A Variscan short-cut thrust complex model for the Precambrian/Cambrian inlier at Martley, Worcestershire

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ABSTRACT

A disused Victorian gravel pit [SO 7450 5956] 1 km west of Martley, Worcestershire formerly exposed an inlier of Neoproterozoic meta-igneous rocks and early Palaeozoic quartz arenite. The pit is now back-filled, but trenching at the site has re-exposed the rocks of the inlier. This has revealed a complex of Variscan thrust-stacked sheets of rocks ranging in age from Neoproterozoic to Carboniferous in the western footwall of the East Malvern Fault (EMF). Detailed petrography of the meta-igneous rocks has been carried out. Limited microfossil evidence suggests a Cambrian age for the quartz arenite. Structures described previously by Groom (1898, 1900) lie within a fault zone named the Martley Rock Fault (MRF). A thrust-complex structural model is suggested for the inlier, the thrusts being interpreted as footwall shortcuts to the EMF. Two trenches will remain open until 2023 as a 'geosite' visitor attraction, with explanatory display boards and plaques marking the boundaries of the geological formations that are exposed.

KEYWORDS Precambrian; Cambrian; Inlier; Martley; Variscan; Footwall short-cut thrusts

1. Introduction

A disused Victorian gravel pit near Martley, Worcestershire (SO 7450 5956; Figure 1), recently named Martley Rock, has attracted geological interest for almost 200 years, since its discovery by Murchison (1839). The presence of Neoproterozoic meta-igneous basement rocks in a very small inlier surrounded by younger sedimentary rocks and overlying quartz arenite of Cambrian age is unique in southern Britain. The inlier lies on the Malvern Axis, immediately adjacent to the East Malvern Fault, lying on its western footwall side. These structures are among the most important lineaments in England and have a prolonged geological history involving repeated tectonic movement and reactivation. Martley Rock provides a window into the complex geology that resulted from these tectonic events and the intervening periods of sedimentary deposition. The younger sedimentary rocks are Late Silurian red-beds of the Moor Cliffs (formerly Raglan Mudstone) Formation of the Daugleddau Group (Lower Old Red Sandstone; Barclay et al., 2015) and mudrocks and sandstones of the Late Carboniferous Halesowen Formation. Red-brown sandstones of the Early to Mid-Triassic Helsby (formerly Bromsgrove) Sandstone Formation (Ambrose et al., 2014) lie in the hanging wall of the East Malvern Fault.

The disused pit was dug in meta-igneous rocks and highly fractured quartz arenite. It was backfilled in the late 1980s. However, a trenching programme carried out in four phases from 2010 to 2014 (Figure 2) re-exposed some of the rocks in the pit and the surrounding younger cover rocks. This has provided new insights into the stratigraphy and complex structure of the inlier and its cover rocks. A progress report on the trenching done to the end of 2011 was given by Barclay et al. (2012).

2. Geological background

A full history of research at Martley Rock, dating back to Murchison's record published in 1839, is given in Barclay et al. (2012). Further to descriptions by Phillips (1848), Symonds (1872), Coles (1898) and Callaway (1898), Groom (1898) provided the most detailed description of the inlier and its structure. He described the quartz arenite then exposed in the pit as somewhat shattered and arranged in the form of a plicated anticline or anticlinal dome, dipping to the west and east and showing a tendency to a quaquaversal arrangement. This was overlain by igneous rock indistinguishable from the crushed coarse diorite of the Malverns, with an intervening zone of greenish schists. Groom later (1900) combined his earlier (1898) sketched section and Phillips's (1848) section to produce a diagrammatic cross-section across the inlier. This shows the Malverns Complex overlying the quartz arenite, with Old Red Sandstone strata faulted by a steep reversed fault against the Malverns Complex in the west and Coal Measures lying unconformably on the Malverns Complex in the east. The East Malvern Fault truncates these rocks to the east, bringing in Triassic rocks on its east hanging wall side. The Malverns Complex/quartz arenite junction is shown as a plicated fault folded into the anticlinal structure seen in the pit.

In the survey of the Droitwich one-inch geological sheet in 1936-7, Hollingworth (in Dinham, 1938; Mitchell et al., 1962) reported that an extensive series of auger holes that showed that Coal Measures almost entirely surrounded the pit. Mitchell et al. gave a detailed geological map of the inlier and a comprehensive account of the work previously carried out, but noted that there was no new information on the relationships of the quartz arenite and the igneous rock. Phipps and Reeve (1969) considered that the emplacement of the igneous rock and quartz arenite post-dated the deposition of the Coal Measures and that the inlier was probably a remnant of an upthrust system to which they attributed the tectonics of the Malverns.

Brooks (1968) postulated that the Precambrian basement lies at over 1000 m depth east of Martley and concluded that the Martley inlier may comprise material thrust westward from the axial zone of the Malvern Axis prior to the formation of the Triassic Worcester Basin. One of us (WJB) visited the pit in 1985 in the course of mapping the area at 1:10 000 scale (British Geological Survey, 1990; Barclay and Rathbone, 1990). There were small exposures of shattered and disturbed rock visible in the northern part of the pit, including a green, micaceous schistose shear zone, white sheared clay gouge, pegmatitic, quartz-feldspar rock with a little mica and a small outcrop of greenish dioritic rock. A BGS seismic line (Chadwick, 1985; Chadwick and Smith, 1988) 2 km north of the pit proved the structure of the Malvern Axis at depth. A brief summary of the geology and structure was given by Barclay et al. (1997).

