



Outcrop-scale manifestations of reactivation during multiple superimposed rifting and basin inversion events: the Devonian Orcadian Basin, northern Scotland


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Abstract: The Devonian Orcadian Basin in Scotland hosts extensional fault systems assumed to be related to the initial formation of the basin, with only limited post-Devonian inversion and reactivation. However, a recent detailed structural study across Caithness, underpinned by published Re–Os geochronology, shows that three phases of deformation are present. North–south- and NW–SE-trending Group 1 faults are related to Devonian ENE–WSW transtension associated with sinistral shear along the Great Glen Fault during the formation of the Orcadian Basin. Metre- to kilometre-scale north–south-trending Group 2 folds and thrusts are developed close to earlier sub-basin-bounding faults and reflect late Carboniferous–early Permian east–west inversion associated with dextral reactivation of the Great Glen Fault. The dominant Group 3 structures are dextral oblique NE–SW-trending and sinistral east–west-trending faults with widespread syndeformational carbonate mineralization (\pm pyrite and bitumen) and are dated using Re–Os geochronology as Permian (*c.* 267 Ma). Regional Permian NW–SE extension related to the development of the offshore West Orkney Basin was superimposed over pre-existing fault networks, leading to local oblique reactivation of Group 1 faults in complex localized zones of transtensional folding, faulting and inversion. The structural complexity in surface outcrops onshore therefore reflects both the local reactivation of pre-existing faults and the superimposition of obliquely oriented rifting episodes during basin development in the adjacent offshore areas.

Supplementary material: Stereographic projections of compiled structural data from individual fieldwork localities are available at <https://doi.org/10.6084/m9.figshare.c.5115228>

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The phenomenon of structural inversion, in which pre-existing normal faults formed during the development of a rift basin are reactivated as reverse faults, sometimes with associated folding, is recognized worldwide across a broad range of scales (e.g. Williams *et al.* 1989). A key feature of many examples is that the distribution and kinematic character (e.g. contractional or transpressional) of the later inversion structures are strongly controlled by the location and orientation of the pre-existing rift-related structures (e.g. Peacock and Sanderson 1995). The consequences of the superimposition of later rifting episodes – related, for example, to the development of an adjacent, or superimposed, younger basin – have been explored extensively using analogue and numerical modelling approaches (e.g. Agostini *et al.* 2009; Corti 2012). It has been demonstrated that, if suitably oriented for reactivation, old rift basin faults can influence the location of later rift-related faults and their kinematic character. In the younger basin fill, a general consequence of superimposed rifting seems to be an increase in the structural complexity of younger deformation events. The consequences for structures developed in the older basin fill are less explored and are not so readily investigated using modelling. These processes have significant potential to influence the development of fault damage zones (*sensu lato*) and thus fluid transport and the storage capacity of subsurface reservoirs, including aquifers and hydrocarbon and geothermal reservoirs.

The scenario in which an older rift basin fill is affected by a younger rift-related deformation event (or events) is likely to be

common in the geological record. This situation will most often be preserved in areas where an old basin exposed at the surface in an onshore, coastal location lies adjacent to a younger rift basin developed immediately offshore. This is a common situation in the region of the British Isles, which is surrounded by younger offshore basins (e.g. Woodcock and Strachan 2012), and it is probably also found in many other regions worldwide.

We present a detailed case study of the Devonian strata of the Orcadian Basin in northern Scotland (Fig. 1a). These strata are affected by at least three phases of superimposed deformation: early rifting related to Devonian basin formation; a later episode of regional Carboniferous inversion; and a younger episode of Permian rifting related to the development of the West Orkney Basin, which lies offshore and immediately to the north of the Scottish mainland. We use field-based observations and measurements to characterize the structural geometries, kinematics and associated fault rocks/fracture fills that are related to each of the regionally recognized deformation events as manifest in the Devonian strata. Cross-cutting and reactivation–inversion relationships are explored, with constraints on the absolute timing of particular events being provided by published Re–Os and other dates for the associated vein fills and minor intrusion events. Finite strains and fault-related block rotations are modest on a regional scale, so we additionally use stress inversion of slickenline lineations on faults to reconstruct the regional tectonic history. Our findings show how multiscale reactivation leads to a prevalence of mesoscale transpressional

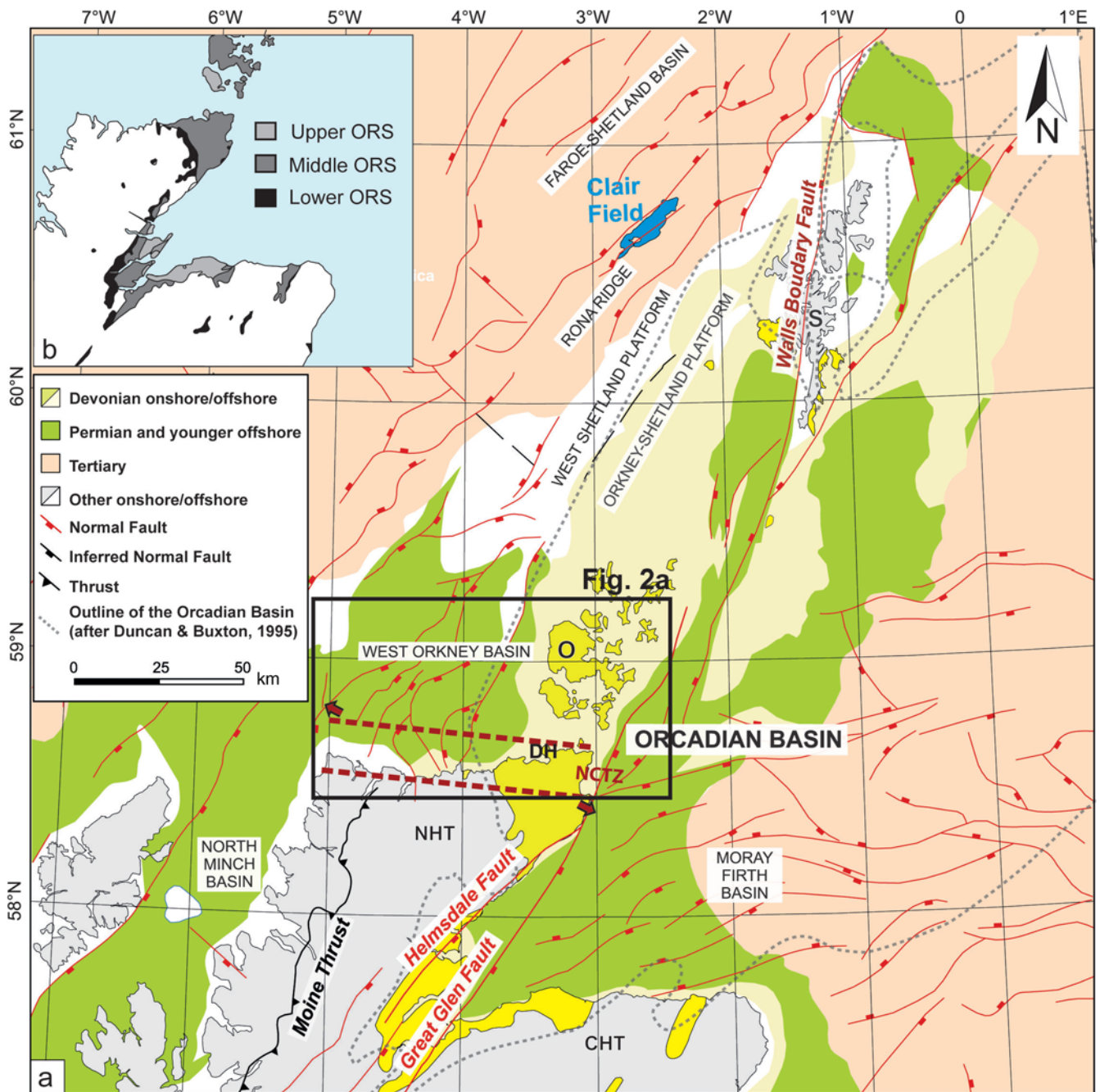


Fig. 1. (a) Regional geological map of northern Scotland and associated offshore regions adapted from *Evans et al. (2003)* showing the main basins, regional fault systems, offshore seabed outcrops and onshore Devonian sedimentary outcrops. (b) Simplified geological map of the onshore Orcadian Basin in mainland Scotland and Orkney showing onshore outcrops of Lower, Middle and Upper Old Red Sandstone. CHT, Central Highland (or Grampian) Terrane; DH, Dunnet Head; NCTZ, North Coast Transfer Zone after *Wilson et al. (2010)*; NHT, Northern Highland Terrane; O, Orkney; ORS, Old Red Sandstone; S, Shetland.

and transtensional structures in the Devonian strata of the Orcadian Basin, with significant implications for the exploration and exploitation of subsurface hydrocarbons in older Devonian–Carboniferous reservoirs, such as the giant Clair Field west of Shetland.

Geological setting

Orcadian Basin

The Devonian Orcadian Basin occurs both onshore and offshore in the Caithness, Orkney and Moray Firth regions of northern Scotland, overlying Caledonian basement rocks of the Northern (Moine) and Central Highland or Grampian (Dalradian) terranes

(*Fig. 1a*; *Johnstone and Mykura 1989*; *Friend et al. 2000*). The Orcadian Basin belongs to a regionally linked system of Devonian basins that extend northwards into Shetland, western Norway and eastern Greenland (*Seranne 1992*; *Duncan and Buxton 1995*; *Woodcock and Strachan 2012*). It is partially overlain by a number of Permian to Cenozoic, mainly offshore, depocentres, including the West Orkney and Moray Firth basins (*Fig. 1a*).

Lower Devonian (Emsian) synrift alluvial fan and fluvial–lacustrine deposits are mostly restricted to the western fringes of the Moray Firth region (*Rogers et al. 1989*) and parts of Caithness (*NIREX 1994a*), occurring in a number of small fault-bounded basins of limited extent (*Fig. 1b*). These are partially unconformably overlain by Middle Devonian (Eifelian–Givetian) synrift alluvial, fluvial, lacustrine and locally marine sequences that

dominate the onshore sequences exposed in Caithness, Orkney and Shetland (Marshall and Hewett 2003). Upper Devonian (latest Givetian–Famennian), post-rift fluvial and marginal aeolian sedimentary rocks (Friend *et al.* 2000) are only found as fault-bounded outliers at Dunnet Head in Caithness and on Hoy, in Orkney (Figs 1b, 2a–c).

Basin formation, inversion and superimposed rifting events

The origin of the Orcadian and nearby West Orkney basins has been controversial. Interpretations of deep crustal and shallow commercial seismic reflection profiles north of Scotland show that the West Orkney Basin comprises a series of half-graben bounded by easterly

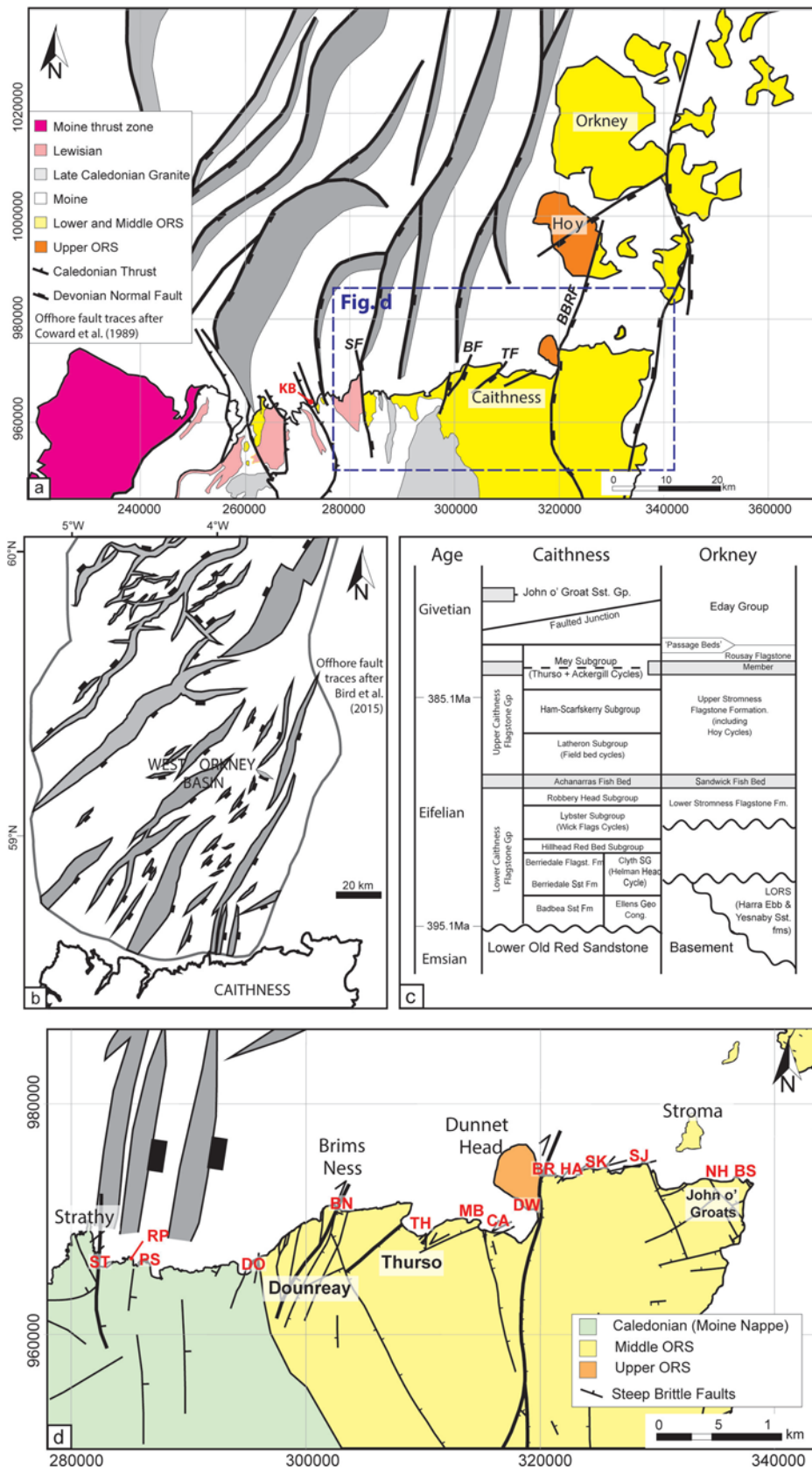


Fig. 2. Regional onshore and offshore structures, stratigraphy and localities studied. (a) Onshore geology of the northern Scottish coastline with main fault zone traces mapped from seismic reflection data in the offshore West Orkney Basin by Coward *et al.* (1989). (b) Offshore faults in the West Orkney Basin based on more recent re-interpretation of seismic reflection data by Bird *et al.* (2015). (c) Regional stratigraphy of Devonian rocks in Caithness and Orkney area based on lithology and fossil content (after Andrews *et al.* 2016). (d) Main fieldwork localities discussed in the text or in the Supplementary Material. Offshore faults from Bird *et al.* (2015). BN, Brims Ness; BR, Brough Harbour; BS, Bay of Sannick; CA, Castletown; DO, Dounreay; DW, Dwarwick; HA, Ham Bay; KB, Kirtomy Bay; MB, Murkle Bay; NH, Ness of Huna; PS, Portskerra; RP, Red Point; SJ, St John's Point; SK, Scarfskerry; ST, Strathy; TH, Thurso Bay. Major Devonian-age faults as follows: BBRF, Brough–Brims of Risa Fault; BF, Bridge of Forrs Fault; SF, Strathy Fault; TF, Thurso Bay Fault.

