Transactions of the Royal Society of Edinburgh: Earth Sciences, **94**, 299–308, 2004 (for 2003)

The geology of the northern half of the Rhynie Basin, Aberdeenshire, Scotland

C. M. Rice and W. A. Ashcroft

ABSTRACT: A new geological map of the Early Devonian Rhynie Basin has been produced by traditional methods supplemented by trenching to bedrock and a ground magnetic survey. This shows that the basin margins are mostly fault-controlled and three trends are recognised: NE–SW, NNE–SSW and N–S. Three sets of open folds are distinguished with axial traces trending NE–SW, E–W and roughly NW–SE. The faults defining the basin margin and the folding may be related to basin formation within a regional strike-slip system of Early Devonian age.

The stratigraphic succession comprises three mappable units: a lower mixed unit of sandstones, shales, conglomerates and andesitic lava (>700 m), a middle unit of laminated grey shale and siltstone (>300 m); and an upper unit of laminated sandstones and shales (>300 m). These correlate with the Tillybrachty Sandstone and Quarry Hill Sandstone Formations (lower unit), and the Dryden Flags Formation (middle and upper units).

Small areas containing abundant chert float found outside the Rhynie SSSI may represent the surface expression of chert pods within the middle unit of laminated grey shale and siltstone, which also hosts the Rhynie cherts. The Windyfield cherts occur within the upper unit. No further centres of hydrothermal activity have been found in the northern half of the basin.

KEY WORDS: Cherts, Early Devonian, stratigraphy, strike-slip, structure.

The Rhynie Basin was first mapped by the Geological Survey at the end of the nineteenth century (Horne *et al*. 1886; Grant Wilson & Hinxman 1890) and the beginning of the twentieth century (Horne *et al*. 1923; Read 1923). It was resurveyed at the end of the twentieth century by the British Geological Survey (BGS 1993; Gould 1997). These workers identified a sequence of Devonian shales, sandstones, conglomerates and an andesite lava which they subdivided into five units, three of which are seen in the northern half of the basin (Fig. 1).

The western margin of the basin was interpreted as bounded by a fault in the south and an unconformity in the north, whereas on the eastern side, the beds mainly rest unconformably on basement. The beds generally dip to the west or northwest with some open folding. The basin is cut by NW-striking cross-faults and is divided in half by the ENE-striking Auchinleith Fault (BGS 1993). More recent work has shown that the western margin of the basin in the Rhynie area is bounded by a low-angle fault zone which controlled sedimentation (Rice *et al*. 2002). Thus, the entire western margin appears to be fault-bounded. The fault zone in the Rhynie area was a major conduit for hydrothermal fluids and the surface expression of these fluids was a hot spring system in which the celebrated Rhynie cherts were deposited. The heat energy for the system was provided by local igneous activity (Rice *et al*. 1995).

The aims of the present study are: (1) to trace the full extent of the Rhynie hot spring system; (2) to search for other evidence of hydrothermal activity; and (3) to better understand the geological structure and history of the Rhynie Basin. Detailed mapping by the Rhynie Research Group has previously been confined to the Rhynie area, and has been supported by ground magnetic survey, drilling and trenching (Rice *et al*. 1995, 2002). Poor exposure is the main problem besetting attempts to extend the mapping to include the rest of the basin and to add significantly to previous studies. Therefore, the present authors have supplemented surface exposures with trenching, magnetic surveys and a limited stream-sediment analysis programme (not included herein). This work was started in 1999 and the authors present here the part of the work which is concerned with the northern half of the basin that contains the Rhynie cherts. They show that the sediments in the Rhynie Basin are folded and faulted to a much greater extent than indicated by previous workers. This refinement of the structure has important implications for understanding the distribution of the Rhynie cherts and the formation of the Rhynie Basin.

1. Methodology

Trenching. The trenching was carried out with a mechanical digger (JCB), and consisted of digging holes to bedrock and extending these into trenches where appropriate (Fig. 2a). Drift cover was a constant problem that frequently could not be penetrated by the JCB (maximum depth under optimum conditions c. 6 m). Nevertheless, the method was found to be extremely cost-effective, and of 260 holes completed, 68% hit bedrock.

Geophysics. Total field ground magnetic surveys were carried out on selected areas of the basin margin where andesite had been reported and/or magnetic basement might be present (Fig. 2c). Traverses were directed NW–SE or E–W and set 100 m apart with readings taken every 8 m. Diurnal variation was monitored on a separate base magnetometer and the data corrected to an arbitrary datum. The magnetic data were presented as either profiles, on which significant features were picked and mapped, or as colour contour maps using the Surfer software package. Two-dimensional forward modelling was carried out at a few locations to provide subsurface insight.

2. Results

2.1. Stratigraphy and mapping units

One of the key objectives was to establish in detail the stratigraphy in the northern part of the basin and to identify

https://doi.org/10.1017/S0263593300000705 Published online by Cambridge University Press

