioned 3-D strain, then it is possible that the deformation was contemporaneous on a regional scale. Conversely tectonic events that are unrelated, and that occur at different times are much less likely to show consistent geometric and kinematic patterns. Our study illustrates that we cannot always reliably assume that infinitesimal strain or stress axes resolved in one part of a study area are parallel to regional transport directions, unless their relationship to the deformation patterns in adjacent crustal domains is also considered. This can lead to misunderstandings concerning the regional meaning of the bulk strain and nature of the tectonic regime (Tikoff and Wojtal, 1999). Hence, the scale of observation is crucially important during crustal deformation.

Pulsed extension–inversion–extension models are commonly invoked for many basins of different ages in onshore and offshore environments from all around the world in extensional and strike-slip settings. Phases of compression or transpression are typically related in some way either to the far-field affects of some distant orogenic event of similar age or to geometric features of strike-slip faults (bends, offsets, etc) leading to local inversions. We suggest that these models need careful reappraisal to see whether strain partitioning into extension- and wrench-dominated transtensional deformation domains may provide an improved and more elegant explanation for the observed structural complexities. This may eventually help to simplify our increasing complex plate–tectonic models in ancient environments and lead to an improved understanding of basin dynamics that is central to hydrocarbon and other economic exploration activities in obliquely tectonic regimes.

Acknowledgements

The authors would like to thank Richard Jones at Durham for useful discussions. De Paola gratefully acknowledges the support of the Universities of Perugia and Durham. Donatella Zappalà is thanked for her help during fieldwork. The journal referees, Nigel Woodcock and Anonymous, made helpful and very constructive comments.

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