dipping normal faults (e.g. Brewer and Smythe 1984; Coward and Enfield 1987; Bird *et al.* 2015). Earlier interpretations (e.g. Enfield and Coward 1987; Norton *et al.* 1987) suggested that much of the basin fill was Devonian and that both the Orcadian and West Orkney basins formed due to the extensional collapse of the Caledonian orogeny. In these models, the graben-bounding faults were interpreted to root downwards into extensionally reactivated Caledonian thrusts. More recent studies have cast doubt on these models, showing that the fill of the West Orkney Basin is predominantly Permo-Triassic (e.g. Stoker *et al.* 1993) and that there is only limited onshore evidence for the reactivation of basement structures (e.g. Roberts and Holdsworth 1999; Wilson *et al.* 2010).

The Devonian rocks in the onshore Orcadian Basin are cut by numerous sets of faults and fractures and, more locally, are also folded (e.g. Enfield and Coward 1987; Norton *et al.* 1987; Coward *et al.* 1989; Fletcher and Key 1992; NIREX 1994a, b). Most researchers have assumed that the structures are either Devonian rift-related features and/or that they are a result of later Permo-Carboniferous basin inversion, possibly related to the far-field effects of the Variscan orogenic event and/or to dextral strike-slip reactivation of the Great Glen Fault (e.g. Coward *et al.* 1989; Seranne 1992).

A regional study along the northern coastline of Scotland in the basement-dominated region lying to the west of the Orcadian Basin presented field evidence that the faults hosted in basement rocks and overlying Devonian and Permo-Triassic red bed outliers are the result of two kinematically distinct and superimposed phases of rifting (Wilson *et al.* 2010). An early phase of ENE-WSW extension was documented and thought to be related to Devonian sinistral transtension associated with movements on the Great Glen Fault (Dewey and Strachan 2003). This was overprinted by a widely developed later phase of NW-SE extension. Geological and palaeomagnetic evidence from fault rocks and red bed sedimentary rocks in the Tongue and Durness regions (Fig. 2a; Blumstein *et al.* 2005; Elmore *et al.* 2010; Wilson *et al.* 2010) suggest that this later rifting was Permo-Triassic and related to the offshore development of the West Orkney and Minch basins. The general north-south trends of the half-graben-bounding faults onshore were therefore interpreted to be Devonian structures entirely older than the more NNE/NE-SSW/SW fault trends related to the Permo-Triassic fill of the West Orkney Basin offshore (Fig. 2a, b). This suggestion has been confirmed by recent re-mapping of the top-basement faults from offshore seismic reflection data (Fig. 2b; Bird *et al.* 2015).

Dichiarante *et al.* (2016) showed that faulting in the Middle Devonian rocks in the Dounreay district (Fig. 2d) is dominated by NNE- to NE-striking faults associated with syntectonic carbonate-base metal sulfide-hydrocarbon mineralization hosted in tensile veins, dilational jogs and along shear surfaces. Stress inversion analyses carried out on slickenline-bearing mineralized faults in the region consistently show that they are associated with a regional phase of NW-SE extension. Re-Os geochronology on two samples of fault-hosted pyrite yielded a weighted average model age of 267.5 ± 3.4 [3.5] Ma (Dichiarante *et al.* 2016). This suggests that the main phase of extensional-transtensional faulting cutting the Devonian rocks of the Dounreay district (and, by inference, a substantial part of Caithness) is mid-Permian. Following on from the model proposed by Wilson *et al.* (2010), Dichiarante *et al.* (2016) speculated that the dominant set of faults seen all along the north coast of Scotland form a regional-scale North Coast Transfer Zone (NCTZ; Fig. 1a) related to the tectonic development of the latest Paleozoic to Mesozoic basins offshore and to the north. The Devonian fill of the older Orcadian Basin in onshore Caithness has therefore experienced a later superimposed episode of rift-related deformation related to the Permo-Triassic West Orkney Basin offshore.

Magmatism

During the Late Carboniferous-Early Permian, a widespread and locally intense magmatic event (*c.* 305–260 Ma) occurred across NW Europe related either to extension/transtension in the Variscan foreland region or to the development of a regional mantle plume (Upton *et al.* 2004). An extensive suite of lamprophyre dykes with NW-SE to ENE-WSW trends was emplaced in the Scottish Highlands. According to Stephenson *et al.* (2003), the magmas are dominantly transitional to mildly alkaline, becoming generally more highly alkaline and silica-undersaturated with time. They are clearly mantle-derived and some are characterized by very primitive and compositionally extreme alkali-rich lamprophyric and feldspathoid-bearing rocks.

The Scottish lamprophyre dykes are classically divided into three groups with preferred NW-SE, east-west and NE-SW strike directions, the last group being centred on Orkney and extending into Caithness (Rock 1983). The age range of the Orkney dyke swarm is 268–249 Ma, with a K-Ar age of 252 ± 10 Ma obtained from three dykes in the Thurso region (Baxter and Mitchell 1984). In addition to the dykes, a series of volcanic necks and plugs are also sporadically distributed across the Scottish Highlands (e.g. Dunnet Head and the Ness of Duncansby) and are largely composed of explosion breccias related to the degassing of the volatile-rich magmas, possibly those feeding the lamprophyre dykes (Read *et al.* 2002). Macintyre *et al.* (1981) obtained a poorly defined K-Ar age from the vents at Ness of Duncansby, 0.5 km west of the Bay of Sannick (Fig. 2d), of *c.* 270 Ma.

Structural geology of the Orcadian Basin in Caithness

Methodology

The fieldwork reported here focused on the faults, folds, fault rocks and associated mineralization cutting Devonian strata along the northern coast of Caithness from Kirtomy Bay to John O'Groats (Fig. 2a, d). A summary of the structural data collected from each locality is given in Figures S1–4 of the Supplementary Material. The relative ages of structures, mineral veins, fault rocks and minor igneous intrusions were ascertained from cross-cutting relationships observed in multiple outcrops. Structural geometries were recorded through the collection of orientation data and the fault kinematics were determined based on offsets of markers in the host rocks, the local preservation of slickenline lineations and the preservation of asymmetrical brittle shear criteria, such as en echelon veins and slickenline steps (Petit 1987).

Fault-slip slickenline data were collected *in situ* and conventional stress inversion techniques (Angelier 1979, 1984; Michael 1984) were carried out using MyFault software (version 1.05 by Pangea Scientific Ltd.) to calculate the minimized shear stress variation. This method assumes that all slip events are independent, but occur as a result of a single stress regime. The small (<5 m) displacements observed on most structures suggest that the regional strain intensities were low and the degree of rotational strain was negligible. The minimized shear stress method of Michael (1984) consistently gave regional extension directions that fitted best with the poles to contemporaneous tensile veins measured in the field, or to the directions that bisected the conjugate shear fractures; it also yielded the smallest errors. A regional summary of the stress inversion data is given in the following sections, whereas the inversions carried out at individual localities are given in Figure S5 of the Supplementary Material.

Basement-cover relationships and basin architecture

The Middle Devonian rocks of the Caithness area are in excess of 4 km thick and are divided into three stratigraphic groups based on

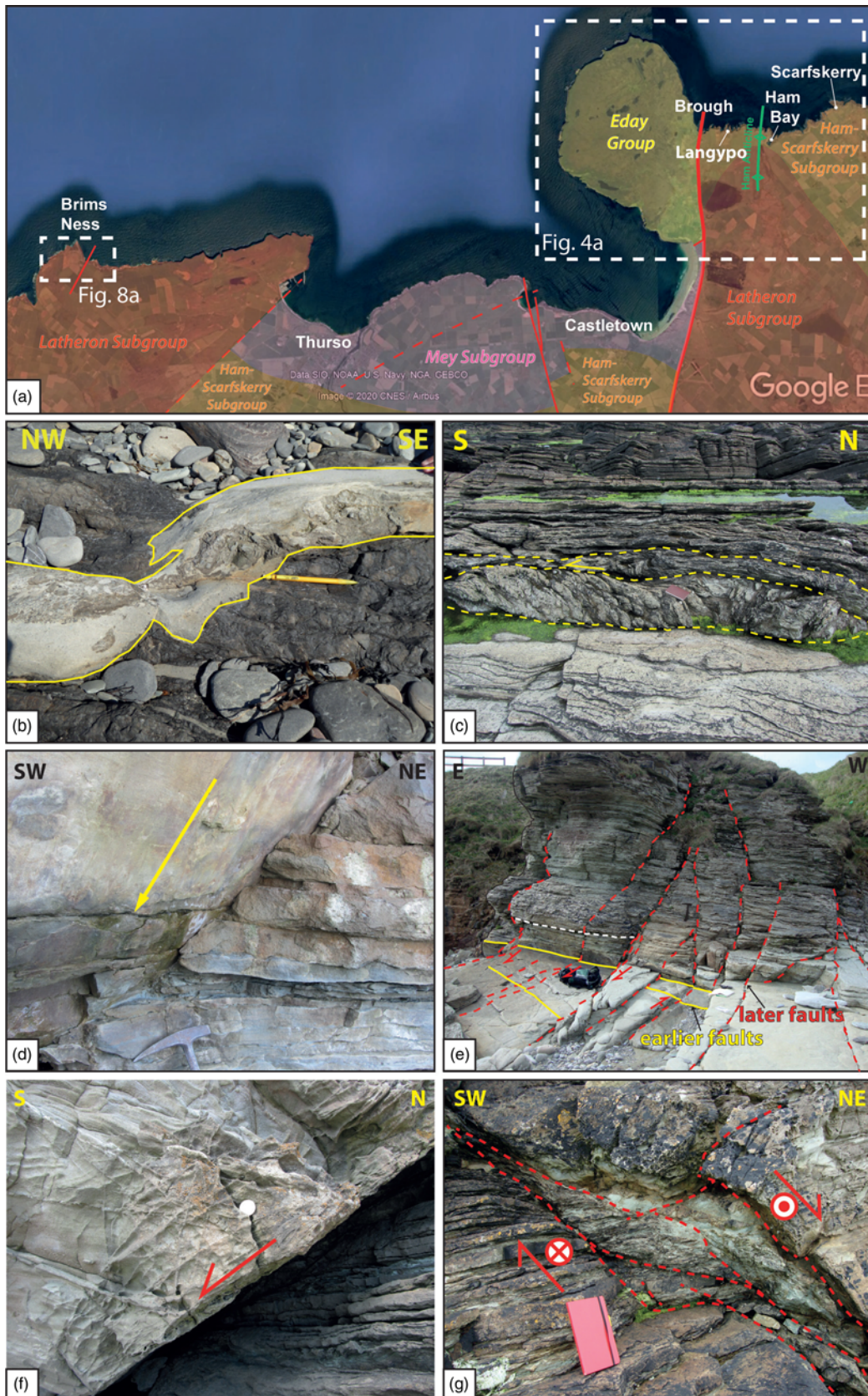


Fig. 3. Group 1 structures in the field. (a) Simplified geology map between Brims Ness and Scarfskerry showing localities and locations of Figures 4a and 8a. (b) Oblique view of a pale Neptunian sandstone injection (highlighted in yellow) and breccia cross-cutting shales and siltstones close to the trace of the inferred early synsedimentary fault trending NW-SE in Scarfskerry harbour (see Fig. 10a). (c) Cross-section view of bedding-parallel detachment and thrust duplex with inferred top-to-the-SE displacement, Scarfskerry foreshore. (d) Typical 'clean break' Group 1 fault with downdip slickenlines, Thurso foreshore. (e) NW-SE Group 1 faults (yellow) cross-cut and offset with small dextral offsets by NE-SW Group 3 faults (red), Thurso foreshore. (f) Cross-section view of multiple sets of deformation bands developed in sandstone from the hanging wall of a Group 1 fault, Brims Ness foreshore. (g) Plan view of green fault gouge associated with a Group 1 fault, probably derived from adjacent mudstone wall rock units, Brims Ness foreshore.

lithology and fossil content (from oldest to youngest): the Lower Caithness Flagstone Group, the Upper Caithness Flagstone Group and the John O’Groats Sandstone Group (Fig. 2c; Andrews *et al.* 2016). With the exception of the Upper Devonian rocks of Dunnet Head and the John O’Groats Sandstones that crop out east of St John’s Point (Fig. 2d), the rocks studied along the north coast during this work all belong to the Upper Caithness Flagstones. In the region east of the NNE–SSW-trending Bridge of Forrs Fault (Fig. 2a), this group is conveniently subdivided on the basis of fossil associations into three formations that are collectively estimated to form a succession up to 1 km thick (oldest to youngest): the Latheron Subgroup (155 m), the Ham–Skarfiskerry Subgroup (750 m) and the Mey Supergroup (>583 m) (Fig. 2c; Donovan *et al.* 1974; Trewin 2002; BGS 2005).