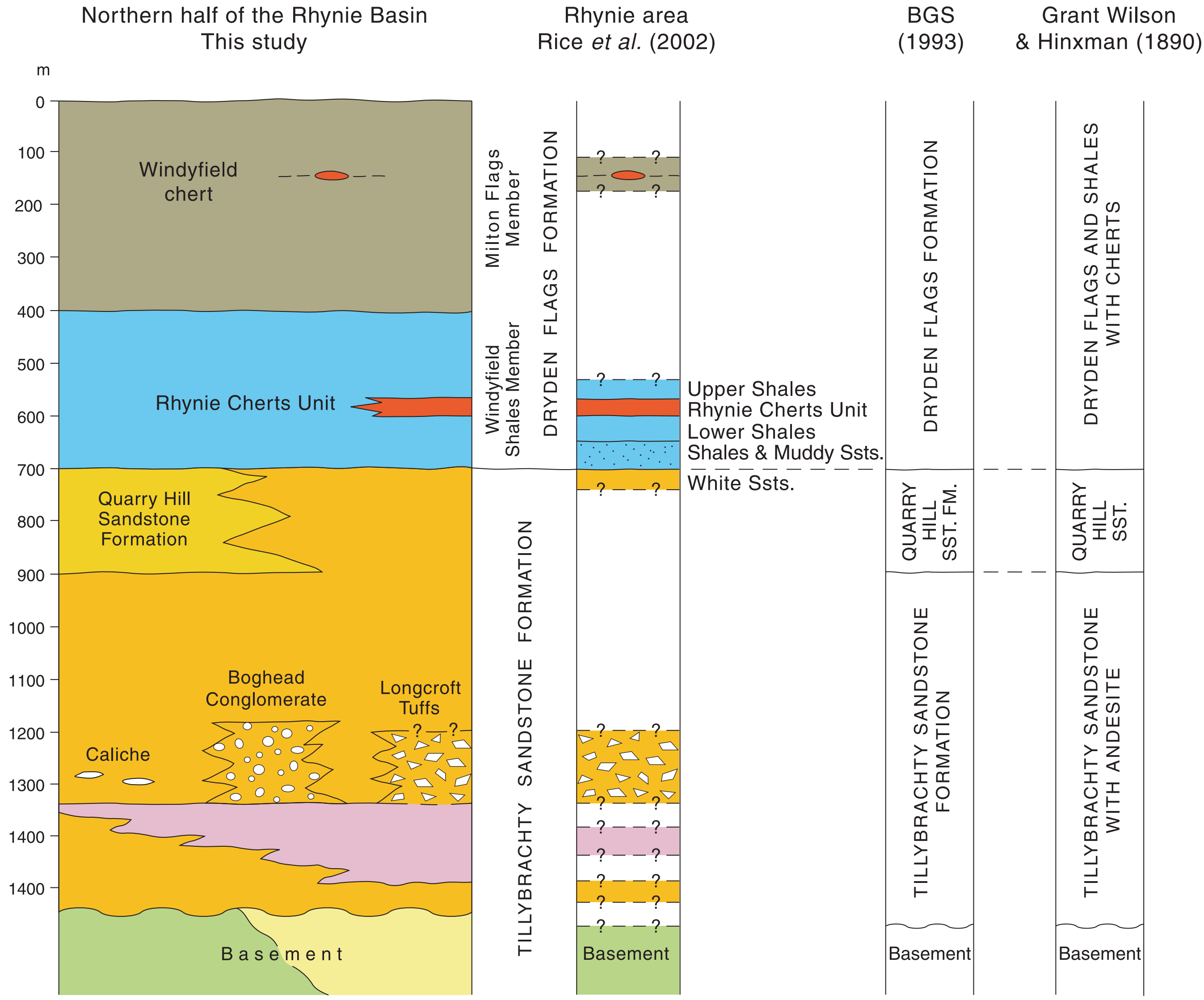

Figure 1 Devonian stratigraphy of the northern part of the Rhynie Basin compiled from the present study and compared with the stratigraphies of previous workers.

mappable units. A traverse across the basin from Boghead [NJ 522 272] to Milton of Noth [NJ 505 285] was chosen because previous studies (Horne *et al*. 1886; BGS 1993) had indicated that this was likely to yield the most complete succession from the basal unconformity through the Tillybrachty Sandstone Formation to the Dryden Flags Formation (Figs 2c, 3a). The traverse was offset in places depending on ground accessibility.

The oldest unit is mixed but dominantly 'sandy' as compared to other units, and is at least 800 m in thickness. It mainly consists of red-brown laminated impure sandstones with subordinate volumes of red and grey shales, conglomeratic beds, and a unit of andesite lava near the base. These lithologies compare closely with those assigned to the Tillybrachty Sandstones of previous workers (Grant Wilson & Hinxman 1890; Gould 1997) Trenching combined with a geophysical survey showed that the Devonian–Basement contact on the eastern side of the basin at Boghead is in fact faulted (Figs 2c, 3a, 4). The missing part of the succession between the andesite and the unconformity is present further north on the eastern side of the basin at Glen of Cults [NJ 535 314] (Fig. 2c). This sandy unit can be traced throughout the eastern side of the basin with little variation except for a distinctive coarse conglomerate at Boghead and cross-bedded sandstones at Quarry Hill [NJ 489 256].

The Boghead conglomerate is not exposed and can be followed by trenching along strike for about 1·5 km. It is at least 35 m and possibly as much as 150 m in thickness. The pebbles reach 25 cm along the maximum dimension and are mainly composed of quartzite. Other pebble types include locally derived metasediment, diorite, Devonian sandstones and andesite. The matrix is commonly purple in colour and dominated by andesite debris. The conglomerate is separated from the underlying andesite by about 10 m of red siltstone with sparse andesite and diorite pebbles. The top has not been seen.

The Quarry Hill Sandstone Formation was thought to occur throughout the basin by previous workers, but the present authors have been unable to trace it with confidence north of Quarry Hill. Top-of-bedrock drilling and trenching between Upper Ord and the SSSI encountered thin-bedded pale sandstones and siltstones with minor and small scale cross-bedding (Rice *et al*. 1995, 2002). The White Sandstones encountered in Borehole 97/2 show some resemblances to the Quarry Hill Sandstones (Rice *et al*. 2002), but the present authors consider it likely that the latter wedge out north of Quarry Hill (Figs 1, 2c, 3b, c).

Red-brown andesite, which may be either vesicular or non vesicular, is a distinctive rock type found around the edge of

https://doi.org/10.1017/S0263593300000705 Published online by Cambridge University Press