3. Geology of the site

The geology of the site (Figure 3), as previously recorded (Mitchell et al., 1962) and mapped most recently by the BGS in 1985 (BGS, 1990), comprises a small inlier of meta-igneous rocks of the Precambrian Malverns Complex (Figure 3). This forms a topographic mound covered by gravelly soil of weathered igneous rock, into which the pit was excavated. A quartz arenite shown previously to underlie the Precambrian rocks has been correlated with both the Lickey Quartzite of the Lickey Hills and the Malvern Quartzite of the Malvern Hills. Barclay and Rathbone (1990, Figure 3a), following Groom (1898, 1900), interpreted a thrust relationship between the units, with the Malverns Complex and the Malvern Quartzite occurring in a thrust system produced as a splay off the East Malvern Fault during Variscan transpression. The older Malverns Complex was interpreted to 'piggyback' over the younger Martley Quartzite Formation, the latter being thrust over the Raglan Mudstone Formation. However, there was very little exposure during the BGS survey in 1985 to allow a more definitive picture of the relationships. The more extensive exposures recorded by Groom and others indicate, as shown by Groom, an anticline in which the thrusting was subsequently folded. The inlier lies within metres of the East Malvern Fault, with the Triassic Helsby (formerly Bromsgrove) Sandstone Formation in close proximity to the east in the hanging wall of the fault. Surrounding the inlier on the western footwall side of the fault is a thin drape of mudstones correlated with the Late Carboniferous Halesowen Formation (formerly Highley Beds). This rests unconformably on red mudrocks of the Old Red Sandstone-facies Moor Cliffs (Raglan Mudstone) Formation of Late Silurian age on the west side of the inlier. Similar red mudrocks occur in a complex thrust-faulted relationship with the Halesowen Formation on the east side of the inlier, in close proximity to the East Malvern Fault.

4. Trenching programme

The first trench (Trench 1; Figure 2) and a side trench (Trench 2) were excavated in February 2010 (Barclay, 2010). These remain open as a ‘geosite’ visitor attraction, with explanatory display boards and plaques marking the boundaries of the geological formations. Temporary trenching was carried out in October 2011 (trenches 3 and 4) and these trenches were back-filled soon after digging. In December 2011, an area of Malverns Complex in and adjacent to the backwall of the former pit where it was intersected by Trench 1 was excavated and this remains open. An eastward extension to Trench 1, also dug in December 2011, and still open, exposed the East Malvern Fault and a short section of Helsby (Bromsgrove) Sandstone Formation on its hanging wall (east) side. Further temporary trenching was carried out in January 2013 (trenches 5, 6 and 7; Barclay and Payne, 2013) and September 2014 (Trenches 8, 9, 10, 11, 12 and 13; Barclay and Payne, 2014). Three shallow pits were also dug by JCB in September 2014, further to some earlier very shallow hand-dug pitting.

5. Stratigraphy

5.1. Neoproterozoic - Malverns Complex

All previous workers have correlated the meta-igneous rocks of the inlier with the Precambrian (Neoproterozoic) Malverns Complex of the Malvern Hills (Pharaoh and Gibbons, 1994). These have an igneous crystallisation date of 677 Ma, with subsequent thermal reactivation at c. 610-600 Ma and metamorphic recrystallization at c. 550 Ma (Strachan et al., 1996; Barclay et al., 1997). Hollingworth (in GSGB, 1955) called the meta-igneous rocks at Martley the Martley Granite. The rocks have been variously described as syenite (Callaway, 1898; Coles, 1898), (crushed) diorite (Groom, 1898, 1900), altered gabbro and crushed granite (Phemister in Mitchell et al., 1962). The rocks of the Malverns Complex in the Malverns have been described most recently (Barclay and Pharoah, 2000) as diorites, tonalites, granites and their sheared derivatives. They show abundant evidence of hybridisation, metasomatism and metamorphism, in addition to the shearing which imparts a gneissose fabric to much of them. The Martley rocks are little different. In addition to the mafic varieties, felsic quartz-feldspar pegmatitic rocks occur to a minor extent. All the lithologies show a high degree of shearing.