Middle Devonian strata are seen to unconformably overlie basement rocks in eastern Sutherland either in small isolated outliers separate from the Orcadian Basin (e.g. Kirtomy, Baligill; Fig. 2a) or where strata in the marginal, western parts of the basin overlie basement inliers (e.g. Red Point, Portskerra; see Trewin 1993 and references cited therein) (Fig. 2d). In both settings, well-developed buried landscapes are preserved, with the local topographic relief exceeding 30 m and the development of onlapping sequences of Devonian strata, synsedimentary slumping and local differential compaction features (Donovan 1975; Trewin 1993).

Regional mapping has revealed a series of generally north–south-trending faults that delimit a series of half-graben, which step progressively down to the east and form the structural backbone of the Orcadian Basin in Caithness (Fig. 2a, d). In detail, the orientations vary from NW–SE to NE–SW. Some of the more important structures are, from west to east, the Kirtomy, Strathy, Bridge of Forrs, Thurso Bay and Brough faults. As a result of the present day flat topography and strong erosion along the coast, almost all of these faults are obscured by bays and are not exposed. They can be identified from offsets of the mapped geological units (e.g. Fig. 3a) and many preserve good evidence for major changes in stratigraphy and/or the thickness of units, which suggests that they were active during Devonian times as basin or sub-basin-bounding structures (Fletcher and Key 1992). Devonian age movements on some other faults – such as the NW–SE Scarfiskerry Fault – are indicated by the presence of narrow zones of abundant sedimentary (‘Neptunian’) dykes (e.g. Fig. 3b) and soft sediment deformation features, including bedding-parallel detachments and associated folds (e.g. Fig. 3c).

Regionally recognized outcrop-scale deformation events

Across all of the north coastal outcrop in Caithness, large areas of the Devonian strata are shallow-dipping (<20°) and are essentially undeformed, although well-developed, strata-bound joint systems – not specifically discussed in this paper – are ubiquitous. Deformational features are dominated by faults and fractures, with widespread hydrothermal mineralization, small volumes of locally derived hydrocarbons and mostly metre- to decametre-scale developments of folds and thrusts. All the regions of more intensely deformed strata are highly localized on scales of metres to tens of metres and most lie close to larger kilometre-scale fault zones. Lineament analyses across the Orcadian Basin in Caithness (Dichiarante 2017) and a more detailed study in the Dounreay area (Dichiarante *et al.* 2016) reveals three main structural trends related to fractures onshore: north to NNE–south to SSW, NE–SW and NW–SE. The north–south lineaments are typically two to three times longer than those trending in other directions.

Three distinct sets of deformation structures are recognized in the Devonian rocks across Caithness and can be distinguished based on trend, structural style, cross-cutting relationships and – importantly – the associated fault rocks and vein fills (Figs 3–6). These are termed here (earliest to latest) Group 1, Group 2 and Group 3. Group 3

structures dominate in the region west of St John’s Point (Dichiarante *et al.* 2016).

Group 1 structures

Group 1 structures are either steeply to moderately dipping normal faults or highly localized systems of metre- to millimetre-scale folds and low-angle, often bedding-parallel detachments, which appear to have formed early in the geological history of the region during the Devonian. The detachments are mostly small-scale bedding-parallel features with centimetre-thick zones of thrust duplexes (Fig. 3c) or chaotic folds locally injected by grey gouges originating along the bounding basal detachment surfaces. Isolated examples of larger metre-scale structures are preserved in Lower Devonian strata at Sarclett Point on the northern shore of the Moray Firth (see Trewin 1993). These structures may have formed prior to full lithification and been driven by downslope gravity-driven collapse in response to the local basin topography, which may itself be fault-controlled (e.g. Parnell *et al.* 1998).

No known example of major Group 1 fault cores are exposed anywhere onshore. Steeply dipping Group 1 minor faults are fairly widespread and are mostly north–south to NNE–SSW and NW–SE oriented (Fig. 6a). The strata are always extended across fault traces and, where preserved, slickenlines are predominantly dip-slip to oblique-slip (e.g. Figs 3d and 6b). Those minor faults reliably identified as Group 1 structures are usually recognized as they are consistently cross-cut by younger Group 2 or 3 structures (e.g. Fig. 3e). Given the diversity of structures and orientations, it is conceivable that more than one phase of deformation is represented by Group 1 structures, but it is difficult to separate these out given the widespread development of later faults and fractures across the region. What all the Group 1 structures share in common is that they lack widespread carbonate–sulfide–bitumen mineralization (Fig. 3d–g; unlike Group 3 structures), except where they have experienced later reactivation. In addition, they are often associated with the widespread development of cataclastic deformation bands (Fig. 3f) in sandstones and more localized clay-rich gouges in areas where siltstone/mudstone units are caught up in the deformation adjacent to Group 1 faults (Fig. 3g).

Group 2 structures

Group 2 structures comprise zones of centimetre- to kilometre-scale north–south to NE–SW folds, with both east- and west-verging geometries and associated top-to-the-east/SE or top-to-the-west/NW thrusts (Figs 4a–d, 6a, b, d). Folds are open to tight, are locally kink-like, with box fold geometries and poorly developed sub-centimetre spaced crenulation cleavages parallel to local axial planes (Fig. 4c, d). Bedding-parallel slickenlines are locally developed and are consistently oriented at high angles to the fold hinges, with senses of shear consistent with flexural slip folding (Fig. 6e). Major folds formed at this time are consistently located close to pre-existing north–south Group 1 faults, the largest being the regional Ham Anticline located east of the Brough Fault (Fig. 4a). More isolated sets of metre- to decametre-scale Group 2 folds, such as those seen at Brims Ness Chapel (Fig. 4c) and Langyop (Fig. 4d), may well overlie reactivated Group 1 faults buried at depth, although this is difficult to prove. At outcrop scales, the Group 2 structures are once again characterized by a lack of associated syntectonic mineralization; if veins are present, then they cross-cut the folds and thrusts and are inferred to be related to overprinting Group 3 events.

Group 3 structures

Group 3 structures comprise faults and fractures sets that consistently reactivate or cross-cut Group 1 and 2 structures and

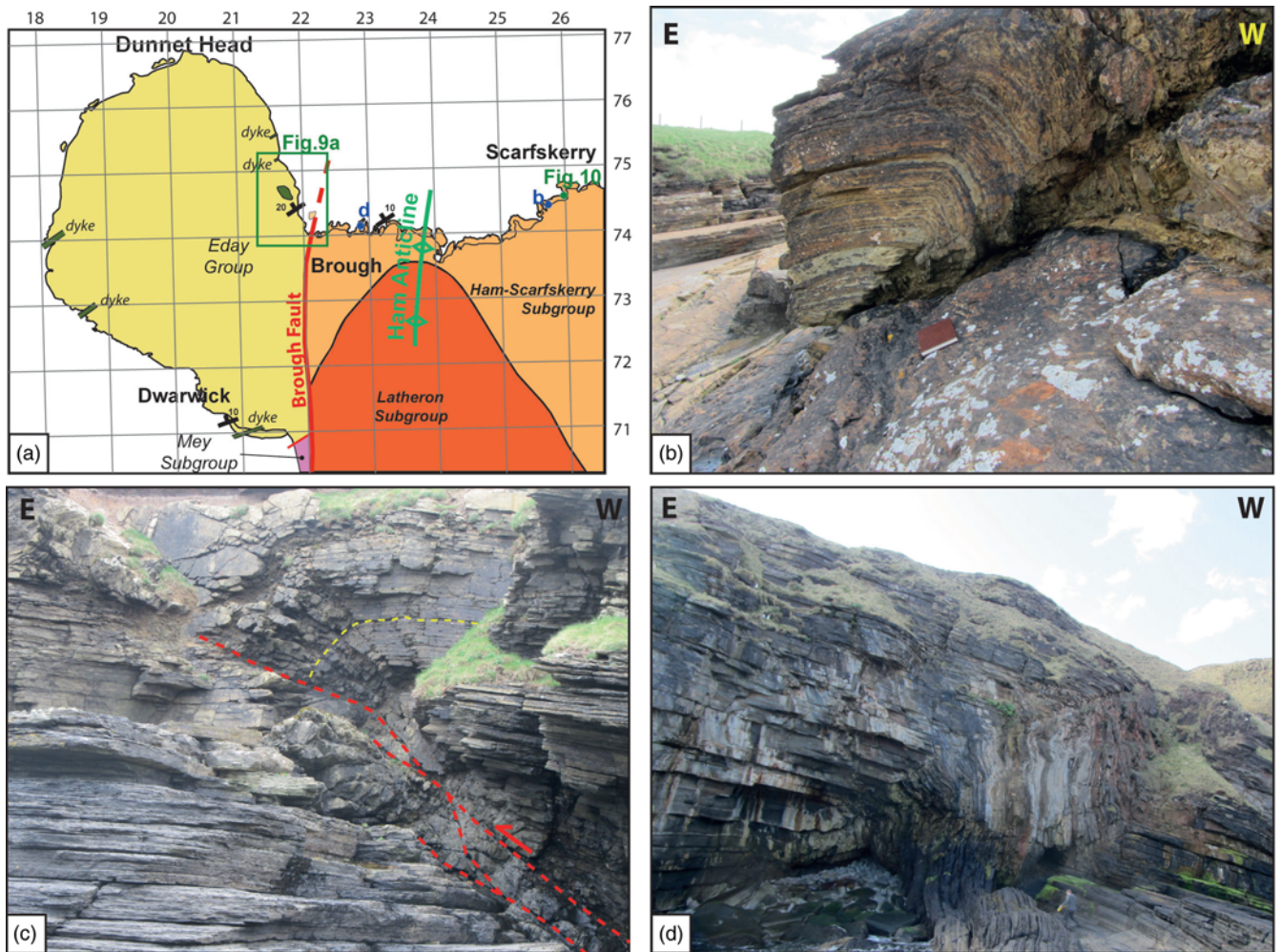


Fig. 4. Group 2 structures in the field. (a) Sketch map of the Dunnet Head to Scarfskerry coastal section showing the axial trace of the Ham Anticline and its location relative to the Brough Fault (after BGS 2005). The locations of the images shown in parts (b) and (d) are also shown. (b) West-verging anticline in the hanging wall of a small top-to-the-west thrust fault, foreshore SW of Scarfskerry harbour. (c) Metre-scale east-verging composite anticline-synform pair with minor top-to-the-east thrusts (red) and crudely developed crenulation cleavage, Brims Ness Chapel. (d) Decametre-scale west-verging anticline-synform pair at Langyppo; note the kink-like geometry of the fold pair.

comprise generally NE-SW-trending faults with dextral normal kinematics (e.g. Fig. 5a-c; see Dichiarante *et al.* 2016), together with east-west to ENE-WSW trending faults with sinistral kinematics (e.g. Fig. 5d) (see also Fig. 6a, b). Deformation intensities are regionally low, with the displacements along many minor faults rarely being greater than a few metres. As shown by Dichiarante *et al.* (2016), Group 3 brittle structures are widely and consistently associated with pale carbonate-base metal sulfide (pyrite-chalcopyrite-chalcocite)-bitumen mineralization that developed synchronously with faulting (e.g. Fig. 5c, d). The development of centimetre- to metre-width fault-bounded fracture corridors comprising interlinked systems of shear, hybrid and conjugate shear fractures is widespread (Fig. 5a). Open oil-filled vuggy cavities and fault-bounded lenses of breccia are widely developed along these fracture corridors and suggests that, in the geological past, many of these fault zones have acted as efficient fluid flow pathways. The hydrocarbons appear to be sourced from organic-rich horizons in the local Devonian stratigraphy (Marshall *et al.* 1985; Parnell 1985).

Millimetre- to metre-scale, gentle to tight minor folds are locally associated with Group 3 faults with oblique kinematics, especially (but not always) in areas where pre-existing Group 1 faults have been reactivated. NNW- to NW-trending folds are commonly associated with dextrally reactivated north-south or NNE-SSW

faults (e.g. Fig. 5e), whereas more east-west-trending folds are locally associated with ENE-WSW-trending sinistral faults (e.g. St John's Point). These structures can be distinguished from earlier Group 2 folds by their different orientations (Fig. 6d) and close spatial association with Group 3 age faults, which commonly bound the localized regions of folding (e.g. Fig. 5e). More importantly, however, they are widely associated with carbonate-sulfide-bitumen mineralization that, unlike the Group 2 folds, was emplaced synchronously with folding – for example, in the stretched outer arcs of folded beds (Fig. 5f).

Stress inversion analysis

A regional-scale stress inversion analysis of the correlated structural groups was carried in the Caithness study area (Fig. 6a, b). Locality-based stress inversions are presented in Figure S5 of the Supplementary Material.