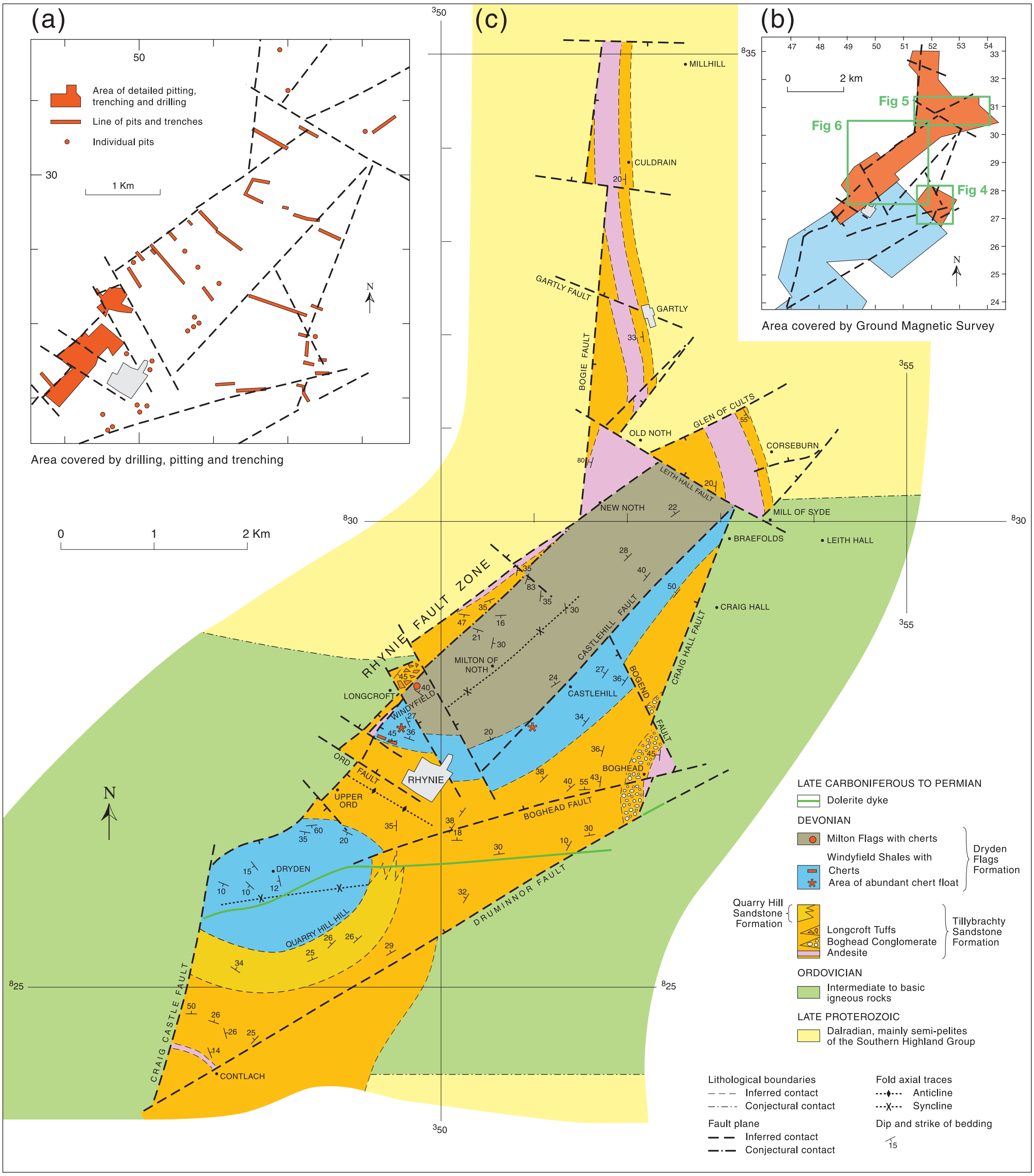

Figure 2 (a) Location of pitting, trenching and drilling. (b) Location of geophysical surveys: (blue area) line spacing 150 m, station spacing 20 m; and (red area) line spacing 100 m, station spacing 8 m. Traverses oriented NW–SE and E–W. Figures 4, 5 and 6 are outlined. (c) Geological map of the northern part of the Rhynie Basin.

the basin. Geochemically and petrographically, it shows no significant variation except for a more basic variety found near Gartly (Rice *et al.* 1995). Where its stratigraphic position is reasonably certain, the andesite occurs close to the base of the Tillybrachty Sandstone Formation and is separated from the basal unconformity by about 50 m of red sandstones and shales. The andesite is over 100 m thick in the east and north of the basin, but is only about 15 m thick in the south at Contlach [NJ 476 241]. The various occurrences are interpreted as remnants of a single episode of volcanic activity. All the occurrences where the stratigraphic position is uncertain are found close to the faulted north western margin of the basin, where they are interpreted as fault slices preserved on the shoulders of the basin as it subsided (Rice *et al.* 2002).

The Longcroft Tuffs are a distinctive and enigmatic fault-bounded unit that was identified during drilling in the Longcroft area [NJ 494 282] (Rice *et al.* 2002). They have been found nowhere else, and are interpreted as the erosional and airfall products from a nearby andesite volcanic centre (Rice

https://doi.org/10.1017/S0263593300000705 Published online by Cambridge University Press

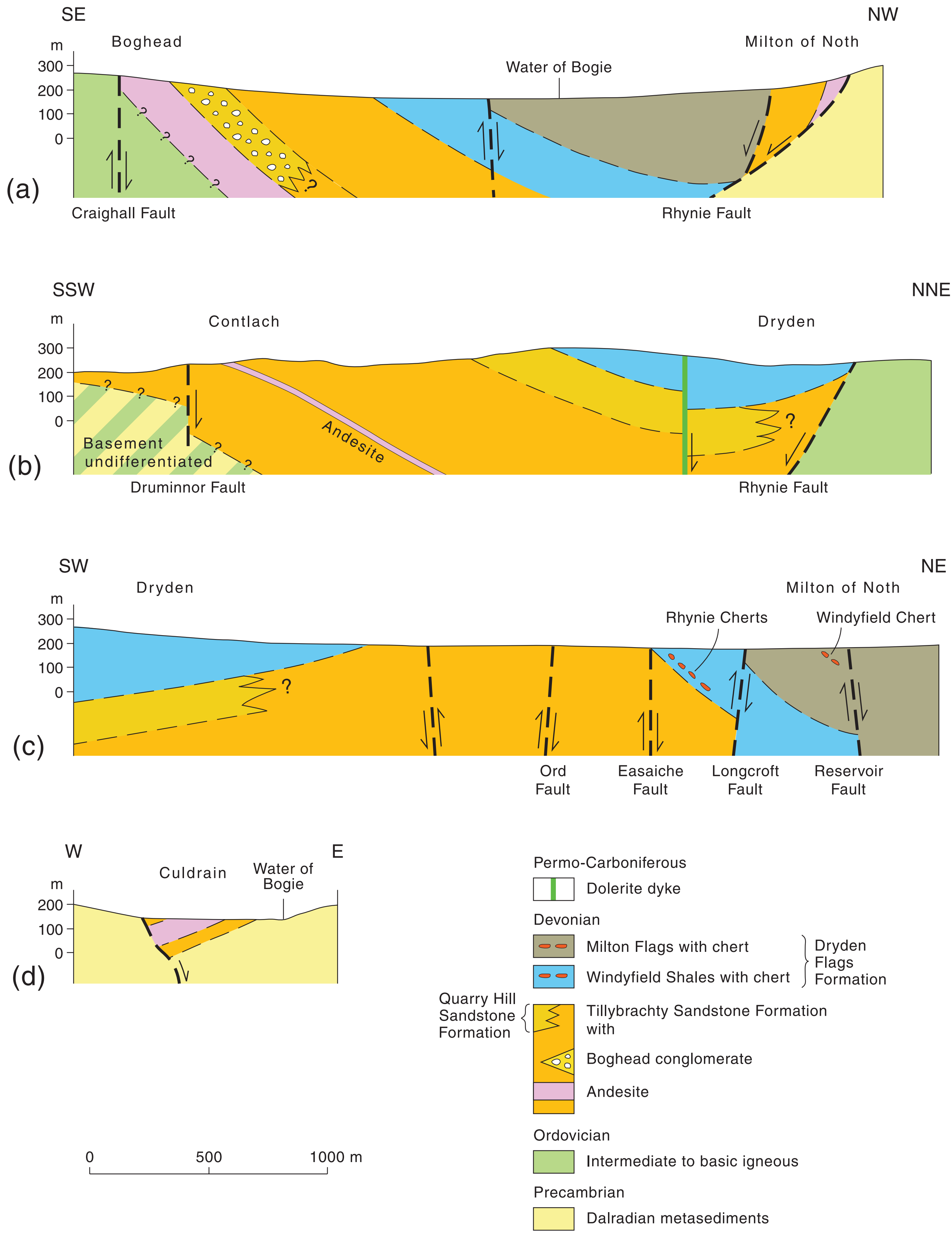

Figure 3 (a–d) Cross-sections of the Rhynie Basin. Locations marking lines of section on Figure 2c.

et al. 2002). They are assumed to be part of the same volcanic episode as the andesite lavas.