Detailed petrography has been carried out on samples from the trenches by SH and EC. Sample details are given in Table 1. Samples MP6 and MP8 from Trench 1 and MP1 and MP2 from Trench 2, although altered, are most likely to have been tonalities. MP6 is a pale pink rock with plagioclase crystals up to 5mm long. All are altered to sericite and white micas, with corroded ends and sides. Some have slightly curved albite twins and fractures showing lateral movement, but the crystals are too altered to estimate composition. Remnants of large quartz crystals show undulose extinction. They and the larger plagioclase crystals are surrounded by smaller fresh crystals showing straight extinction and 120˚ triple junctions. This granulation of grain boundaries is known as mortar texture. The igneous rocks in Trench 3 were sampled at 3 m intervals. Sample MP13, 15 m from the intersection with Trench 1, was chosen for detailed study as the least altered of the samples. It is a grey-pink, medium- to coarse-grained rock with no obvious lineation or foliation and a colour index of 39. White/cream and pink minerals appear to be composite feldspar crystals, over 5 mm in size and with more rectangular shapes. Its mineral composition is given in Table 1. The freshest plagioclase crystals show albite twinning, the extinction angles of which give an anorthite composition of An_{42-54} (andesine to labradorite) with an average composition An_{47} (andesine). Le Maitre et al. (2014) define a diorite as containing less than 5% alkali feldspar, with a colour index greater than 10 and an average plagioclase composition in the range An_{0-50}. Sample MR 13 can therefore be classified as a diorite. Lambert and Holland (1971) reported very similar rocks from North Quarry, Malvern with pink plagioclase, hornblende and biotite (both replaced by chlorite) and interstitial quartz. They termed these diorites also. Sample MP/MR7 from Trench 1 is a reddish green, highly altered rock with red/green-coated slickensided joints. The feldspar is heavily sericitised and the mafic minerals are almost entirely chloritized, but the original rock is likely to have been a diorite.

All the rocks show varying degrees of strain and brittle deformation; some also show heterogeneity and mortar texture, all suggestive of low-grade dynamic metamorphism. The mortar texture, comprising interlocking fine-grained crystals, formed by crushing and recrystallization of a rock that was originally coarser grained. This texture is typical of low-grade dynamic metamorphism in which deformation occurs primarily along crystal boundaries, producing an envelope of mortar texture around individual crystals.

The trenching programme has revealed the precise extent of the outcrop of the Malverns Complex, which is considerably smaller than previously mapped and entirely fault-bounded. It occurs in Trench 1 from close to its intersection with Trench 2 south-eastwards for 18 m. The trench intersected the former side wall of the pit from 6 to 15 m from the junction with Trench 2 and further excavation in this vicinity in December 2011 exposed outcrops of dioritic meta-igneous rocks cut by shear planes (Plate 1). The Malverns Complex extends for a further 3 m south-east of the former pit backwall, where it is overlain by dark grey to black clay correlated with the Halesowen Formation. Less mafic rocks were exposed in Trench 3, from its intersection with Trench 2 for about 25 m to its intersection with Trench 4, and for 3 m in the latter to the junction with the Halesowen Formation. The Malverns

Complex also occurs for a short distance to the west of the intersection of trenches 1 and 2 and in Trench 2 in a shear zone (the Martley Rock Fault) in sheared and folded contact with the Malvern Quartzite Formation. It also occurs in Trench 5 from its south-west end for 6 m to a zone of green sheared igneous rock reduced to sand and in Trench 7 for 6 m from its eastern end to a shear zone of igneous and quartzitic debris (the MRF).

5.2. Cambrian - Malvern Quartzite Formation

The highly sheared quartz arenite of the inlier has been correlated both with the Lickey Quartzite of the Lickey Hills (Coles, 1898) and the Malvern Quartzite Formation of the Malverns (Groom, 1898; 1900; Barclay and Rathbone, 1990). For this reason, Barclay et al. (2012) termed it the Martley Quartzite, following the Geological Survey manuscript map of the 1936-7 survey (GSGB, 1955). It has also been likened to the Wrekin Quartzite of Shropshire (Callaway, 1898). The Lickey Quartzite has been shown by Molyneux (in Old et al., 1991) to be of Ordovician (Tremadoc Series or Arenig Series) age and the Malvern Quartzite and Wrekin Quartzite are of Cambrian (Comley Series) age. A sample from the shattered outcrops in Trench 1 (BGS Sample MPA 61989) yielded a palynological residue comprising small opaque fragments (Molyneux, 2013). A single specimen of a possible acritarch attributed to *Lophosphaeridium*? sp. was recorded. *Lophosphaeridium* is a long ranging genus not diagnostic of age. It is, however, more prevalent in Early Cambrian assemblages than in Early Ordovician, which suggests that the sample might be from the Malvern Quartzite rather than the Lickey Quartzite. More and better data are needed to confirm this, but on the basis of a more likely Early Cambrian age, the rock is named the Malvern Quartzite Formation in this account. The rock is similar to the Malvern Quartzite of the type area in containing large amounts of very rounded, almost spherical grains of clear quartz of quite uniform diameter (about 600 microns), which the Lickey Quartzite does not. It is a very tough, fine-grained quartz arenite. Groom (1900) recorded bedding, and three small areas of mm-scale lamination (including Sample MR10) were seen in a small outlier of unaltered quartz arenite north-east of the main outcrop in Trench 12. Groom (1910) described a large range of grains and pebbles composed of, amongst other lithologies, felsic igneous and metamorphic rock. Examples of these lithologies were noted in samples MR9 and MR10 from Trench 12. Most of the outcrop is tectonised and shattered (Plate 2). In the west of the outcrop, the Malvern Quartzite is thrust over the Halesowen Formation by a flat to very low-angle thrust (Plate 3). Its eastern boundary is marked mainly by a steep zone of faulting (the Martley Rock Fault) that separates it from the Malverns Complex.