Regionally, the Group 1 faults trend NNE-SSW, north-south and NW-SE and display predominantly sinistral strike-slip to dip-slip extensional movements (Fig. 6a, c). The relative paucity of faults with slickenlines explains why there are relatively few measurements relative to the Group 3 structures. A proportion of the Group 3 data probably comes from reactivated Group 1 faults, but it is commonly difficult to prove this in the field. Collectively, the Group

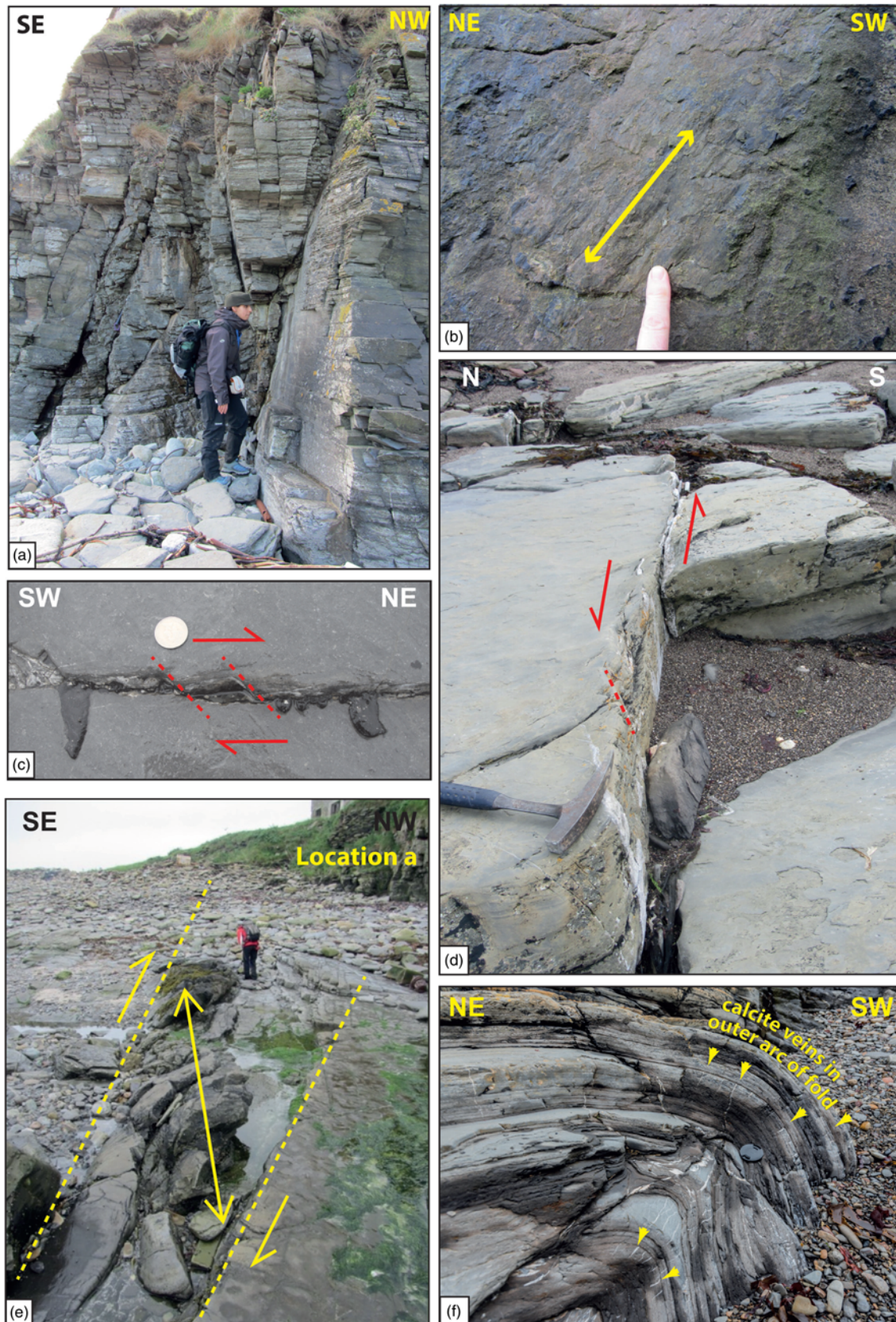


Fig. 5. Group 3 structures in the field. (a) Sectional view of typical fracture corridor and damage zone comprising linked sets of conjugate shear and tensile fractures with associated calcite-fills, Port of Brims harbour, below castle (ND 0434 7103). (b) Oblique view of NE–SW Group 3 fault plane, looking at footwall. Stepped calcite slickenfibres (arrowed) give dextral normal shear sense, Dounreay area. (c) Plan view of NE–SW Group 3 fault with dextral Reidel shears and calcite–bitumen fills, the latter leaking out onto the outcrop, Murkle Bay (ND 1722 6927). (d) Oblique view of ENE–WSW sinistral Group 3 fault with en echelon calcite-filled tensile fractures indicating sinistral shear parallel to slickenfibres exposed on fault plane, Ham Bay (ND 2406 7351). (e) Oblique view of Group 3 NNW–SSE open folds (parallel to yellow arrow) bounded by along-strike continuation of fracture corridor shown in part (a) with inferred dextral shear sense, Brims Harbour foreshore. (f) Tight folds with associated calcite mineralization, Scarferry Harbour (ND 2604 7448); note the tensile veins in the stretched outer arcs of hinge zones suggesting that tightening of folds (at least) is same age as mineralization (i.e. Group 3).

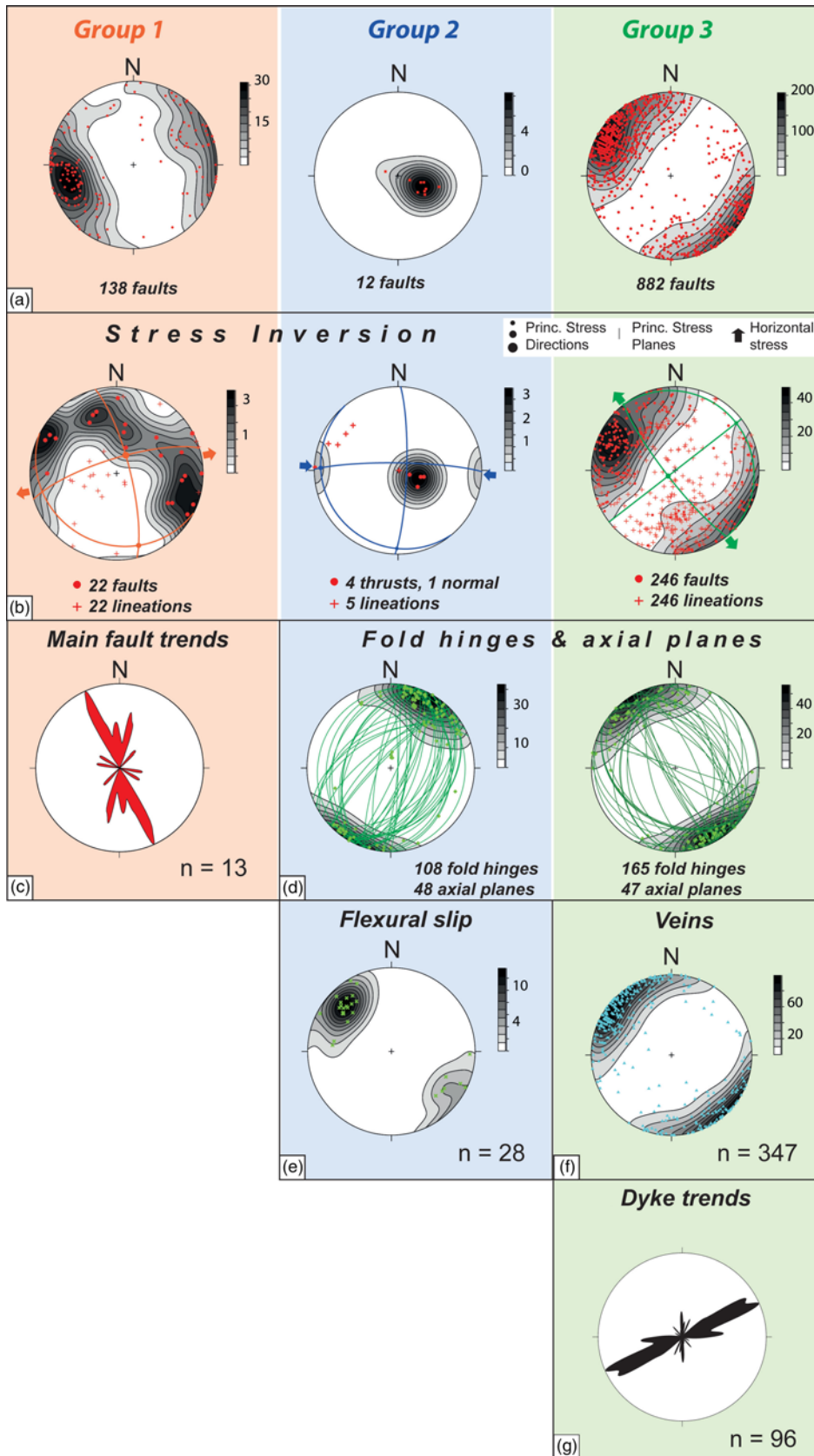


Fig. 6. Regional stereographic data compilations of structural data from the entire study area (a, c–g) and bulk stress inversion analyses (b). Structures are grouped according to relative age and include (a) poles to faults with slickenlines; (c) trends of major faults; (d) fold hinges and axial planes; (e) flexural slip lineations on bedding planes; (f) poles to tensile veins; and (g) dyke trends.

1 data are consistent with an extensional to transtensional regime (σ_1 subvertical) with a sub-horizontal to shallowly plunging regional extension (σ_3) towards the ENE–WSW (orange arrows in Fig. 6b).

The Group 2 structures are systems of metre- to kilometre-scale north–south- to NE–SW-trending folds and thrusts related to a

highly heterogeneous regional inversion event, recognized mainly in the eastern outcrops of the Caithness area, east of the Bridge of Forrs Fault (Fig. 2a). Where stress inversions were possible – bearing in mind that most of these structures are folds – an ESE–WNW compressional to sinistrally transpressional regime is indicated (Fig. 6b). Importantly, this shortening direction is

kinematically consistent with the regional trends of the folds and the associated flexural slip lineations formed by bedding-parallel slip during folding (Fig. 6d, e).

The Group 3 structures are dextral oblique NE–SW-trending faults and sinistral east–west- to ENE–WSW-trending faults (Fig. 6a) with widespread syndeformational carbonate mineralization (\pm sulfides and bitumen) both along the faults and in the associated mineral veins. In a few localities (e.g. Kirtomy, Brough and Skarfskerry), strike-slip inversion events occurred at this time, leading to localized folding during the reactivation of pre-existing (Group 1) Devonian faults. These folds trend generally NW–SE (Fig. 6d) with hinges oriented sub-parallel to the regional extension vector, as is typical in strike-slip/transensional regimes (e.g. De Paola *et al.* 2005). Regionally, Group 3 yields an extensional to transensional regime with a well-defined NW–SE extension direction, which is consistent with the trend of tensile vein arrays and dykes (Fig. 6b, e, f).

The stress inversion results compare well with the findings of Wilson *et al.* (2010) in the basement-dominated terranes of Sutherland. This seems to confirm the suggestions made by Wilson *et al.* (2010) and Dichiarante *et al.* (2016) that the onshore normal faulting in Sutherland and Caithness is dominated by structures related, and peripheral, to the offshore Permo-Triassic West Orkney Basin. It also further supports the existence of a broad ESE–WNW-trending zone of transensional faulting: the NCTZ a diffuse system of synthetic, generally ESE–WNW to ENE–WSW

sinistral and antithetic north–south to NE–SW dextral extensional faults running from Cape Wrath to Dunnet Head (Fig. 1a). The predominance of dextral extensional north–south to NE–SW faults in the western onshore parts of the Orcadian Basin (e.g. Kirtomy, Dounreay, Brims and Thurso) may reflect the preferential reactivation of fault trends first established in the Devonian during the initial development of the basin. The Group 3 structures are less widespread east of St John's Point and this, together with the predominance of ENE–WSW sinistral faults in eastern Caithness, as opposed to the ESE–WNW trends in Sutherland, may be due to the intensity of deformation associated with the NCTZ progressively weakening eastwards as it transfers Permian to Triassic extension into the West Orkney and North Minch basins (Fig. 1a).

Examples of local-scale structural inheritance

Having defined the sequence of the far-field controls of deformation, the key roles of local-scale reactivation, inversion and oblique tectonics in influencing the development of successively later structures can now be assessed using the representative structural relationships seen at six key localities (Figs 7–13). For each locality discussed, a local stress inversion analysis has been carried out on the structures recognized and assigned to each group (see also Figure S5 in the Supplementary Material), but, in all cases, the stress configurations deduced are consistent with the regional patterns discussed in the preceding sections, although there may be local

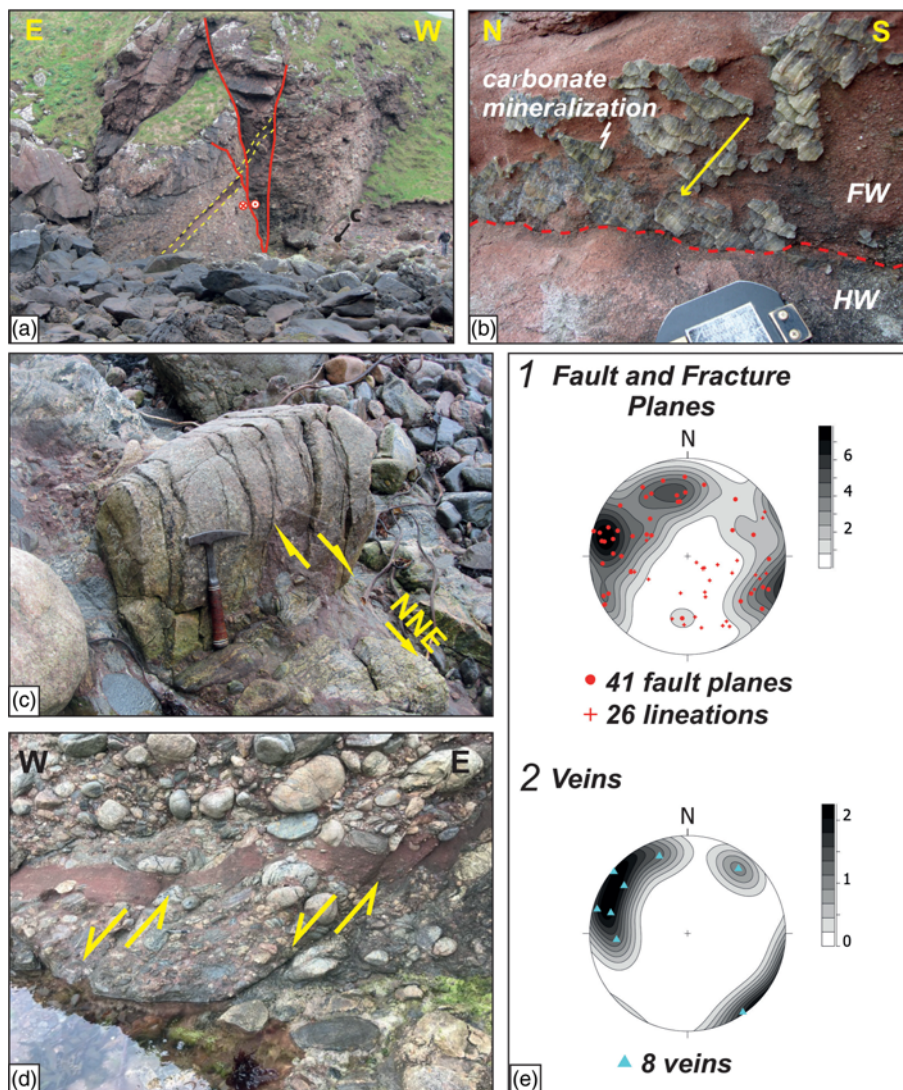


Fig. 7. Structural observations and data from Kirtomy Bay (NC 7420 6410); see also Figure 2a. (a) Cross-section view of north–south curvilinear flower structure close to main fault bounding Devonian outlier, which is unexposed and lies just to the right of this image. Note moderate dips of breccia–conglomerates close to this fault and complex offset of sandstone interbed. (b) Plan view of north–south fault plane with oblique stepped calcite slickenfibres giving dextral normal shear sense. (c) Side view of Moine basement boulders cut by diffuse sets of NNE–SSW fractures with small dextral offsets in region close to north–south faults shown in part (a). (d) Plan view of minor ENE–WSW faults with sinistral offsets, which are inferred to be conjugate with the north–south dextral faults with which they show mutually cross-cutting relationships. (e) Stereonets of faults and calcite veins at Kirtomy Bay. FW, footwall; HW, hanging wall.

variations in the directions of extension or compression (of up to 50°) as a result of the influence of the local reactivation of structures. This illustrates the generally robust nature of the stress inversion analysis at different scales.