The reddish sandstones of the Tillybrachty Sandstone Formation are succeeded by a unit that is at least 300 m thick, and which is dominated by dark grey-green laminated shales and micaceous siltstones with subordinate thin sandstones. The shales and siltstones are similar to those seen in the SSSI at Windyfield [NJ 495 280] (Upper and Lower Shales of Rice

https://doi.org/10.1017/S0263593300000705 Published online by Cambridge University Press

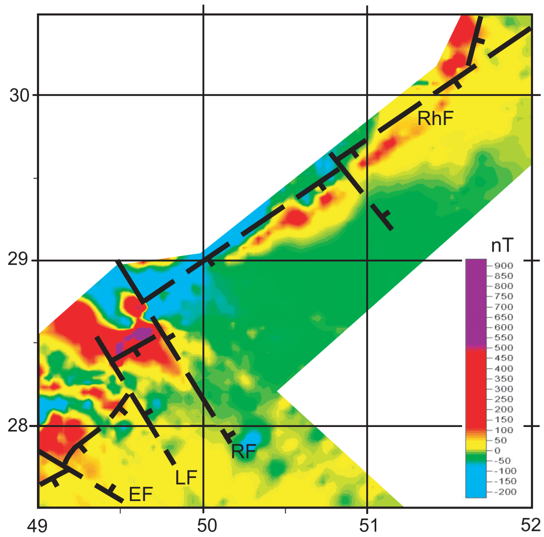

Figure 4 Magnetic expression of faulting on the NW margin of the Rhynie Basin. The data are residual values of total field derived from a regional field calculated on a four by four matrix covering this map area: (RF) Reservoir Fault; (LF) Longcroft Fault; (EF) Easaiche Fault; and (Rh) Rhynie Fault.

et al. 2002), and on structural grounds, together with evidence found in the intervening ground by the digging programme, may be correlated with them. There are also similarities between these shales and those at Dryden [NJ 482 263], as noted by Grant Wilson & Hinxman (1890). The present authors have identified this as a mappable unit, the Windyfield Shales, which is here defined as the lower member of the Dryden Flags Formation (Fig. 3). It contains the Rhynie Cherts Unit of Rice *et al.* (2002), and also within its outcrop, two small areas near the Glamlach Burn [NJ 4961 2771] and at Castlehill [NJ 5126 8015] where chert float is abundant (Fig. 2c). These may represent either the eroded and scattered remains of small isolated chert pods, as seen at the site of the Windyfield chert (Fayers & Trewin 2004) or glacially dispersed chert from the SSSI. Because of access problems, these two areas have not been fully investigated by trenching.

The youngest unit seen in the traverse and the youngest beds found in the basin are grey green flags and shales. These occur in the northwestern part of the basin around Milton of Noth and are at least 400 m thick. They are the upper member of the Dryden Flags Formation and constitute the Milton Flags. They differ from the Windyfield Shales in that flaggy sandstones dominate over shales. The lower contact with the Windyfield Shales is nowhere exposed and is believed to be mainly faulted.

2.2. Faulting

The main part of the Rhynie Basin described here, i.e. north of the Druminnor Fault, is rhomb-shaped and entirely fault-bounded by the Rhynie, Druminnor, Craig Castle and Craig Hall faults. A narrow extension of the basin to the north, the Gartly extension, is bounded on the west by a fault, the Bogie Fault, and on the eastern side by an unconformity.

2.2.1. Northwestern margin: Rhynie Fault Zone. The Rhynie Fault Zone is the most important structure in the basin. It is the main structural control on hydrothermal activity and sedimentation (Rice *et al.* 1995, 2002). It can be traced from Dryden in the southwest to Newnoth [NJ 517 302] and then northeastwards up the Glen of Cults, and may continue for a further 25 km northeastwards to Turriff to link with the fault defining the western margin of the Turriff Basin (Horne *et al.* 1923; Norton *et al.* 1987). The fault is low angle, and appears to vary at the surface from a single fault plane, as between Dryden and Upper Ord, to a complex fault zone, as seen in the Rhynie area (Rice *et al.* 2002). Here it is offset by a number of cross-faults which downthrow to the north between Upper Ord farm and Windyfield, and to the south from Upper Ord farm to Dryden (Figs 2c, 3c). The cross-faults separate contrasting rock types within the fault zone and contribute to the preservation of the Milton Flags, the youngest unit in the basin.

Between Longcroft and Newnoth, there is convincing evidence for a single fault plane only. However, a second basinward fault is inferred because of the presence of andesite close to the basement–sediment contact in an analogous position to that seen at Windyfield. Magnetic modelling here is inconclusive. While the present authors believe that the balance of evidence indicates that this andesite is from the lower part of the succession, they cannot rule out the possibility that it is a separate and younger volcanic episode (Rice *et al.* 2002)

The andesite can be traced as a continuous magnetic anomaly running parallel to the basin margin from Milton of Noth to New Noth (Fig. 4). There is a clear offset in the anomaly, which is interpreted as a fault trending NW–SE and downfaulting the andesite vertically 104 m to the northeast. Modelling of the anomaly indicates that the andesite is about 40 m thick and dips 54° to the southeast; the latter is comparable to that seen in nearby excavations where the andesite is conformable with the sediments.

A fault parallel to the Rhynie Fault Zone, hereafter called the Castlehill Fault, is inferred from vertical strata found in trenches at Castlehill and Mains of Craighall [NJ 523 292].

2.2.2. Southern margin: Druminnor Fault. This is a major fault with a NE–SW trend which can be traced from Boghead to Contlach and divides the basin in two (Figs 2c, 8a). It is distinct from the Auchinleith Fault of Gould (1997), but follows a similar line at its southwestern end. The Druminnor Fault is nowhere exposed, but may be traced by a linear alignment of topographic features, by the truncation of strata at Boghead and Contlach, and by a strong magnetic feature at Boghead, which is interpreted as a dolerite dyke filling the structure (Fig. 2c). The fault can be placed to within 100 m behind Druminnor Castle [NJ 514 264], and elsewhere, there are sufficient exposures and good magnetic features to accurately constrain its position. An ENE-WSW-trending dolerite dyke that spans the basin appears to cut the fault near Druminnor Castle. The fault dips steeply and downthrows to the northwest, juxtaposing elements of the lower part of the Tillybrachty Sandstone Formation. Therefore, the throw does not exceed several hundred metres, but it partly accounts for the preservation of the youngest beds (Dryden Flags Formation), including the Rhynie cherts, in the northern half of the basin.

2.2.3. Western margin: Craig Castle Fault. This NNE-trending fault is not exposed, but can be placed to within a few metres in the stream section immediately below Craig Castle [NJ 471 248], where dark basic rocks are adjacent to orange sandstones, and at Upper Wheedlemont Farm [NJ 476 261], where grey shales abut serpentinite. Elsewhere, its position is marked by a linear topographic feature, by ponds and springs, and by a magnetic feature. Magnetic modelling indicates that it dips west at about 60°.

2.2.4. Eastern margin: Craig Hall Fault and unconformity at Glen of Cults. The eastern margin is marked by the Craig Hall Fault between Boghead and Braefolds [NJ 531 298], and further north around the Glen of Cults area by an unconformity. The Craig Hall Fault occurs at the base of a low hill composed of diorite and has a similar trend to the Craig Castle Fault. There is no exposure, but the fault was proved in a trench 460 m northeast of Bogend [NJ 521 278] and can be

https://doi.org/10.1017/S0263593300000705 Published online by Cambridge University Press