Phemister (in Mitchell et al., 1962) described a sample (E 17612J) as a quartzitic sandstone with average grain-size about 0.5 mm and a siliceous cement. The rock was subsequently fractured and the cracks filled by quartz, feldspar and calcite. There are apparently two generations of cracks, the earlier accompanied by straining throughout. Petrographic analysis of samples from the trenches is given in Table 2. Samples MR9 and MR10 are unaltered quartz arenites similar to that described by Phemister, the others being altered to some extent. Samples MR3 and MR4 are located within the Martley Rock Fault Zone. MR5 is on the edge of the fault zone and is generally less deformed than the other two samples. Most of the deformation appears to be due to granulation along the quartz grain boundaries, which is more severe in MR3 and MR4 and less so in MR5. This suggests dynamic metamorphism within the Martley Rock Fault Zone. MR4 has undergone extensive mineral replacement by secondary calcite. Samples MR3 and MR4 show signs of recrystallization of quartz as the result of fluid influx, probably at raised temperature (N. Henwood, personal communication). Comparison of these thin sections and that described by Phemister demonstrates the variations in the late-stage alteration of the quartzite. MR3 and MR4 are about 1 m apart, but their alteration is very different. None of the veining seen by Phemister was seen in MR3, the only veining being Fe-rich. Only one phase of veining was noted. The replacement calcite in MR4 is much more extensive than that described by Phemister and again only one phase of veining is present. The veining in MR5 is closest to that described by Phemister, but the straining he noted is not seen and no feldspar appears to have been involved.

5.3. Silurian – Moor Cliffs (Raglan Mudstone) Formation

Late Silurian (Pridoli Series) alluvial floodplain red-beds exposed in the trenches are correlated with the Moor Cliffs (formerly Raglan Mudstone) Formation of south Wales and the Welsh Borderland (Barclay et al., 2015). These outcrop extensively around the inlier in the footwall of the East Malvern Fault and were referred previously to the Downton Series of the Old Red Sandstone (Mitchell et al., 1962). The strata in the trenches consist of brick red to red-brown (mainly) to purplish mudrocks with pale green mottling. They are largely weathered to stiff red, green- and purple-mottled clay. A thin Intraformational mudrock clast conglomerate is present near the base of the clays in Trench 1. Stiff, red clay on the eastern side of the inlier in Trench 1, in proximity to the EMF, was initially correlated with the Late Carboniferous Etruria Formation (as on the on-site geological map), but is now considered to be the Moor Cliffs Formation. Red clay is exposed below the Halesowen Formation at the western end of Trench 1 and was exposed at the western ends of trenches 6, 7 and 11 and towards the eastern ends of trenches 4, 5, 8, 9 and 10.

5.4. Carboniferous - Halesowen Formation

Carboniferous rocks are exposed at the west and south-east ends of Trench 1 and south-west end of Trench 2. They were also exposed in trenches 4, 5, 6, 7, 8, 9, 10, 11 and 12. Formerly referred to the Highley Beds (Mitchell et al., 1962), they are correlated with the Halesowen Formation of the Midlands, of Late Carboniferous (Asturian) age (Waters et al., 2011). They comprise multi-coloured mudrocks with hard, fine-grained, green and grey tabular sandstones and either rest unconformably on the underlying rocks or are in faulted contact with them. The mudrocks are pale grey, pale green-grey, orange, dark grey and black, the darker lithologies being carbonaceous. The black ones are coal-rich. Colour-banding reflects differing oxidation states of the mudrocks. Petrographic analysis of samples of the sandstones from trenches 1 and 12 (Table 3) show them to be arkosic arenites.

In Trench 5, clays of the Halesowen Formation extend for 3m from the faulted contact with the Malvern Quartzite Formation to the north-east where they overlie red clays of the Raglan Mudstone Formation seen in the base of the trench. The junction of the Halesowen Formation and Raglan Mudstone Formation is both straightforward and complex. Where straightforward, a basal Halesowen Formation layer of orange sand overlies unconformably a flat-lying surface of red clays of the Moor Cliffs Formation, infilling hollows in the latter. Where complex, on part of the north-west wall of the trench, red and green clays are apparently tectonically inter-sliced. Above the basal orange sandy layer, which is about 0.1 m thick, the Halesowen Formation comprises mainly greenish clays with some dark grey carbonaceous clays and pale grey clays.

In Trench 6, tectonised, shattered, orange-stained quartz arenite of the Malvern Quartzite is thrust over green clays and hard, dark grey-green tabular sandstones of the Halesowen Formation. At one point [SO 74502 595621], a 0.2 m-thick tabular bed of hard, dark green, fine-grained sandstone overlies yellow/orange/greenish stiff clay. The sandstone dips about 20˚ to 320˚. The outcrops of Halesowen Formation indicate the presence of structural complexity, with the beds seen younging north-westwards towards a flat-lying, unconformable junction with the Raglan Mudstone Formation. To the south, there is little sandstone in Trench 7, with greenish clays predominating. These clays unconformably overlie stiff red clay of the Raglan Mudstone Formation, seen in the westernmost 3m of the trench.

In Trench 4, none of the Carboniferous rocks are indurated. They comprise a basal 0.25 m-thick mottled dull red, green and orange silty sandstone containing grains with a large range of sizes, including angular pink and white feldspars up to 4 mm and angular to sub-rounded quartz grains of 1 mm size. The sandstone passes up into an olive-grey silt about 0.25 m thick which is truncated by a sharp, very irregular boundary overlain by black clay. The beds dip about 20° eastwards near the Precambrian edge but are gently folded synclinally to dip westwards a few metres to the east. These silts and clays extend for 7 m and show a gradation from pale grey-brown silt to pale yellow-brown silt and finally to brown silt. The last rests on dark red silty clay of the Raglan Mudstone Formation. The junction appears to be an irregular erosion surface dipping about 45° west.