Structural relationships adjacent to reactivated north–south basin/sub-basin-bounding faults

Kirtomy Bay is one of several half-graben outliers located onshore west of the main Orcadian Basin (Fig. 2a; Donovan 1975; Enfield and Coward 1987; Coward *et al.* 1989; Wilson *et al.* 2010). A sequence of Devonian red sandstone and local marginal breccia–conglomerate is bounded by a NNW–SSE fault along its western margin and underlain by Moine basement (for a map, see Wilson *et al.* 2010, fig. 7c). Breccio-conglomerate units (Fig. 7a) exposed directly adjacent to the basin-bounding fault die out rapidly eastwards over a distance <10 m and clearly formed adjacent to an active scarp feature during deposition (Wilson *et al.* 2010). NNW–SSE- to north–south- and ENE–WSW-trending faults cut the Devonian strata, showing dextral oblique-slip and normal sinistral movements, respectively (Fig. 7b–e). Stepped carbonate slickenfibres are widely preserved on exposed fault planes (Fig. 7b), many of which offset basement clasts in the conglomerates (Fig. 7c). Dextral reactivation of the NNW–SSE-trending basement fabric in the underlying metamorphic Moine rocks is also observed, together with a set of ENE–WSW sinistral faults cutting across it at high angles, which are also seen in the Devonian strata (Fig. 7d; Wilson *et al.* 2010). The interconnected fault systems exposed cutting the red beds close to the bounding fault of the half-graben form a flower structure at the mesoscale (Fig. 7a). The Kirtomy locality therefore provides direct evidence that a generally north–south- to NNW–SSE-trending fault bounding a Devonian age half-graben with demonstrable synsedimentary movements (e.g. a Group 1 structure) has been reactivated during later (Group 3 age) NW–SE rifting associated with carbonate mineralization very similar to that of likely Permian age found in the Dounreay area by Dichiarante *et al.* (2016). This is consistent with the general NE–SW trend of steeply dipping carbonate veins cutting both the Devonian red beds and the basement (Fig. 7e).

Brimms Ness and the Port of Brimms, c. 28 km to the east, preserve deformation patterns developed either side of the Bridge of Forss Fault Zone (BFFZ) (Fig. 8a; Fletcher and Key 1992; Nirex 1994c; Nirex 1994a), the core of which is not exposed, forming a narrow, shingle-filled inlet. Lithologically distinct silty sandstones of the Crosskirk Bay Formation to the west are juxtaposed against a more diverse assemblage of sandstones and shales from the Mey Flagstone Formation to the east, with an offset of least several hundred metres (e.g. BGS 2005).

The earliest structures recognized here are normal faults in various orientations (north–south, NNE–SSW, east–west and possibly NW–SE, Fig. 8b), which are spatially restricted to the region a few tens of metres either side of the BFFZ. They are characteristically associated with the widespread development of multiple sets of millimetre-wide deformation bands in the sandstone units (Fig. 3e) and, locally, with green gouge or hematite staining (Fig. 3f). Other mineralization is absent. These features are interpreted to be Group 1 structures of Devonian age and are thought to have formed during normal faulting along the BFFZ during the initial development of the basin. A local stress inversion analysis of faults with slickenlines yields an ENE–WSW extension direction (Fig. 8b), consistent with Group 1 structures regionally.

Millimetre- to decametre-scale north–south to NE–SW Group 2 folds are found locally in regions immediately east of the BFFZ and in localized zones of folding in rocks to the west. A prominent zone of folds and top-to-the-east thrusting is exposed 730 m to the west of the BFFZ (Chapel locality; Figs 3c and 8a). Exposed thrust faults

are characterized by slightly sinistral-reverse oblique kinematics, with the fold hinges lying slightly clockwise of the thrust faults, consistent with this sinistral oblique shear sense (Fig. 8b); bedding-parallel flexural slip lineations are also oriented slightly clockwise of the thrust fault lineations (summary given in Fig. 8d). These structures are everywhere cross-cut by Group 3 age carbonate–bitumen veins and dextral oblique normal faults trending NE–SW. A local stress inversion analysis of the thrust faults here yields an east–west compression direction consistent with Group 2 structures regionally (Fig. 8b).

Well-defined Group 3 fractures trending NNE–SSW and ENE–WSW are widespread in the rocks either side of the BFFZ (e.g. Figs 5a, 8b, c, e) and decrease in intensity moving away from the BFFZ within 30–50 m on either side. They are widely associated with carbonate and, locally, bitumen mineralization and are characterized by dextral normal and sinistral normal senses of shear, respectively (Fig. 8a). Immediately west of the BFFZ, a series of sub-parallel NNE–SSW fracture corridors up to 5 m wide with interlinked north–south-trending subvertical faults containing intensely brecciated zones is present (e.g. Fig. 5a). Carbonate mineralization is widely observed on exposed fault panels and in smaller veins; exposed slickenlines everywhere show dextral oblique kinematics. In the flat-lying platform (ND 0435 7105), clast-supported carbonate-mineralized breccias and dilational veins occurs in mesh arrays between two main fault planes, which show overall dextral kinematics (Fig. 8c). NNW–SSE-trending open folds also occur in the platform related to compressional jog features consistent with dextral shear along the associated NNE–SSW-trending faults (Fig. 5e). A local stress inversion analysis of faults with slickenlines yields an NNW–SSE extension direction consistent with Group 3 structures regionally (Fig. 8b). This result is notably clockwise of both the regional Group 3 extension direction and those obtained at most other localities. This may reflect a higher degree of finite strain due to dextral shear localizing along the BFFZ, leading to a clockwise rotation of the derived extension vector.

Immediately east of the BFFZ, folds are observed in two orientations and styles (Fig. 8b). Open to tight NNE- to NE-plunging folds on centimetre to metre scales dominate and are consistently cross-cut by dextral oblique normal faults with associated carbonate mineralization. These appear to be Group 2 minor structures, possibly related to inversion along the BFFZ. East of the fault, a large open NW-plunging fold refolds Group 1 deformation bands and faults developed in a prominent sandstone unit seen on the foreshore. A small number of centimetre-scale folds in the rock platform close to the BFFZ also display shallow to moderate NW plunges (Figs 3e and 8e), but no clear refolding of NNE/NE minor folds is preserved. Many of these NW-plunging folds occur in rock panels bounded by NNE–SSW Group 3 faults and are interpreted to be associated with the dextral reactivation of the BFFZ.

Brough Harbour preserves structures associated with the NNE–SSW Brough Fault, the single largest regional fault in the Caithness area (Fig. 2a, d; Crampton and Carruthers (1914); Trewin and Hurst 2009). It juxtaposes the Middle Devonian Ham–Skarfskerry Subgroup to the east, against Upper Devonian Dunnet Head Sandstone Group to the west, and is widely regarded as the southern continuation of the Brimms–Risa Fault on Hoy, Orkney (Fig. 2a; Enfield 1988; Coward *et al.* 1989; Seranne 1992). The fault core runs through the harbour and is unexposed. It has been described as both a westerly-dipping normal fault (e.g. BGS 1985) and as an easterly dipping reverse fault (e.g. Coward *et al.* 1989). The magnitude of movement along the Brough Fault is uncertain, although it is likely to be significant (e.g. hundreds of metres) given the observed map-scale stratigraphic offset. It is also associated with a large regional-scale open north–south antiform (the Ham

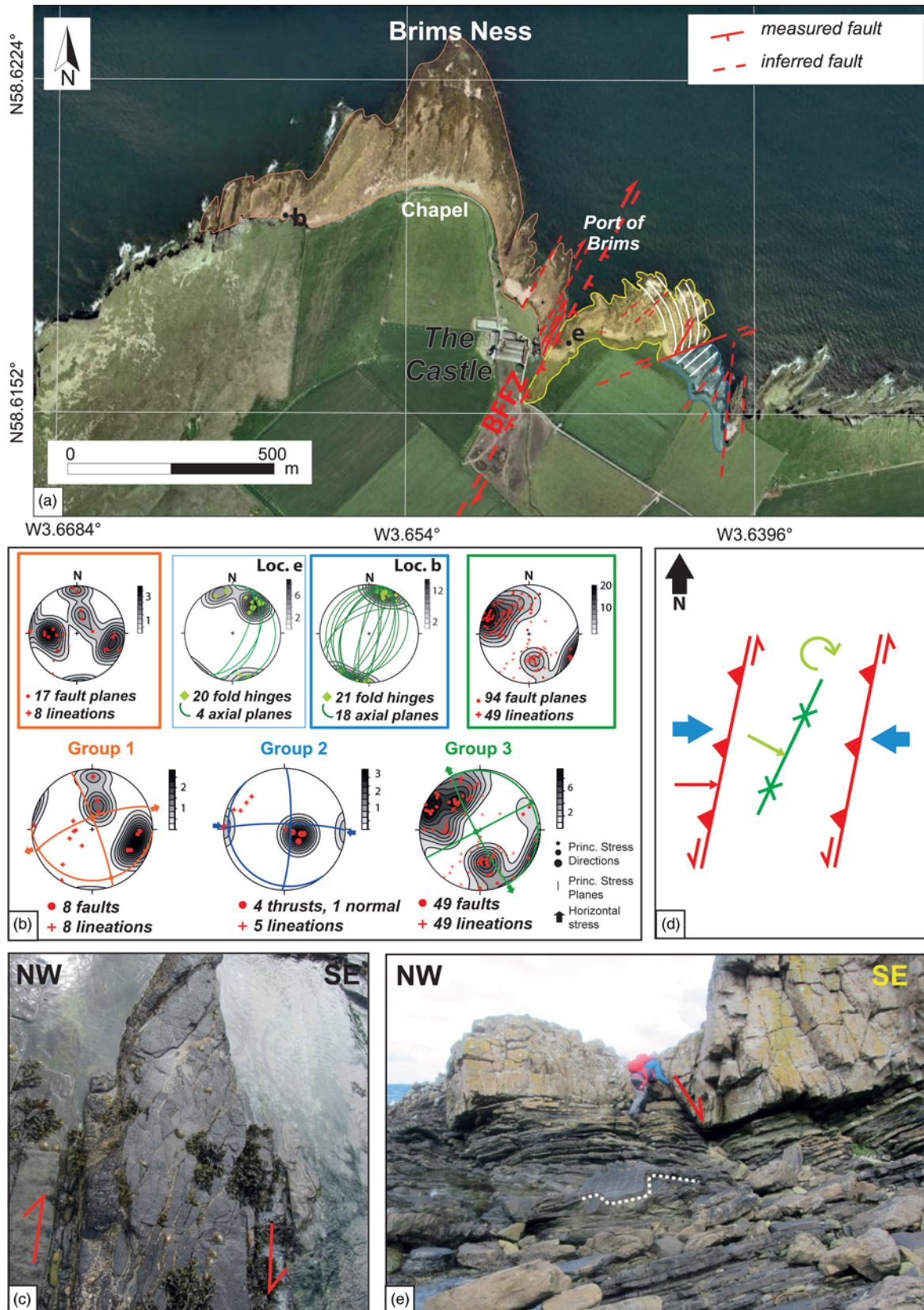


Fig. 8. Structural observations and data from Brims Ness, Port of Brims and Chapel. (a) Interpreted GoogleEarth image of Brims Ness region showing the locations of the Bridge of Forrs Fault Zone, associated structures and features described in text (areal image ©2019 Google). (b) Brims Ness equal-area stereonet plots and with density contours of poles. Upper row, from left to right: Group 1 faults and fractures; fold hinges and axial planes immediately east of the Bridge of Forrs Fault Zone (locality e); Group 2 fold hinges and axial planes west of Chapel (locality b); Group 3 faults and fractures. Lower row, from left to right: stress inversion results (all localities) for Group 1, Group 2 and Group 3 structures at Brims Ness. (c) Oblique plan view of dextral dilational jog along NE–SW Group 3 fault with calcite mineralization and associated lens of breccia, foreshore, Port of Brims (ND 0435 7105). (d) Schematic plan view with relative orientation and kinematics of Group 2 thrust faults and associated folds at Brims Chapel locality (ND 0372 7136). (e) NE–SW dextral normal Group 3 faults in background, which offsets the base of the prominent sandstone unit on the SE side of the Bridge of Forrs Fault Zone, Port of Brims foreshore (ND 0442 7105). An open to closed NNW–SSE possible Group 3 fold is highlighted in the foreground. BFFZ, Bridge of Forrs Fault Zone.

Anticline, Fig. 4a; BGS 1985), which lies to the east (NIREX 1994c).