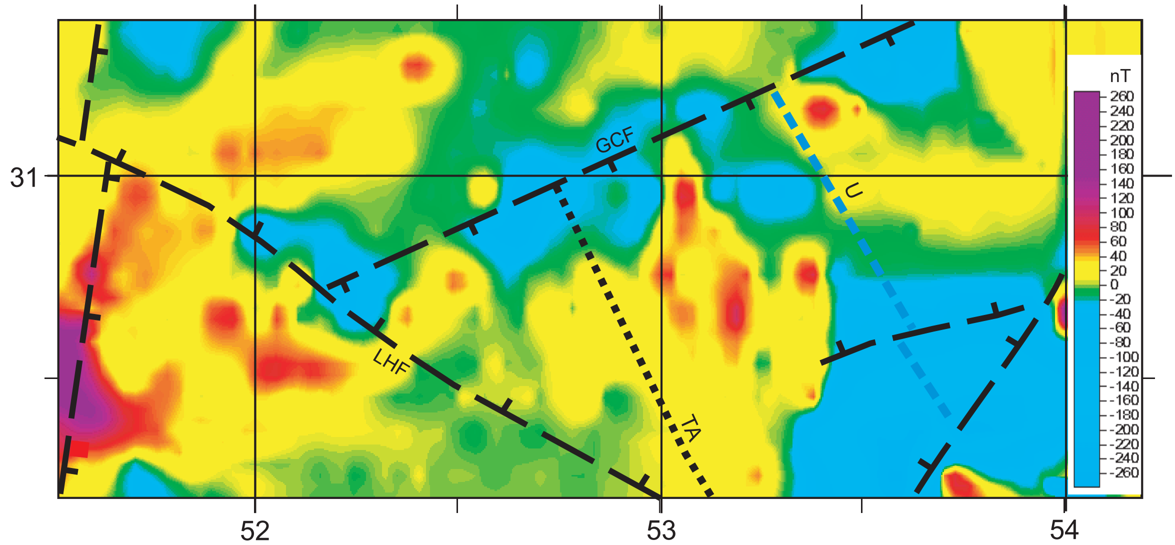

Figure 5 Magnetic expression of faulting in the Old Noth area of the survey. The data are residual values of total magnetic field derived from a regional field calculated on a seven by three matrix covering this map area: (GCF) Glen of Cults Fault; (LHF) Leith Hall Fault; (TA) top of Andesite; and (U) unconformity.

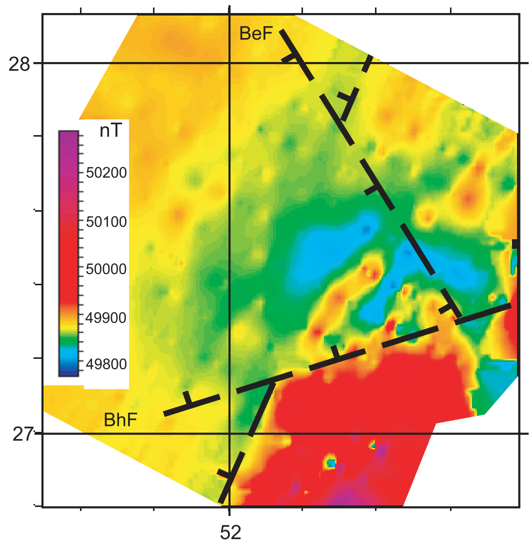

Figure 6 Total field magnetic anomaly map of the Boghead–Bogend area: (BhF) Boghead Fault; and (BeF) Bogend Fault.

placed to within 60 m near Craig Hall between conglomerate found in a pit and exposed diorite in the knoll on which Craig Hall stands. At its southern end, the Craig Hall Fault is offset by two important faults which have NW (Bogend Fault) and ENE (Boghead Fault) strikes before being truncated by the Druminnor Fault. The Bogend and Boghead Faults show up clearly on a contour map of the magnetic field (Fig. 6). The Boghead Fault appears to be continuous with a dolerite dyke at its southwestern end (Fig. 2c), and indeed, is parallel to an extensive suite of ENE faults in northeastern Scotland which are linked to Late Carboniferous dolerite dykes.

The Craig Hall Fault is terminated in the north at Braefolds by the Leith Hall Fault, which trends northwest through the stream valley west of Leith Hall [NJ 541 298] to Old Noth [NJ 522 308]. It offsets the eastern margin of the basin, plots as a topographic lineament, and truncates geologic and magnetic features (Fig 5). North of this fault, the eastern margin is marked by an unconformity that used to be exposed in the Glen of Cults (Grant Wilson & Hinxman 1890) and whose position was further constrained to within 100 m at Coresburn by digging. The unconformity is affected by small cross-faults interpreted from geophysics, one of which truncates it at the Mill of Syde [NJ 535 300]. Further north, the unconformity terminates against the Glen of Cults Fault, a continuation of the Rhynie Fault.

2.2.5. The Gartly extension. North of the Rhynie Fault Zone from New Noth to Millhill [NJ 522 347], poorly exposed andesite and sediments from the lower part of the Tillybrachty Sandstone Formation are found in a narrow strip along the floor of the Bogie valley (Figs 2c, 3d). These rocks represent the deepest part of the basin in, contrast to those preserved south of the Rhynie Fault Zone, which represent higher levels. The western margin is fault-bounded. Evidence for this, the Bogie Fault, may be seen in a roadside quarry near Culdrain [NJ 520 339], where steeply dipping sheets of fault breccia occur within grey pelites, and also at Old Noth, where trenching exposed steeply dipping sediments occurring within a few metres of grey pelites and in well defined magnetic features (Fig. 5). In the hillside above New Noth, pelites close to the fault are hydrothermally altered and contain anomalous arsenic levels, indicating that the Rhynie hydrothermal system may have extended from here southwards to Upper Ord Farm, a total distance of 4 km.

The eastern margin of the Gartly extension is nowhere exposed, but red shales and sandstones close to the base of the succession are present. Therefore, the contact is believed to be an unconformity and a continuation of that present in the Glen of Cults. This part of the basin is cut by several cross-faults varying WNW–ENE to E–W, which are inferred from magnetic (e.g. the Gartly Fault), topographic and geologic evidence. One of these is interpreted as forming the northern margin of the basin at Millhill.

2.3. Folding

The general dip of the sediments is to the northwest (with the exception of the Gartly extension), but southwards and eastwards dips prevail near the Rhynie Fault Zone on the northern and northwestern limbs of synclinal structures in the Dryden and Milton of Noth areas. These folds have gently plunging NE–SW and E–W fold axes (Figs 2c, 3a, b, 7). The swing in strike around the synclinal structure at Dryden can be seen from Quarry Hill northwards to Upper Ord (Fig. 2c). In addition, there is a prominent anticlinal fold with an approximately NW–SE axis running through Upper Ord [NJ 489 271] creating opposing dips in the Windyfield Shales at Dryden and Windyfield (Figs 2c, 3c). Other folds with similar fold traces