In Trench 8, olive green and blue-grey clays with black carbonaceous and coaly lenses are over-thrusted by red clays of the Moor Cliffs Formation, the junction dipping about 40˚ to the south-east.

At the south-east end of the Trench 1, very stiff, dark blue-grey to black organic clay overlies the Malverns Complex, the junction dipping moderately eastwards. A 1 cm-thick impersistent gravelly layer of angular Malverns Complex clasts and granules lies at the base of the clay. Palynological analysis of the clay (BGS Sample MPA 61990; Molyneux, 2013) yielded a palynological residue comprising large and numerous opaque fragments and scarce miospores. Altogether, only five definite and two possible miospore specimens were recorded. Preservation is fair to good and all the specimens are small and relatively simple. One specimen is identified as a specimen of *Lycospora*, probably *L. pusilla*. This species is not particularly diagnostic of age as it ranges from the Mississippian into the Permian, but is consistent with a Carboniferous age (Molyneux, 2013). The stiff, dark blue-grey to black organic clay appears to be truncated by a steep thrust trending at 163˚. Red and green/grey mottled clay of the Moor Cliffs Formation lies to the south-east.

Olive green clay at the south-west end of the Trench 2 is in faulted contact with the Malverns Complex. The fault is a steep reversed north-west – trending fault, truncating the inlier on its south-west side. Dark grey-green sandstone at the end of the trench by the roadside is similar to the hard, fine-grained sandstones seen in Trench 6. The roadside sandstone was tentatively compared to the Cambrian Hollybush Sandstone Formation by Barclay and Rathbone (1990), but is now recognised as belonging to the Halesowen Formation.

5.5. Triassic – Helsby (Bromsgrove) Sandstone Formation

Traditionally named the Bromsgrove Sandstone Formation of the Sherwood Sandstone Group, this has been renamed in a recent rationalisation of nomenclature as the Helsby Sandstone Formation (Ambrose et al., 2014). It was proved in trenches 1, 4, 5, 9 and 10, lying to the east of the East Malvern Fault. Only short sections were excavated in the trenches, in which it consists of soft, weakly consolidated to weathered and unconsolidated, orange-brown, fine-grained sandstone.

6. Details of the trenches

Figure 2 shows the locations and numbering of the trenches. The following notes summarise the details recorded.

6.1. Trench 1

The trench (Figure 4) is about 50 m long and extends NW-SE across the inlier and the former pit. Superficial head or fill deposits form a veneer up to 1 to 1.5 m over much of the excavation. Up to 0.4 m of red mudrock of the Moor Cliffs Formation is exposed in the base of the trench at its north-west end. This is paler and more clay-rich towards its top and is truncated by an irregular unconformable surface dipping about 20^o to the east overlain by mudstones of the Halesowen Formation. Millimetre-scale grey/blue lamination dipping about 10^o to the east is preserved locally and an intraformational conglomerate of angular, 12 to 22 mm-length red mudstone clasts aligned parallel to the lamination are present near the base of the trench.

At the west end of the trench, the beds of the Halesowen Formation dip gently (3 – 5^o) to the west, becoming flatter eastwards to dip gently to the east. They consist mainly of colour-bedded mudrocks (Barclay et al., 2012, Figure 2.4 and Plates 2.9 and 2.13), the colours of dark grey/black, orange and pale green reflecting differing stages of oxidation. The presence of black millimetre-scale laminae extending into an oxidised orange horizon from the underlying black mudrock at several places demonstrates the secondary nature of the colour variations. A very fine-grained sandstone is composed mainly of sub- to well-rounded quartz grains with scattered fragments of dark material. Thin vertical zones of pale clay in at least three places penetrate the black and orange horizons and probably mark the positions of rootlets. The succession is overlain by a cream clay horizon forming the fault gouge of a flat-lying to gently dipping thrust separating the Halesowen Formation from the overlying Malvern Quartzite Formation (Plate 3). The clay contains tabular rock fragments up to 7 cm long that become larger south-eastwards along the trench. They are very fine-grained (0.01-0.05 mm) immature sandstones composed of quartz, feldspar, micas and some dark fragments (Table 3). Millimetre-scale laminae comprise quartz-rich horizons alternating with those containing a few white altered randomly shaped or euhedral feldspar crystals in a transparent matrix. This bedding-parallel clay-rich horizon would have acted as the ideal medium with which to take up the thrust movement, with the fine-grained sandstone fragments representing a Carboniferous sandstone disrupted, broken, entrained and transported during the thrusting. Petrographic analysis of a sandstone fragment (Sample MR14) is given in Table 3.