On the wave-cut platform west of the Brough Fault, bedding in the Dunnet Head Sandstones is generally steeply dipping to subvertical and strikes sub-parallel to the Brough Fault (Fig. 9a, b). This contrasts with the shallower westerly dips of the same rocks in the cliffs to the west and reflects large-scale fault drag against the Brough Fault (Trewin 1993). At low tide, a series of moderately to steeply plunging Z-folds, metre- to tens of metre-scale, open to tight north-south-trending Z-folds is exposed (Fig. 9b). These folds face south based on sedimentary cross-laminations preserved in the sandstones, with local upward- and downward-facing along axial planes due to the variable fold plunges and the moderately curvilinear nature of the associated fold hinges. The general steep plunges, Z-vergence and south-facing direction of these folds are consistent with a dextral sense of shear on the adjacent Brough Fault.

A previously unrecognized volcanic vent measuring 5 m × 2 m occurs close to the steeply plunging Z-folds in the wave-cut platform (Fig. 9a–c). It is elongated north-south sub-parallel to the axial surfaces of the adjacent folds and contains angular to subrounded clasts of green mafic volcanic rock and country rock sandstones set in a carbonate-rich matrix. The well-exposed southern contact is offset by a series of small NNE–SSW-trending dextral faults with centimetre-scale displacements (Fig. 9c). This suggests that the vent is at least in part post-dated by local fault movements, but its age relative to the folding cannot be ascertained. A much larger and compositionally similar vent breccia occurs inland in the Burn of Sinnigeo stream c. 300 m to the NNW (Dichiarante 2017; ND 2178 7463, Fig. 9a). Although its contacts with the adjacent Dunnet Head Sandstones are not exposed, this vent is believed to be Permian in age. An ENE–WSW subvertical monchiquite dyke also occurs in the coastal cliffs still further to the north at ND 2159 7551 (Fig. 9a; BGS 1985).

In the cliffs to the east of the Brough Fault trace, bedding dips are generally shallow to moderate west-dipping with small-scale westerly-verging NNE–SSW Group 2 folds plunging gently SSW (Fig. 9e). Several much larger Group 2 folds are exposed in the cliffs along the coast for several hundred metres to the east of the Brough Fault and one, at Langypso (ND 2292 7408), is accessible (Fig. 4d). Axial planes trend north-south to NNE–SSW and dip steeply east (Fig. 9e). These folds are consistent with east-west compressional inversion along the Brough Fault. They are consistently cross-cut by moderately to steeply dipping dextral oblique normal to dextral strike-slip faults trending north-south to NE–SW (Fig. 9d). Faults trend between 000° and 040° and form as conjugate sets dipping moderately to both the SE and NW (Fig. 9e). These faults are everywhere associated with calcite mineralization in veins and local breccias. A local stress inversion analysis of faults with slickenlines either side of the Brough Fault yields an NNW–SSE extension direction consistent with Group 3 structures regionally (Fig. 9f).

Following Coward *et al.* (1989), it is suggested that the Brough Fault initiated as a basin- or sub-basin-controlling Group 1 normal fault during the Devonian (Fig. 9g i). The direction of dip and therefore the relative sense of downthrow along this precursor structure is unknown, although it is assumed to be ESE in common with other large Devonian age faults in Caithness with this trend. The development of north-south- to NNE–SSW-trending, west-verging Group 2 folds and the Ham Anticline east of the fault is consistent with east-west compression and substantial inversion along the Brough Fault in Permo-Carboniferous times (Fig. 9g ii, g iii). It is suggested that the Brough Fault was then reactivated again as a dextral strike-slip Group 3 structure during Permian times (Fig. 9g iv); this event may have overlapped with the development of local volcanic vents and ENE–WSW dyke emplacement. The magnitude of dextral offset is uncertain, but may be significant in regional terms given the substantial amount of cataclasis and

brecciation seen immediately adjacent to the Brough Fault in The Clett and the development of the large drag fold and meso-scale Z-folds in the Dunnet Head Sandstones to the west. The more NNW–SSE orientation of the extension direction obtained by stress inversion for the Group 3 structures is notably clockwise of both the regional Group 3 extension direction and those obtained at most other localities. As with the BFFZ, this may reflect a higher degree of finite strain due to dextral shear localizing along the Brough Fault, leading to a clockwise rotation of the derived extension vector. It is also consistent with the well-developed deformation zone with curvilinear Z-folds seen in the Dunnet Head Sandstones immediately west of the fault (Fig. 9b).

Structural relationships associated with the reactivation of NW–SE faults

Scarfskerry, which lies 15 km east of Thurso, preserves a large-scale NW–SE fault structure, part of which is sometimes exposed following storms in the area below the shingle beach in the Haven (Figs 2d and 10a). In the foreshore region flanking the Haven, the Ham–Scarfskerry Subgroup beds become progressively steeper moving towards the centre of the bay as a result of the presence of a large NW–SE-trending structure. Bedding on the northeastern side dips shallowly to moderately NE, decreasing to more shallow dips (10–15°) eastwards to Tang Head. On the SW side, moderate SW dips occur, flattening rapidly southwestwards along the coast into a region of variable bedding dips and open gently north- to NW-plunging decametre-scale folds. The erosional gully forming the Haven (Fig. 10a) thus superficially appears to have formed due to the preferential erosion of a NW–SE anticline. However, in a region no wider than 5 m, a complex zone of brecciated shales is cross-cut by a system of anastomosing and coalescing Neptunian dykes (Fig. 3b). These can be traced for at least 10 m into the surrounding rocks on the SW side of the bay, where well-developed bedding-parallel detachment faults with associated clay gouge injections are also seen (Fig. 3c). These observations suggest that the Haven marks the trace of a NW–SE fault that was active prior to full lithification of the sediments – that is, an early Group 1 structure.

On the northeastern side of Scarfskerry Bay (ND 2604 7448), a 25 m wide zone of complex deformation occurs in the moderately NE-dipping sequence with interconnected systems of high- to low-angle faults, detachments, regions of intense veining and centimetre- to decimetre-scale folds, some of them very tight (Fig. 10a–e). Partitioning of deformation is observed at a local scale in this area: regions with dominant brittle extensional structures (high-angle normal to dextral oblique-slip faults and tensile carbonate-pyrite-bitumen veins) (Fig. 10b, c) alternate with areas where folds and local thrust faults are dominant (Fig. 10d, e). Both sets of structures link upwards or downwards into local detachment faults (e.g. Fig. 10b), whereas in other places faults with identical geometries, kinematics and associated mineralization locally cross-cut detachments (Fig. 10c). These structures are interpreted to be broadly contemporaneous Group 3 structures of Permian age based on their mutually cross-cutting relationships and the similarity of the associated mineralization to Group 3 structures recognized elsewhere. A local stress inversion analysis of the slickenline data associated with the carbonate-mineralized faults (high-angle and low-angle faults; Fig. 10g) yields a NW–SE extension direction consistent with these features being Group 3 structures.

The timing of folding at Scarfskerry is difficult to fully ascertain. The folds are mostly shallowly plunging and show a range of azimuth orientations from north to NW with NW–SE- to north-south-trending axial planes dipping moderately west–SW or north–NE (Fig. 10g). Some folding and thrusting is associated with

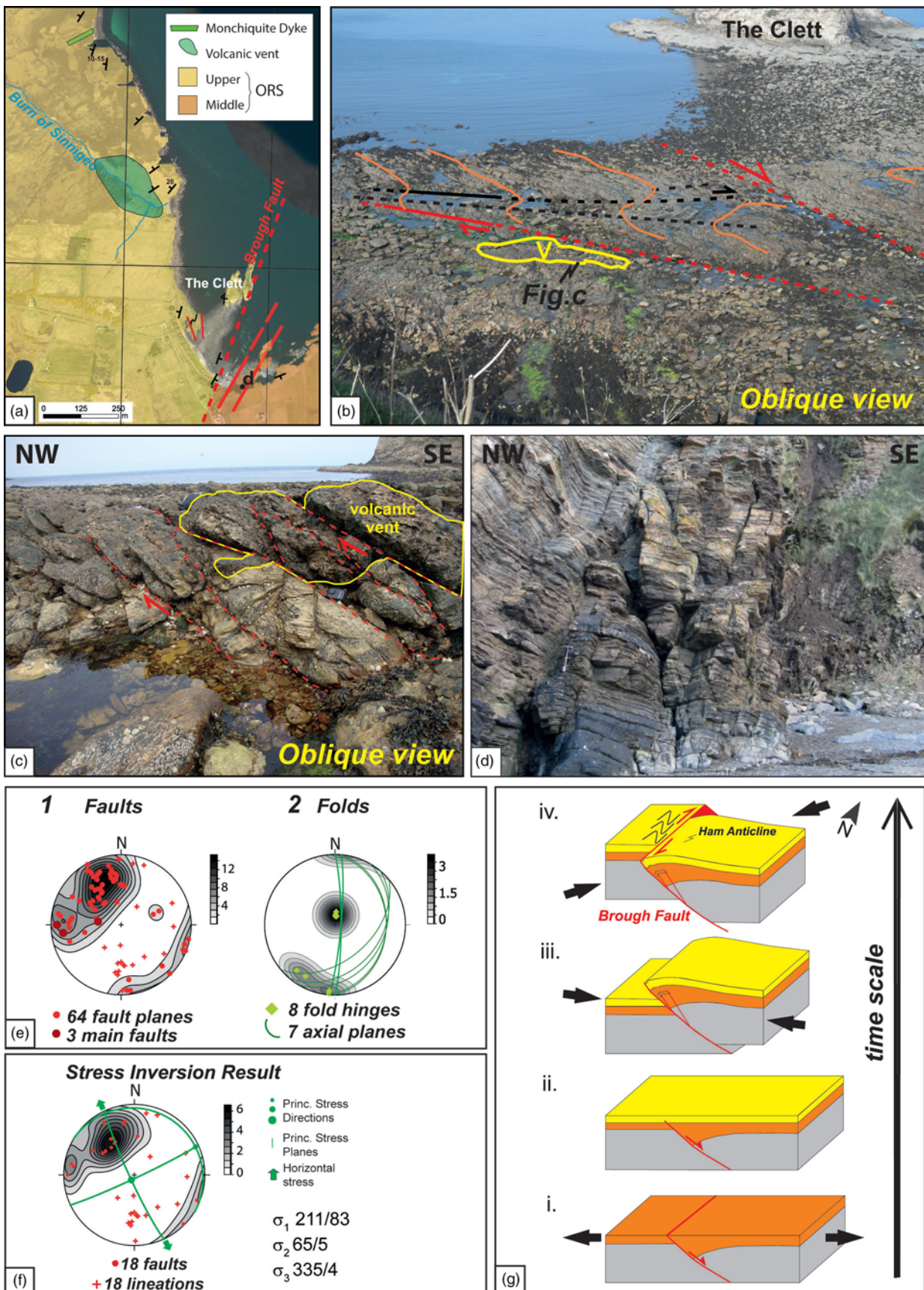


Fig. 9. Structural observations and data from Brough Harbour (ND 2178 7463). (a) Aerial image of Dunnet Head and geological map (in part after Enfield 1988). (b) Oblique panoramic view of the steeply plunging Group 3 Z-folds and volcanic vent (V) occurring in the platform west of The Clett. (c) Oblique view of NNE–SSW dextral normal minor Group 3 faults offsetting margin of volcanic vent feature shown in part (b). (d) Sectional view of typical NE–SW Group 3 faults forming mesh-like fracture corridor in rocks exposed immediately ESE of the Brough Fault. (e) Equal-area stereonets showing (1) poles to faults and fractures and (2) fold hinges and axial planes. (f) Stress inversion analysis of Group 3 faults at Brough Harbour. (g) Simplified reconstruction of the structural evolution and reactivation of the Brough Fault.