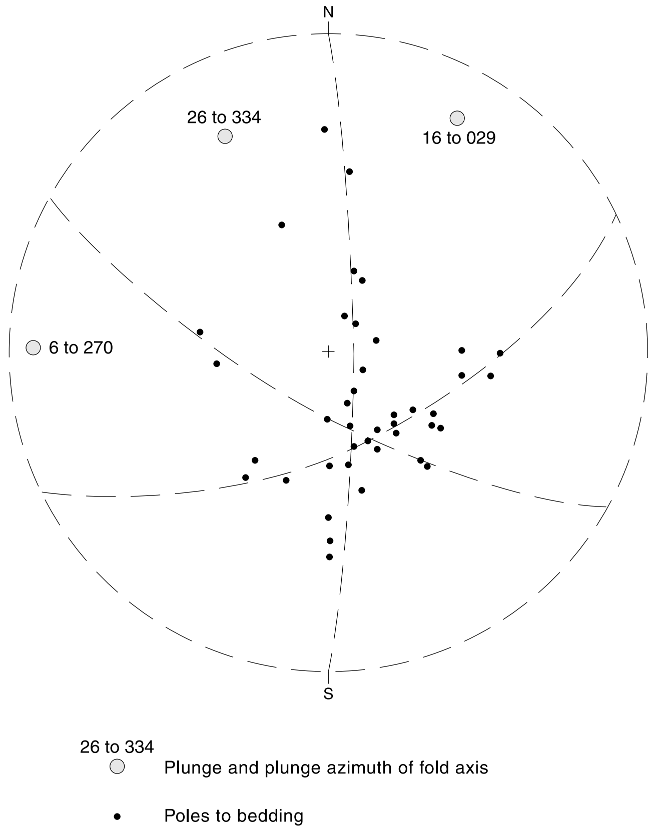

Figure 7 Equal area plot of 41 poles to bedding. Pi axes (i.e. fold axes) for three best-fit pi circles are indicated.

(NNW–SSE in Fig. 7) plunging at about 26° occur along the Druminnor Fault, and can be seen affecting the andesite lava at Contlach and the conglomerate at Boghead (Figs 2c, 7). Small discrepancies between the orientation of fold traces in Figure 2c and those calculated using a stereogram may be attributed to the small number of data points and poor exposure of contacts. All of the folds are open and upright, and steep dips (>45°) are attributed to faulting. On the basis of this structural geometry, the continuation of the Rhynie Cherts Unit might be expected in the outlier of Windyfield Shales to the southwest near Dryden and in the continuation of the same shales to the northeast through Castlehill [NJ 514 283] (Fig. 2c).

3. Discussion

3.1. Boundaries of the Rhynie hot spring system

The present study has established that the Rhynie Cherts Unit occurs towards the base of the Windyfield Shales Member, whereas the Windyfield chert is found some 200 m above the base of the Milton Flags Member (Figs 1, 2c, 3c). At Castlehill [NJ 5126 8015], there is a steeply dipping thin pyritic sandstone that may be evidence for hydrothermal activity along the Castlehill Fault in an analogous manner to that occurring within the parallel Rhynie Fault Zone (see below). Closely spaced sampling (25-m intervals) of the Windyfield Shales at Blairindinny [NJ 518 289] near Castlehill revealed no further evidence of hydrothermal activity in the form of cherts, mineralization or geochemical anomalies, nor has any evidence been found in the most southerly outcrop of the Windyfield Shales at Dryden. Plant remains are present in the Quarry Hill Sandstone Formation (N. H. Trewin, pers. comm.), and there are unconfirmed reports of plant remains being found at Dryden and Upper Ord Farm, but these are not associated with hydrothermal activity.

The feeders to the hot spring activity are now preserved as hydrothermally altered, mainly silicified, fault zones adjacent to the cherts in the Rhynie area (Rice *et al.* 1995; Baron *et al.* 2004). The extent of this alteration also provides evidence for the likely extent of the hot spring activity. The most intense alteration can be traced for about 2 km along the fault zone from Upper Ord Farm to Longcroft. Weaker alteration continues to the northeast as far as New Noth, but no evidence of hydrothermal activity has been found southwest of Upper Ord Farm. Thus, the estimated minimum lateral extent of the cherts from Windyfield to Castlehill is 1·5 km (the cherts are eroded to the southwest) and comparable to that of the most intense alteration. Calcite veining and clay gouge occur in the fault zone on the eastern margin at Boghead, but no metalliferous anomalies are present and the fluids involved in this veining are dissimilar to those seen in the Rhynie Fault Zone (Baron *et al.* 2004). These studies have shown that the stratigraphic interval in which cherts are found is wider than previously thought and confirmed that they are confined to the Rhynie area in the northwestern part of the basin.

3.2. Evolution of the Rhynie Basin

3.2.1. Sedimentation. The earliest sediments found within the basin predate the andesite, and are thin shales and sandstones of local derivation (Trewin & Rice 1992). The onset of major subsidence along the Rhynie Fault Zone probably coincided with the onset of volcanic activity and the development of a fluvial system along the axis of the basin. Roughly 700 m of mainly sandy detritus was brought into the basin by this fluvial system, now preserved as channel (conglomerates and cross-bedded sandstones) and overbank flood deposits (laminated sandstones) represented by the Tillybrachty Sandstone and Quarry Hill Sandstone Formations. The Boghead Conglomerate and Longcroft Tuffs may represent laterally derived alluvial fan deposits. This relatively high-energy regime was succeeded by a lower energy lacustrine environment, possibly reflecting a decreasing subsidence rate and is represented by the Dryden Flags Formation (Trewin & Rice 1992; Rice *et al.* 2002).

3.2.2. Deformation. The earliest evidence of deformation is provided by faults which controlled hydrothermal activity and these are characterised in the Rhynie area by wallrock alteration, mainly silicification, and quartz veining. Faults in this category define the western margin of the basin or cross-cut it, and have NE–SW, N–S (Bogie Fault) and NW–SE trends. The Rhynie Fault Zone is the most important in this respect, and demonstrates a complex history of movement and associated hydrothermal activity. Late movement on this fault was critical in preserving the Rhynie Basin and the distal part of the Rhynie hot spring system (the cherts). The Ord Fault is a good example of a mineralised cross-fault (Fig. 1a) (Rice *et al.* 2002).

The NE–SW and E–W trending synclines at Milton of Noth and Dryden, the NW–SE trending anticline at Upper Ord, and the cross-faults are probably all related to basin subsidence (Fig. 2a). The synclines may be interpreted as drag folds against the footwall of the bounding fault and the anticline could have been generated by differential subsidence along the cross-faults (Fig. 3c). The other basin margin-defining faults (i.e. Craig Hall, Craig Castle and Druminnor), which have NNE to NE trends, truncate this folding. They also truncate NNW–SSE-trending folds which occur close to the Druminnor Fault. This may indicate that these faults formed later than Early Devonian but before Permo-Carboniferous dyke intrusion. However, an alternative interpretation is that initial movement on these faults was essentially coeval with the

https://doi.org/10.1017/S0263593300000705 Published online by Cambridge University Press