From about 8m from the north-west end of the trench, greenish clay/mudstones of the Halesowen Formation underlie shattered, tectonised pale grey quartz arenite of the Malvern Quartzite Formation. Tectonised, shattered quartz arenites extend from this point south-eastwards for about 7m where they are faulted against Malverns Complex rocks, present from there to the intersection of trenches 1, 2 and 3. Jointed, sheared mafic and intermediate meta-igneous rocks are exposed in the trench and widened embayment south-east of the intersection with Trench 2 (Plate 1). Grey clay/mudstones of the Halesowen Formation overlie the Malverns Complex to the south-east. The Malverns Complex/Halesowen Formation junction is an uneven surface, with small ‘steps’, dipping generally eastwards about 10^0 to 15^0. The basal laminae of the Halesowen Formation contain feldspar and quartz granules. The junction is interpreted as a west-directed thrust, the steps perhaps marking small extensional faults related to the East Malvern Fault. Red clay of the Moor Cliffs Formation in faulted contact with the Halesowen Formation extends south-eastwards to the East Malvern Fault. Here, the red clay is juxtaposed against reddish brown to orange-brown, fine-grained sandstone with scattered quartz granules of the Helsby Sandstone Formation along a fault plane trending at 170^0 and lined with green ?carbonate nodules.

6.2. Trench 2

Named ‘the side trench’ by Barclay et al. (2012), Trench 2 is a 13.8m offshoot or side trench dug at right angles to Trench 1, 20.5m from its north-west end. It intersected and re-exposed part of the north-west wall of the old pit. Tectonised, highly fractured quartz arenites of the Malvern Quartzite Formation (Plate 2) are in faulted contact with tectonised, weathered Malverns Complex in a fault zone termed the Martley Rock Fault. The contact between the units ranges from low to steep angle, with the Malverns Complex thrust over the Malvern Quartzite in a complex folded arrangement in part (Plate 4). This is probably the plication in the thrust described by Groom (1898). Tectonised rocks of the Malverns Complex extend almost to the south-west end of the trench, where they are truncated by a steep reversed north-west – trending fault. To the west is green clay with some dark grey-green sandstone fragments of the Halesowen Formation, poorly exposed to the end of the trench.

6.3. Trench 3

Named ‘the October 2011 trench’ in Barclay et al. (2012), this extended from the intersection of trenches 1 and 2 for 20 m north-north-eastwards before turning east-south-east. This section is now named Trench 4. Trench 3 exposed a fairly level rockhead surface of meta-igneous rocks of the

Malverns Complex at a depth of about 0.3 m. The rocks were altered, but not noticeably weathered diorite similar to those in Trench 1. Six samples were collected at 3m intervals from the south-west end of the trench. They range from white/cream to pale pink and pink and green in colour.

6.4. Trench 4

A similar rockhead surface of Malverns Complex to that in Trench 3 extended east-south-east from its junction with Trench 3 for 4 m before ending abruptly in a vertical north-south – trending edge of highly weathered rock (Figure 4). This edge, lying 0.4 m below ground level was excavated to a further 0.4 m depth and was draped by clays and sands of the Halesowen Formation. They comprised a basal 0.25 m-thick, mottled dull red, green and orange silty sandstone containing grains with a large range in sizes, including angular pink and white feldspars up to 4 mm and sub-angular to sub-rounded quartz grains of 1 mm size. The sandstone passes up into olive-grey silt about 0.25 m thick which is truncated by a sharp, very irregular junction overlain by black clay. The beds dip about 20˚ eastwards near the Precambrian edge, but are gently folded synclinally, dipping westwards a few metres to the east. The silts and clays extend for 7 m and grade from pale grey-brown to yellow-brown to brown, the last resting on a sharp surface of dark red, silty clay of the Moor Cliffs Formation. The steep edge to the Malverns Complex, previously interpreted as an unconformity (Barclay et al., 2012), is now considered more likely to be a ramp or small extensional fault within a thrust complex. Similarly, the Halesowen Formation/Moor Cliffs Formation junction is now considered to be a thrust.

6.5. Trench 5

Trench 5 repeated 7m excavated at the north-east end of Trench 3 and continued north-eastwards for about 37m. Pink and green dioritic meta-igneous rocks of the Malverns Complex crop out for about 11m from the south-west end of the trench. They are truncated by a 1m-wide zone of sheared igneous debris reduced to greenish clayey sand, interpreted as the Martley Rock Fault. To its north-east, from about 2m south-west of the 'crossroads' of trenches 5, 6 and 8 to 3m north-east of the 'crossroads' are shattered, tectonised rusty, orange-stained quartzite of the Malvern Quartzite. These are truncated by a sharp faulted junction trending NNW-SSE against clays of the Halesowen Formation. The clays extend for 3m to the north-east before underlying red clays of the Raglan Mudstone Formation were dug in the base of the trench. The junction of the Halesowen Formation and Moor Cliffs Formation is both straightforward and complex. Where straightforward, a basal Halesowen layer of orange sand overlies unconformably a flat-lying surface of Raglan Mudstone Formation red clays, infilling hollows in the latter (Plate 5). Where complex, on part of the north-west wall of the trench, red and green clays are apparently tectonically inter-sliced. Above the basal orange sandy layer, which is about 0.1 m thick, the Halesowen Formation comprises mainly greenish clays with some dark grey carbonaceous clays and pale grey clays. The Moor Cliffs Formation extends for 20 m north-east and comprises stiff red clays with blue-grey and pale green mottling. These clays are truncated against a zone of pale green leached, water-bearing sandstone marking the East Malvern Fault. To the north-east of this are red-brown sands of the Helsby (Bromsgrove) Sandstone Formation, seen for 7 m to the north-east end of the trench.