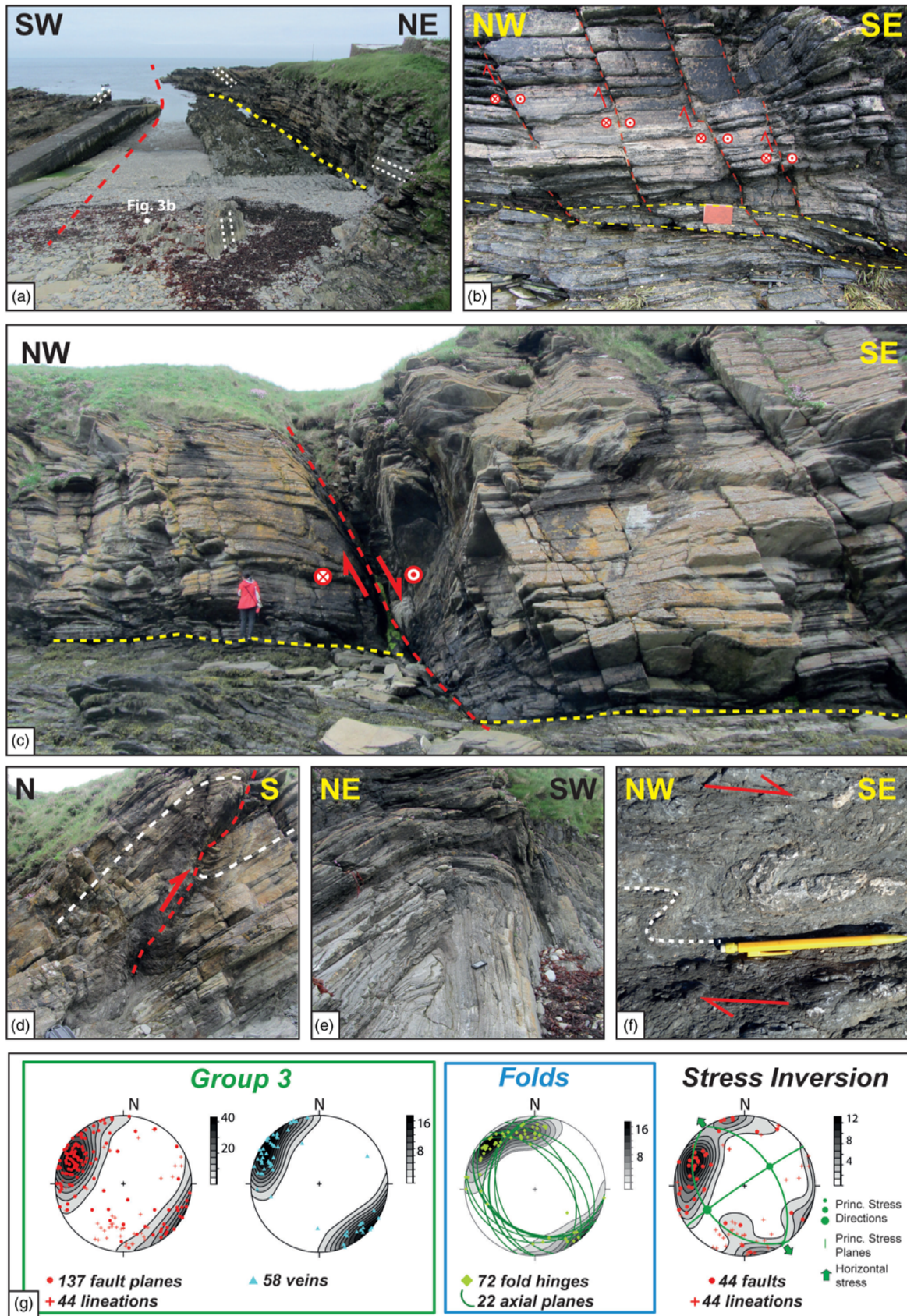


Fig. 10. Structural observations and data from Scarferry Harbour (ND 2604 7448). (a) View NW from harbour showing location of NW–SE fault running parallel to slipway (red line). Selected bedding traces (white) show antiformal arrangement of strata either side of fault. Main detachment shown in parts (b) and (c) also shown (yellow). (b) Sectional view of steeply dipping NE–SW dextral normal Group 3 faults (red) linking down onto a flat top-to-the-SE detachment (yellow). (c) As in part (b), but in one case a larger steep dextral normal fault offsets the basal detachment. (d) Following the basal detachment shown in part (c) to the right, it links into a top-to-the-SE thrust ramp (red) with associated brittle ductile folds (white). (e) Very tight NW–SE folds in Scarferry harbour. (f) Steeply plunging sinistrally verging Group 3 folds in highly sheared rocks exposed in the floor of Scarferry harbour very close to the inferred trace of the NW–SE fault. (g) Stereonets showing: Group 3 poles to faults, fractures (red) and calcite veins (blue); fold hinges and axial planes; stress inversion analysis of Group 3 structures at Scarferry.

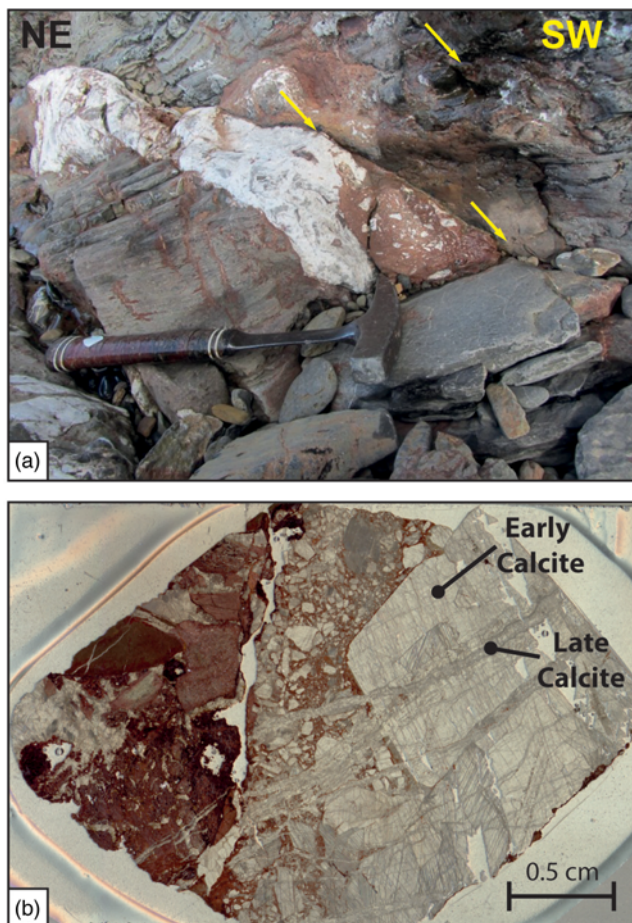


Fig. 11. (a) Oblique view of NE–SW Group 3 fault with red sediment and calcite mineral fills NE of Scarfiskerry (ND 2614 7459). Obliquely oriented slickenfibres on exposed fault plane (arrows) indicate dextral normal shear sense. Note clasts of local calcite fill in red sediment. (b) Low power plane polarized light thin section view of fills from locality in part (a) showing early calcite fill post-dated by red sediment, both of which are post-dated by thin later calcite veins.

contemporaneous carbonate–pyrite–bitumen mineralization (e.g. Fig. 5f), but it is possible that some of the folds first formed as Group 2 structures. This would be consistent with the unusually tight interlimb angles of some folds (e.g. Fig. 10e). Assuming an east–west compression direction, the pre-existing NW–SE Group 1 fault would be expected to localize NNW–SSE folds in a zone of sinistral transpression. When the core region of the fault is exposed, dextral faults and centimetre-scale steeply plunging Z-folds are exposed, overprinting all other structures (Fig. 10f). These are interpreted to be Group 3 folds, suggesting a component of later dextral shear along the fault zone consistent with its sub-parallelism with the regional extension direction at this time.

About 100 m to the NE, on the far side of the peninsula north of Scarfiskerry, a series of steeply ESE-dipping, NNE–SSW-trending faults and veins occur cutting moderately NE-dipping beds. In one example (Fig. 11a, ND 2614 7459), dextral oblique slickenlines are exposed on a fault plane carrying a well-developed breccia with intimately associated red sediment fills and carbonate mineralization. Veins and breccia are locally up to 20 cm thick and are locally associated with bitumen fills. The fault breccia contains angular clasts of sandstone and crystalline calcite set in a matrix of fine hematite-stained red sediment with a pale carbonate cement, all of which are cross-cut by later calcite-filled tensile veins (Fig. 11b). The red sediment and calcite-fills closely resemble those described from the Durness region by Wilson *et al.* (2010), where they are inferred to be Permian in age.

Structural relationships associated with ENE–WSW faults and dykes

The ENE–WSW fault trends become notably more prominent along the Caithness coast to the east of Thurso (Dichiarante 2017). At St John's Point (Fig. 2d), a series of ENE–WSW-trending subvertical faults are exposed in the foreshore (Fig. 12a), cutting a gently NE-dipping sequence of Mey Subgroup strata. The faults continue both to the west across the coastal platform and to the NE, trending towards Stroma Island (ND 3108 7510).

In the harbour area at St John's Point, a series of open to tight folds are developed in a corridor bounded by the two large ENE–WSW faults (Fig. 12b, d). The fold hinges trend WNW–ESE, plunging mainly shallowly ESE (Fig. 12b, f). The associated ENE-trending faults dip mainly to the NNW (Fig. 12f), with well-defined shallowly plunging, stepped slickenlines giving a sinistral sense of shear (Fig. 12c, f). Tensile carbonate veins, millimetres to centimetres thick, trend NNE to NE and dip steeply SE (Fig. 12f). Vuggy infills are locally developed (Fig. 12d).

A local stress inversion analysis of the slickenline data associated with the mineralized ENE–WSW sinistral faults yields a NW–SE extension direction, consistent once again with these features being Group 3 structures (Fig. 12g). The preservation of NE–SW tensile veins is also consistent with NW–SE extension. The unusual WNW–ESE orientation of the folds suggests that these Group 3 structures are locally controlled by sinistral strike-slip kinematics along the ENE–WSW fault planes (Fig. 12h). A Group 2 origin for these folds associated with east–west compression seems unlikely because this would be expected to lead dextral shear along ENE faults that very clearly bound the zone of folding.

Castletown lies immediately south of Dunnet Head, c. 8 km east of Thurso (Fig. 2d). On the coastal platform north of the village, Mey Subgroup rocks dip sub-horizontally to shallowly NW and are cut by prominent fracture sets trending ENE–WSW and, less commonly, NE–SW (Fig. 13a); otherwise, the rocks are for the most part very little deformed.

Five ENE–WSW alkaline lamprophyre dykes occur in these coastal exposures (ND 1867 6910) (Fig. 13b, c). They vary in thickness from <4 cm at their terminations to c. 80 cm, showing an echelon step-over patterns with no systematic sense of offset (Fig. 13b). They are clearly intruded along pre-existing joints and fractures and some show c. 10 cm wide baked margins with hydrocarbon development along fractures in the host rocks (Fig. 13d). Carbonate–pyrite–bitumen mineralized faults occur parallel to the ENE–WSW dyke margins and show sinistral strike-slip stepped slickenlines. Three sets of subvertical tensile carbonate–pyrite–bitumen veins are present: one set parallel to the dyke walls and two obliquely oriented sets running north–south and NE–SW (Fig. 13c–e). The north–south set are preferentially developed in the baked country rock margins (Fig. 13c), whereas the NE–SW set occur in the dyke (Fig. 13d) – both are kinematically compatible with sinistral shear along the ENE–WSW dyke margins (Fig. 13b). In thin section, the tensile carbonate vein fills display crack–seal textures with associated oil inclusions (Fig. 13e, f). A local stress inversion analysis of the carbonate–bitumen-bearing faults and fractures suggests NW–SE extension (Fig. 13g), implying that the faults, tensile veins and the intrusion of the dykes are related to Group 3 Permian extension.

The oblique ENE–WSW trend of the dykes implies that the dykes were intruded along pre-existing, possibly Devonian, structures (joints), which then acted as strike-slip faults immediately following or perhaps contemporaneously with dyke emplacement. The preferential development of bitumen in the baked margins of the dykes (Fig. 13d, e) suggests that emplacement, Group 3 deformation and carbonate–pyrite–bitumen mineralization were broadly contemporaneous. Taken together with the apparent overlap between Group 3 deformation and the emplacement of the volcanic plug at Brough,

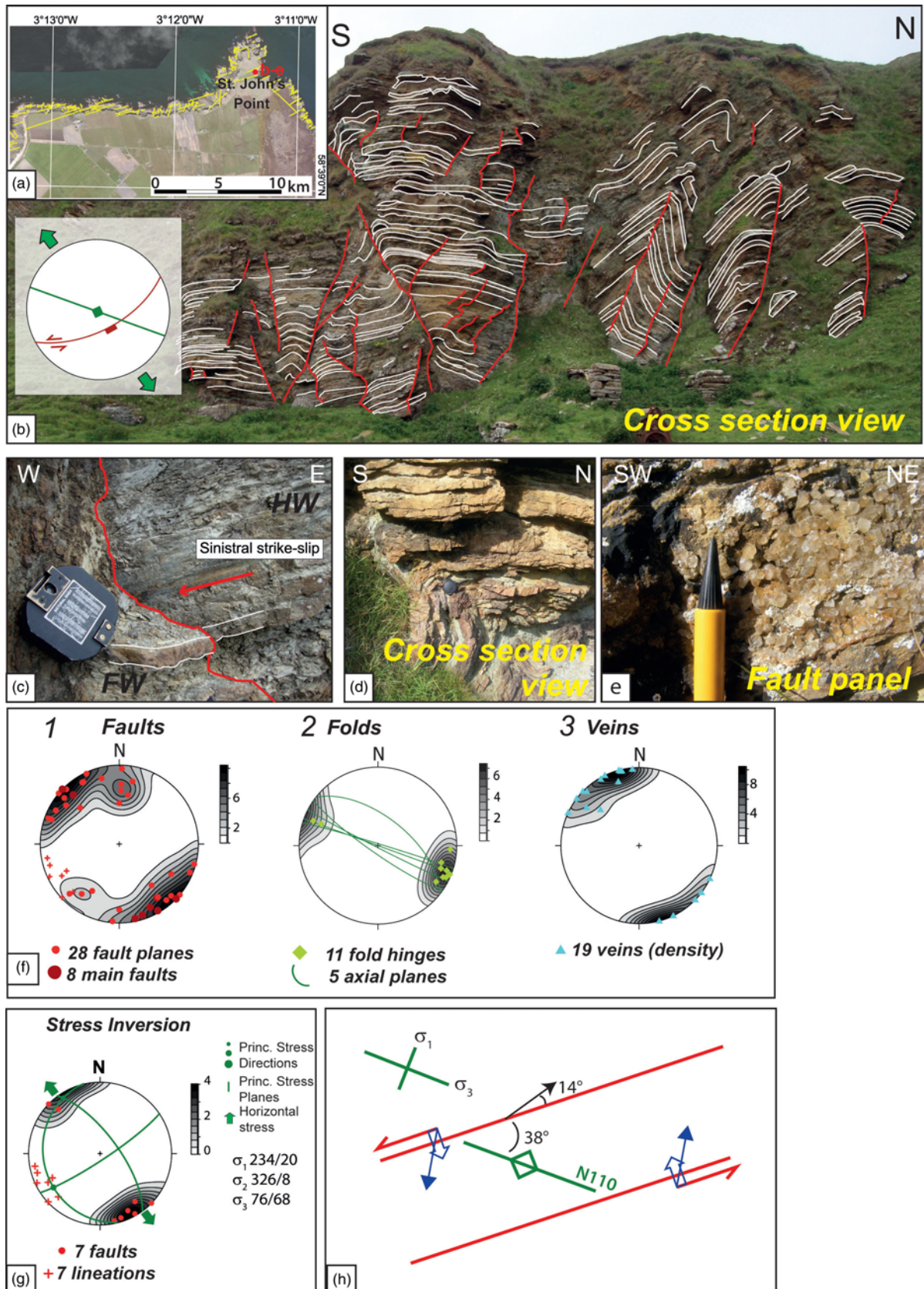


Fig. 12. Structural observations and data from St John's Point (ND 3108 7510). (a) Aerial view of St John's Point showing the major lineaments (yellow); location of images in parts (b–e) also shown in the region of the small harbour. (b) North–south cross-section view of the outcrop at St John's Point showing WNW–ESE-trending Group 3 folds and associated ENE–WSW-trending faults, with summary stereonet. (c) Oblique view of a WNW–ESE-trending fault showing sinistral strike-slip slickenfibres. (d) Cross-section view of a WNW–ESE-trending Group 3 fold. (e) Euhedral calcite crystals on a NE–SW-trending fault. (f) Equal-area stereonet plots and density contours of (1) poles to fault and fractures, (2) fold hinges and axial planes and (3) poles to calcite veins. (g) Stress inversion of mineralized Group 3 structures. (h) Simplified summary map of Group 3 structures and inferred stress field. FW, footwall; HW, hanging wall.