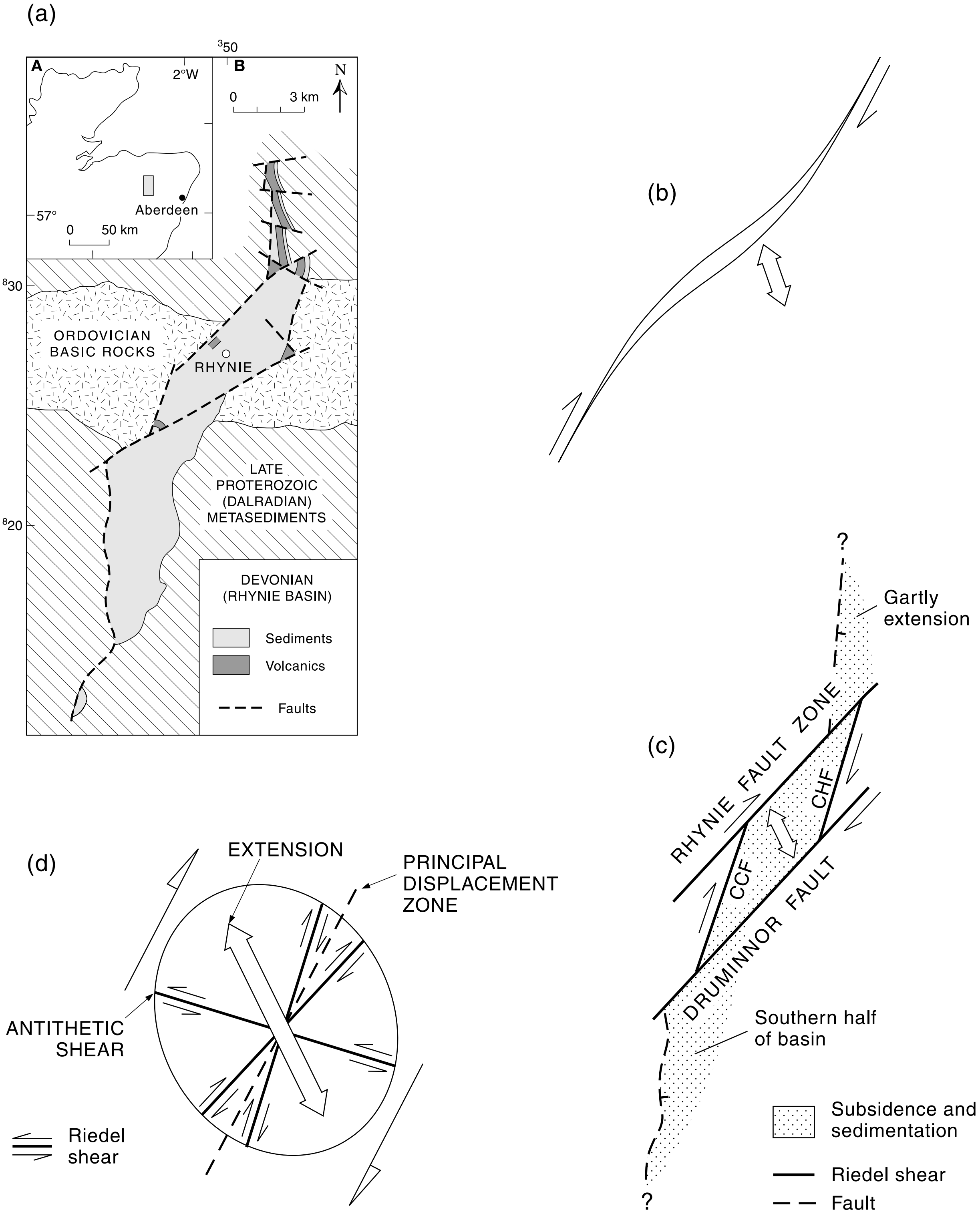

Figure 8 (a) Regional geology of the Rhynie Basin. (b) Releasing bend in NE–SW dextral strike-slip fault inferred to underlie the Rhynie Basin. (c) Formation of the Rhynie Basin above the strike-slip fault as a pull-apart with downthrow to the East: (CCF) Craig Castle Fault; and (CHF) Craig Hall Fault. (d) The NE–SW and NNE–SSW bounding faults to the basin are inferred to be Riedel shears in a simple shear system. The underlying dextral strike-slip fault (Principal Displacement Zone) would then strike about 30° E of N, which is close to the overall trend of the Rhynie Basin.

Rhynie Fault Zone and basin formation, and is developed below. The final phase of deformation is ENE faulting, which is linked to regional Permo-Carboniferous dyke intrusion together with some reactivation and dyke intrusion of the earlier NE-striking faults seen at Boghead and Dryden.

3.2.3. Volcanism. Andesite lavas occur near the base of the sequence throughout the northern half of the basin. However, they are much thinner in the south at Contlach and are not seen in the southern half of the basin, which indicates a source to the north of the Druminnor Fault. The presence of an airfall component in the Longcroft Tuffs and the coarse grainsize of these sediments, which are restricted to the northwest margin of the basin (Rice *et al.* 2002), suggests a nearby volcanic centre. The andesite at Milton of Noth that follows the basin

https://doi.org/10.1017/S0263593300000705 Published online by Cambridge University Press

margin but is also conformable with sediments (Rice *et al.* 2002) could be the remains of a flow-dome complex that was eroded to form the Longcroft Tuffs.

3.2.4. Hydrothermal activity. Hydrothermal activity seems to have been restricted to one centre on the northwest margin of the basin. The concentration of cross-faults in the Rhynie area may have been an important structural (permeability) control on its position. Isotopic evidence indicates that there was a magma at depth (Rice *et al.* 1995), possibly providing the buoyancy to create the anticlinal structure at Upper Ord. The time span occupied by hydrothermal activity is unclear. The presence of the majority of the sinters within the Windyfield Shales Member may reflect a favourable environment for preservation rather than an indication of the actual temporal span of hydrothermal activity. No sinters have been found within the Tillybrachty Sandstone Formation. This may be because of the Formation being deposited before any hydrothermal activity or because of the poor preservation potential of the prevailing (high-energy) environment.

3.3. Basin structure

The essential structure of the Rhynie Basin has been interpreted as a half graben with a low-angle listric fault zone forming the western margin of the northern half (Rice *et al.* 2002). The highest levels of the structure are preserved in the axis of the syncline at Milton of Noth and the lowest levels are preserved in the Gartly extension and Glen of Cults (Figs 2c, 3a, d). The nature of the deep fault structure remains uncertain. Regional extension has been proposed to account for the Devonian basins of northern Scotland (Norton *et al.* 1987), and according to this model, the bounding listric fault would dip less steeply with depth. However, there is evidence that strike-slip faulting was still occurring in northern Britain in the Early Devonian along various major faults (Strachan *et al.* 2002). This suggests an alternative model for the origin of the Rhynie Basin as a pull-apart structure within a strike-slip fault system. Pull-apart structures, especially those generated during transtension, create high permeability, deep conduits for mantle-derived magmas to reach the upper crust (Tosdal & Richards 2001). This model provides a better explanation for the isolated nature (in terms of northeast Scotland) of the volcanic activity in the Rhynie Basin. In contrast, regional extension might be expected to generate multiple volcanic centres (Tosdal & Richards 2001).

The Rhynie Basin, including the Towie outlier and Gartly extension, is extended along a line striking NNE–SSW, which must be the trend of the Principal Displacement Zone (PDZ) of any associated strike-slip faulting. However, the sense of displacement is not immediately obvious. The northern contact of the Insch-Boganclogh intrusion appears to show a sinistral offset, but along this contact, the igneous rocks dip gently north, giving a wide hornfels aureole and possible large offsets even from normal faulting. The picture is further confused by tectonism during emplacement of the later Kennethmont plutonic complex (Gould 1997). The southern contact, which is everywhere steeply dipping and extensively sheared, is complicated by the occurrence of several intrusive masses of sheared and serpentinised ultra-basic rocks, but the aeromagnetic anomaly from these rocks runs uninterrupted under the Rhynie Basin (Gould 1997), as does the southern margin of the gabbroic or noritic rocks of the mafic intrusion.