6.6. Trench 6

Trench 6 extends north-westwards from Trench 5 from the 'crossroads' of trenches 5, 6 and 8, dropping several metres from the high point of the site at the 'cross-roads' down-slope to the end point. Tectonised, shattered, orange-stained quartz arenite of the Malvern Quartzite Formation extends from 'crossroads' for 4 m to a tectonic, flat-lying junction with green clays and hard, dark grey-green tabular sandstones of the Halesowen Formation. To the north-west is a 3m zone of green clay and quartz arenite fragments, followed to the north-west by about 3 m of dark green sandstone fragments and green clay to a point [502 621] where the nature of the Halesowen Formation here is best seen. Here, a 0.2 m-thick tabular bed of hard, dark green, fine-grained sandstone overlies yellow/orange/greenish stiff clay. The sandstone dips about 20˚ to 320˚. Dark green sandstones with carbonaceous clasts crop from here for 3m to the north-west and are followed by 5 m of greenish clays and fragmented thin sandstones to a sandstone [492 628]. Green clay with some black carbonaceous streaks extends from here until red-brown clay of the Moor Cliffs Formation was dug 1 to 2 m from the end of the north-west end of the trench.

6.7. Trench 7

From its easterly end point, Trench 7 was dug for 9m westwards in dioritic rock of the Malverns Complex (Figure 4). To the west is a 2 m-wide zone of weathered, sheared Malverns Complex debris and shattered, fragmented quartz arenite of the Malvern Quartzite Formation. The quartz arenite crops out for 5 m to the WNW in a highly fractured state, and overlies green clays of the Halesowen Formation in a flat-lying, tectonic junction. These clays unconformably overlie stiff red clay of the Moor Cliffs Formation, seen in the westernmost 3m of the trench.

6.8. Trench 8

Trench 8 extends SSE from the 'crossroads' at the intersection of trenches 5 and 6. It exposes a short 2 m stretch of rusty shattered quartz arenite of the Malvern Quartzite Formation. This is truncated to the south-east by a zone 4 m wide of quartz arenite fragments and green clay. It is interpreted as the southward continuation of a fault seen in Trench 5, here also faulting the Malvern Quartzite Formation (to the north-west) against Halesowen Formation (to the south-east). Some green clay (Halesowen Formation) and red clay (Raglan Mudstone Formation) are interleaved at the south-east end of the 4 m-wide fault zone. Green and blue-grey clays with black carbonaceous lenses (Halesowen Formation) extend from here for about 15 m to the south-east, where they are apparently thrust over by red clays of the Moor Cliffs Formation, the junction dipping about 40˚ to the south-east. The red clays extend for about 1.5m to the south-east where the East Malvern Fault is marked by a 1 m-wide outcrop of pale green, leached sandstone. Red-brown sands of the Helsby Sandstone Formation lie to the south-east.

6.9. Trench 9

Trench 9 commenced in the west in hard meta-igneous rock of the Malverns Complex (Figure 4). A 6m-wide rockhead depression 1.5 m deep 3 m from the end of the trench is filled with soft, weathered Malverns Complex debris and may be a former pit. The eastern limit of the Malverns Complex is marked by an irregular surface of weathered pink rock dipping gently eastwards, although a small rock step on the surface dipping about 40˚ to the south-east may mark a small extensional fault. This surface is draped by grey and green-grey clay of the Halesowen Formation, the junction being interpreted as a west-directed thrust. On and immediately above the surface the clay and the friable, weathered top of the Malverns Complex contain a small amount of copper mineralisation in the form of green malachite and vivid blue azurite. 1.5 m to the east of the surface, stiff, red clay of the Moor Cliffs Formation overlies green-grey and black carbonaceous clays of the Halesowen Formation. The junction is irregular, but generally dips about 20˚ to 30˚ to the east. It is interpreted as a west-directed thrust fault. 3m to the east, the red clay of the Moor Cliffs Formation is truncated by the East Malvern Fault. A 2 m-wide zone of green sandstone along the fault is succeeded by typical orange-brown, soft sandstone of the Helsby Sandstone Formation, seen to the east end of the trench.

6.10. Trench 10

At its western end, Trench 10 proved orange and pale grey orthoquartzite of the Malvern Quartzite Formation, tectonised and mostly shattered to gravel. This outcrop is truncated 8m from the western end of the trench by a fault trending about 193˚. This is the Martley Rock Fault. To its east are grey clays of the Halesowen Formation. 1.3 m to the east, grey, carbonaceous clay appears to be thrust over red clay of the Moor Cliffs Formation in the south wall of the trench, the east-directed thrust junction dipping approximately 20˚ to 272˚. However, the situation in the north wall at this point is less clear, with a complex inter-fingering of red and grey clays. From here eastwards for 11 m, very stiff red clays (Moor Cliffs Formation) and dark grey, green-grey and black carbonaceous clays (Halesowen Formation) display a very complex and intricate inter-relationship. A small, rounded erratic Old Red Sandstone pebble found within these clays suggests that periglacial processes of solifluction or cryoturbation may have been responsible for at least these complexities. At the eastern end of this 11m-wide zone, red clays to the east are juxtaposed against the grey clays along a west-directed thrust junction dipping approximately 50˚ to 102˚ in the south wall of the trench. The red clays, with some pale green mottling, extend eastwards for 4 m to a 0.5 m-wide zone of weathered, clayey pale green sandstone and red clay gouge marking the East Malvern Fault. The fault trends about 9˚. Orange-brown, fine-grained, friable sand/sandstone of the Helsby Sandstone Formation lies to the east.