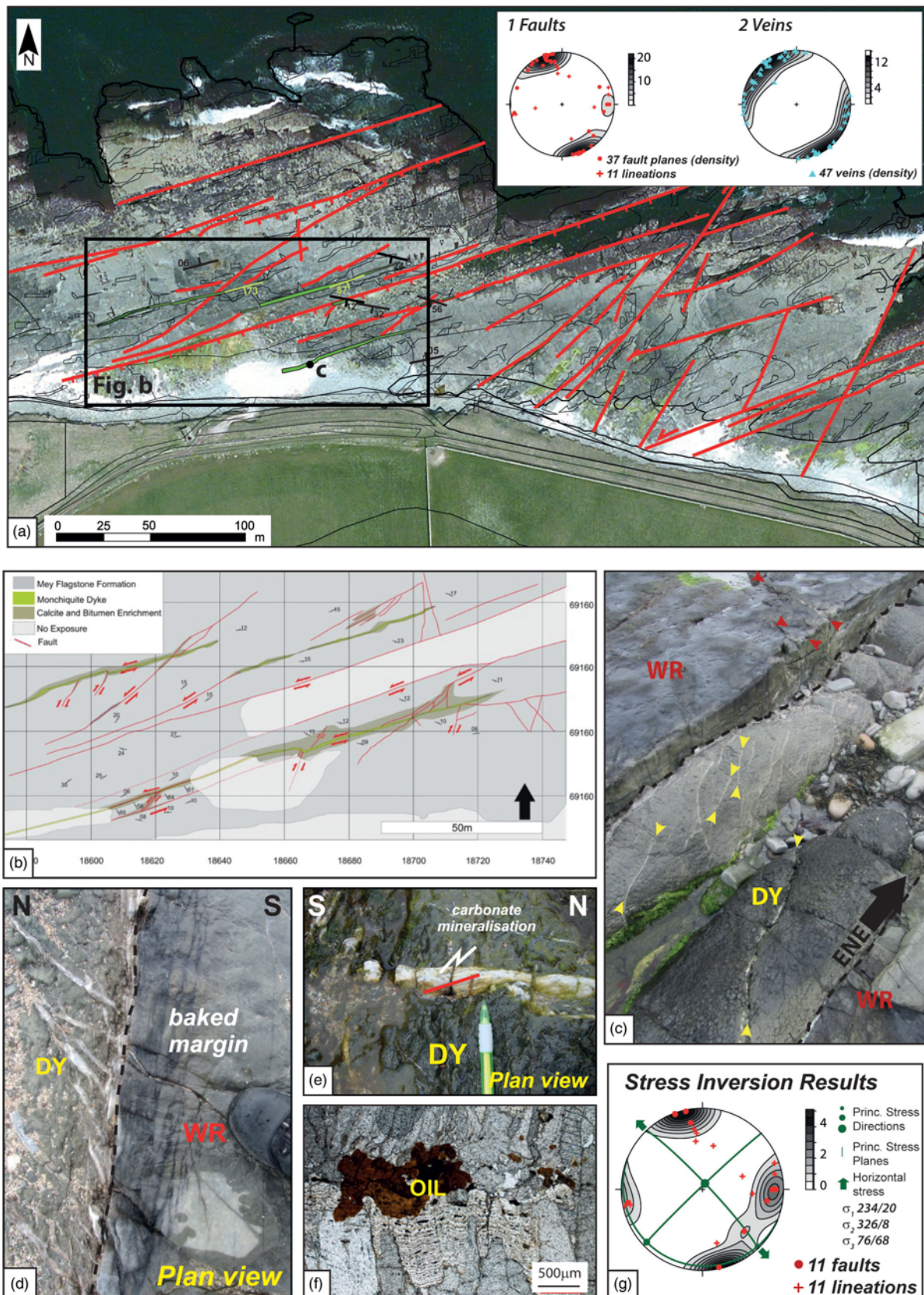


Fig. 13. Structural observations and data from Castletown foreshore (ND 1867 6910). (a) Aerial image with geological map showing dykes and Group 3 faults. Inset shows stereonet of fault and vein orientation data. Box shows location of more detailed map in part (b). (b) More detailed geological map showing relationships between Group 3 faults and dykes in area highlighted in part (a). (c) Oblique view of ENE-WSW dyke and wall rocks showing en echelon calcite mineralized tensile fractures oriented oblique to the contact and consistent with dyke margin-parallel sinistral shear. (d) Plan view of dyke contact showing en echelon tensile veins with calcite consistent with dyke margin-parallel sinistral shear and contact-parallel fractures in wall rocks with leaking hydrocarbons only in the region of the dyke-baked margin. (e) Oblique dextral kinematics associated with a NNE-SSW Group 3 fracture. (f) Plane polarized light thin section of crack-seal calcite crystals with hydrocarbon inclusions and leaking oil. (g) Stress inversion analysis of Group 3 striated faults at Castletown.

this suggests that the alkaline igneous rocks of the Caithness area are Permian. Interestingly, hydrocarbons are also found associated with the vent at the Ness of Duncansby (Parnell 1985). The *c.* 267 Ma age proposed for Group 3 structures by Dichiarante *et al.* (2016) lies almost within error of the K–Ar age of 252 ± 10 Ma obtained for lamprophyre dykes in the Thurso area (Baxter and Mitchell 1984). Lundmark *et al.* (2011) more recently obtained a U–Pb zircon age for a lamprophyre dyke in Orkney of 313 ± 4 Ma, which is 20–60 Ma older than the previously obtained K–Ar ages for Scottish lamprophyres. These researchers suggested that the previously obtained K–Ar ages could have been partially reset by later alteration processes and are possibly not reliable. Our findings suggest that this proposal may not be correct, at least in the Caithness area.

The observed close relationship between alkaline igneous intrusions and hydrocarbon development raises the possibility that the Devonian rocks of the Orcadian Basin may have been taken through the oil window during thermal doming related to regional magmatism in the Early Permian. This possibility has been discussed previously by Parnell (1985), but he opted for an earlier maturation phase following regional burial in the Late Devonian or Carboniferous. The new observations made here suggest that the possibility of Early Permian oil maturation in the Orcadian Basin needs to be reappraised.

Synthesis and conclusions

The onshore Devonian rocks of the Orcadian Basin, NE Scotland show three distinct groups of faults and associated structures, each with different and distinctive fault rocks and fracture fills (Fig. 14).

(i) Group 1 structures formed as a result of Devonian age ENE–WSW extension forming the Orcadian Basin synchronous with regional sinistral transtension along the Great Glen Fault zone, as suggested by Wilson *et al.* (2010). Two very prominent sets of fault structures formed at this time: north–south to NNE–SSW and NW–SE, showing sinistral oblique to dip-slip extensional movements. The associated fault rocks include deformation bands in sandstones and clay gouges in mudstones; mineralization is largely absent.

(ii) Group 2 structures formed during the Late Carboniferous–Early Permian as a result of east–west shortening, most likely related to dextral reactivation of the Great Glen Fault (Wilson *et al.* 2010). This led to the development of north–south- to NNE–SSW-trending folds and associated thrusts with both easterly and westerly vergence. The largest Group 2 folds are apparently related to the significant reactivation and inversion of pre-existing major Group 1 structures, such as the Brough, Scarfskerry and Bridge of Forns faults. Coward *et al.* (1989) highlighted predominance of Group 2 structures in Orkney – this is consistent with their proximity to the Great Glen Fault.

(iii) Group 3 structures formed as a result of Permian NW–SE extension related to the opening of the offshore West Orkney Basin and created new faults in many areas (e.g. Dounreay and Thurso) and locally reactivated earlier Devonian structures in other areas (e.g. Brims, Brough and Scarfskerry). In Caithness, Group 3 faults are dominantly NE–SW- and ENE–WSW-trending with dextral oblique kinematics and sinistral kinematics, respectively. They show widespread syndeformational carbonate mineralization (\pm base metal sulfides and bitumen), both along the faults and in the associated mineral veins. In addition, the deformation, hydrocarbon

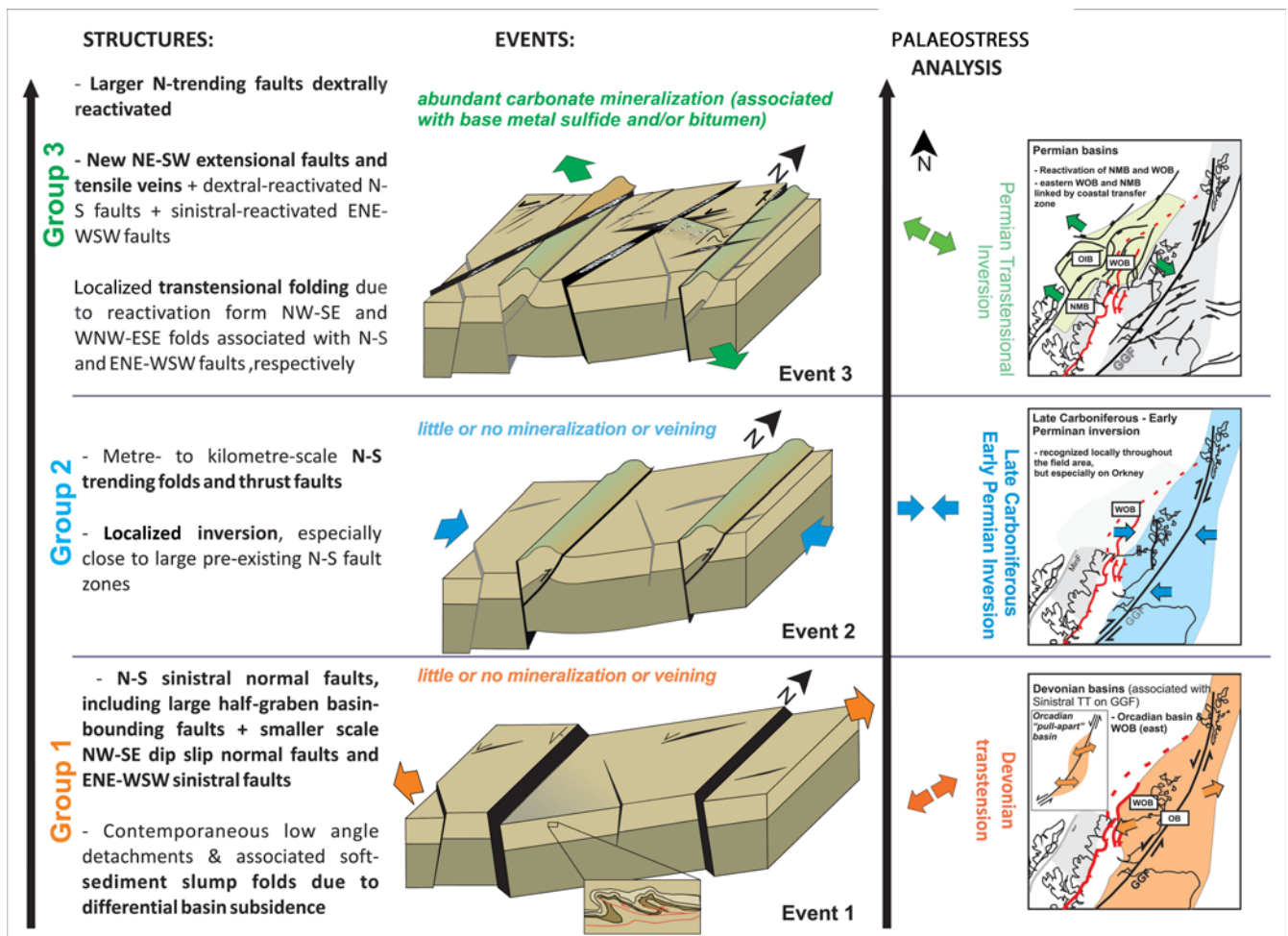


Fig. 14. Regional synthesis and summary, in part after Wilson *et al.* (2010) and Dichiarante *et al.* (2016). See text for details. GGF, Great Glen Fault; MinF, Minch Fault; NMB, North Minch Basin; OIB, Outer Isles Basin; TT, Transtension; WOB, West Orkney Basin.

maturation and associated hydrothermal mineralization appear to be contemporaneous with regional alkaline magmatism, as manifest by the localized emplacement of ENE–WSW dykes and volcanic plugs in Caithness. Regionally, the intensity of deformation related to the Group 3 event appears to die away eastwards as we move further away from the West Orkney Basin.

All three episodes are transtensional or transpressional on local to regional scales, mainly due to the reactivation of pre-existing structures. This leads to highly localized regions of complex deformation that contrast strongly with the intervening regions of relatively undeformed, shallowly dipping strata. Although larger scale folds may be related to regional-scale inversion events, small-scale folds, which are locally widespread, are more diverse in their origins. A proportion are related to either early synsedimentary gravity-driven deformation during Devonian basin development, whereas others are formed by much later transpressional or transtensional movements along local reactivated fault zones during Group 3 regional rifting, suggesting an inherited component to the development of the offshore West Orkney Basin. Not all folds seen in the Devonian rocks of the Orcadian Basin are necessarily related to Group 2 regional inversion during the Permian–Carboniferous.

This study shows that deformation structures preserved in ancient sedimentary basin sequences are not solely related to the initial tectonic development of the basin and later inversion events. Important regional sets of additional later structures and associated hydrothermal–magmatic events may also be present, and even dominant, in older basin sequences, particularly if the region lies close to the margin of a younger rift basin or magmatic centre, which may lie offshore. The geometry and kinematics of these superimposed rifting events and their related phenomena will probably be significantly influenced by the commonly oblique orientation of pre-existing structures in the underlying basement and of earlier rift basin- and sub-basin-bounding faults in the older basin fill. This leads to structural complexity (the partitioning of transpressional and transtensional strains, apparent inversional folding; see De Paola *et al.* 2005) on reservoir to sub-reservoir scales, which needs to be taken into account during exploration programmes for hydrocarbons and other subsurface fluid resources.

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