The principal evidence for strike-slip faulting comes from an analysis of the faulting and folding in the Rhynie Basin. Analogue model studies consistently show that one set of synthetic Riedel shears develops first and is dominant in the early stages of strike-slip basin formation (Wilcox *et al.* 1973; Richard *et al.* 1995; Dooley *et al.* 1999). In the Rhynie Basin, the Rhynie and Druminnor Faults are taken to be that dominant set, and from their left-stepping geometry and trend across the inferred PDZ, they indicate dextral strike-slip (Fig. 8c, d) (Richard *et al.* 1995). The strike of the PDZ is then about 30° E of N, close to the main trend of the Rhynie Basin. A pull-apart basin developing above a release bend in a dextral fault with this orientation would show NW–SE extension and NE–SW compression, which could explain the main synclinal structure of the basin and the folds with NNW–SSE fold axes, and the reverse nature of the Craig Castle Fault (Fig. 8a–d). In this model, the Craig Castle and Craig Hall Faults are also synthetic Riedel shears, determining the rhombic shape and fault-bounded nature of the basin and the E–W to NW-striking cross-faults are antithetic shears (Figs 2c, 8c). The Druminnor Fault shows evidence of later reactivation in that it contains a Permo-Carboniferous dyke. Movement on many of the structures in the northern part of the Rhynie Basin ceased by the late Carboniferous since the basin is cut by a Permo-Carboniferous dyke.

If this interpretation is correct, the current bounding faults should be close to the original basin margins. The immaturity and local source of much of the sediment, the restricted extent of some coarse-grained units, such as the Longcroft Tuffs and Boghead Conglomerate, and the thinning of the andesite to the south against the Druminnor Fault are consistent with this interpretation. Strike-slip displacement may have been small and short-lived, but enough to tap a source of andesite deep in the crust or upper mantle, and initiate basin subsidence by transtension.

The occurrence of dextral movement along a putative wrench fault at Rhynie appears to contrast with movement of the opposite sense occurring at broadly the same time on other faults in Northern Britain (Strachan *et al.* 2002), although it should be noted that late Silurian dextral movement occurred along the Great Glen (Hutton 1988; Paterson *et al.* 1993). The present authors would also point out that the precise timing of movement on most of these faults is not well constrained and it could be significantly different to that occurring at Rhynie. This interpretation of the Rhynie Basin structure must remain provisional and await more rigorous testing when the authors have completed their mapping of the remainder of the basin.

4. Acknowledgements

The authors would like to thank: the farmers and landowners of Rhynie for their much appreciated cooperation; the Lyon bequest for financial support; Alan Crane for many helpful discussions on structural matters and constructive criticism of the manuscript; Kathryn Czapnik for technical assistance; Jim Duncan, JCB driver, for his skill in exposing bedrock and avoiding drains; Barry Fulton for excellent diagrams; and Graham Leslie for provision of BGS fieldslips and constructive criticism of the manuscript.

5. References

Baron, M., Hillier, S., Rice, C. M., Czapnik, K. & Parnell, J. 2004. Fluids and hydrothermal alteration assemblages in a Devonian gold-bearing hot-spring system, Rhynie, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **94** (for 2003), 309–24.

British Geological Survey (BGS) 1993. *Alford. Scotland*. Sheet 76W. Solid Geology 1: 50,000. Keyworth, Nottingham: British Geological Survey.

Dooley, T., McClay, K. & Bonora, M. 1999. 4D evolution of segmented strike-slip fault systems: application to NW Europe. *In*

Fleet, A. J. & Boldy, S. A. R. (eds) *Petroleum geology of northwest Europe: proceedings of the 5th conference*, 215–25. London: The Geological Society.

Fayers, S. R. & Trewin, N. H. 2004. A review of the palaeoenvironments and biota of the Windyfield chert. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **94** (for 2003), 325–39.

Gould, D. 1997. *Geology of the country around Inverurie and Alford* (Sheets 76E and 76W). Memoir British Geological Survey.

Grant Wilson, J. S. & Hinxman, L. W. 1890. *Geology of the area around central Aberdeenshire. Inverurie, Alford, Tarland* (Sheet 76). Memoir Geological Survey, Scotland.

Horne, J., Skae, H. M., Irvine, D. R., Grant Wilson, J. S. & Hinxman, L. W. 1886. Inverurie. *One-inch geological map*, Sheet 76. Geological Survey, Scotland.

Horne, J., Grant Wilson, J. S. & Hinxman, L. W. 1923. Huntly. *One-inch geological map*, Sheet 86. Geological Survey, Scotland.

Hutton, D. H. W. 1988. Igneous emplacement in a shear-zone termination. *Geological Society of America Bulletin* **100**, 1392–9.

Norton, M. G., McClay, K. R. & Way, N. A. 1987. Tectonic evolution of Devonian basins in northern Scotland and southern Norway. *Norsk Geologisk Tidsskrift* **6**, 323–38.

Paterson, B. A, Rogers, G., Stephens, W. E & Hinton, R. W. 1993. The longevity of acid-base magmatism associated with a major transcurrent fault. *Geological Society of America Abstract with Programs* **25**, 6–42.

Read, H. H. 1923. *The geology of the country around Banff, Huntly and Turriff* (Sheets 86 and 96). Memoir Geological Survey.

Rice, C. M., Ashcroft, W. A., Batten, D. J., Boyce, A. J., Caulfield, J. B. D, Fallick, A. E., Hole, M. J., Jones, E., Pearson, M. J., Rogers, G., Saxton, J. M., Stuart, F. M., Trewin, N. H. & Turner, G. 1995. A Devonian auriferous hot-spring system, Rhynie, Scotland. *Journal of the Geological Society, London* **152**, 229–50.

Rice, C. M., Trewin, N. H. & Anderson, L. I. 2002. Geological setting of the Early Devonian Rhynie cherts, Aberdeenshire, Scotland: an early terrestrial hot spring system. *Journal of the Geological Society, London* **159**, 203–14.

Richard, P. D., Naylor, M. A. & Koopman, A. 1995. Experimental models of strike-slip tectonics. *Petroleum Geoscience* **1**, 71–80.

Strachan, R. A., Smith, M., Harris, A. L. & Fettes, D. J. 2002. The Northern Highland and Grampian terranes. *In* Trewin N. H. (ed.) *The Geology of Scotland*, 81–147. London: The Geological Society.

Tosdal, R. M. & Richards, J. P. 2001. Magmatic and structural controls on the development of porphyry Cu-Mo-Au deposits. *Society of Economic Geologists Reviews* **14**, 157–81.

Trewin, N. H. & Rice, C. M. 1992. Stratigraphy and sedimentology of the Devonian Rhynie chert locality. *Scottish Journal of Geology* **28**, 37–47.

Wilcox, R. E., Harding, T. P. & Seely, D. R. 1973. Basic wrench tectonics. *American Association of Petroleum Geologists Bulletin* **57**, 74–96.

C. M. RICE and W. A. ASHCROFT, Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen AB24 3UE, UK.
e-mail: c.rice@abdn.ac.uk

MS received 26 November 2003. Accepted for publication 20 July 2004.