6.11. Trench 11

Trench 11 commenced in mostly broken, shattered pink and green granodioritic rock of the Malverns Complex, which extends 10 m from the eastern end of the trench (Figure 4). Joints 2 m from the end dip 45˚ to 130˚. A vertical fault striking 40˚ separates the Malverns Complex to the east from shattered, orange-weathered, fine-grained quartz arenite of the Malvern Quartzite Formation to the west. This is the Martley Rock Fault. The quartz arenite extends for 5 m to the west, where it overlies green clay of the Halesowen Formation in a gently west-dipping thrust junction. Green clay with thin, dark green, fine-grained hard/tough sandstone layers lie to the west. The sandstones contain carbonaceous fragments. The dip of these beds is low and indeterminable. They extend for 9 m to the west, where they are followed by a 6 m-wide outcrop of mainly very stiff dark grey to black clay. 1 m from the western end of the trench, this rests on very stiff, red clay with pale green mottling of the Moor Cliffs Formation. The junction is near-horizontal and marked by an oxidised orange clay layer up to 0.08 m thick.

6.12. Trench 12

Trench 12 was excavated mainly in beds of the Halesowen Formation, with some quartz arenite of the Malvern Quartzite Formation also encountered. From its northern end, a 1 m-thick sandstone occupies 6 m of the trench to the south. The sandstone is mostly broken, tectonised and fractured, dull darkish green, hard to tough, fine-grained and containing carbonaceous traces. It is underlain by khaki and grey, orange-stained clay with some sandstone that extends for 15 m south to a rock bar in the base of the trench. This comprises a tough, massive quartz arenite with some mm-scale laminations visible in hand specimen. It is interpreted as an outlier of the Malvern Quartzite Formation. Very broken, tectonised, shattered, locally quartz-veined, pale and dark grey quartz arenite extends from there for 9 m to the south. Its southern boundary is unclear, but appears to be a low-dipping surface above clay of the Halesowen Formation. The clay is grey-green, with some dark, carbonaceous layers and orange sandy clay layers. This extends for 9 m south where black clay is truncated against a grey, tough orthoquartzite outcrop about 0.75 m wide in the base of the trench. Clay lies above the quartz arenite in the west wall of the trench, suggesting that the quartz arenite is part of a thin thrust wedge of Malvern Quartzite Formation within the Halesowen Formation, fault bounded on its north side. To the south, orange, sandy clay with some grey-green clay extends for 6 m. It is overlain by dull mid to dark green, hard, broken sandstone which occupies 5 m of the trench southwards. This is overlain by a green-grey clay bed that is in turn overlain by mainly broken, dull green sandstone with an orange/yellow-stained clay bed that crops out 6 m from the southern end of the trench and its junction with Trench 11. Thinner clay beds occur above.

6.13. Trench 13

This trench was dug to locate the position of the East Malvern Fault where it crosses the Worcestershire Way. Barytes? was discovered in the fault zone which separates red clay of the Moor Cliffs Formation to the north against soft orange-brown sandstone of the Helsby Sandstone Formation to the south.

7. Pits

Three temporary pits were dug by JCB in September 2014, further to some previous hand-dug pitting (Pit 1). Pits 2 and 3 proved red clay of the Moor Cliffs Formation. Pit 4 [SO 74520 59687] proved red clay of the Moor Cliffs Formation overlying grey clay of the Halesowen Formation. The junction dips 10˚ to 15˚ to 290˚ and is interpreted as a west-directed thrust fault. A vertical fault striking c. 184˚ apparently truncates the Moor Cliffs Formation thrust sheet against grey-green clay of the Halesowen Formation in the east side of the 2 m-wide pit.

8. Structure

8.1 Previous work

Groom (1900) noted that the "Archean rocks have been *apparently* thrust on the Cambrian quartzite, the base of the former having undergone shearing parallel to the thrust plane. The overthrust series has been subsequently folded along a north-and-south axis, together with the Old Red Sandstone. This secondary folding has been accompanied by upthrust of the Archaean and Cambrian. The Coal Measures were subsequently deposited unconformably on the faulted and folded series, and in later times the old rocks covered by the Trias were let down on the eastern side. We appear to have in this small area an epitome of the history of the Malvern and Abberley Ranges”.

Groom (1898) described the quartzite as somewhat shattered and arranged in the form of a plicated anticline or anticlinal dome, dipping to the west and east and showing a tendency to a quaquaversal arrangement. About 42 inches of quartzite were exposed, but with the base unseen, Groom surmised that a much greater thickness may be present. He could find no fossils in the rock, unlike the quartzite in the Malverns, which was richly fossiliferous in places. He described the overlying igneous rock as being indistinguishable from the crushed coarse diorite prevalent in many parts of the Malverns. It is separated from the quartzite by two feet or more of greenish schists, the “powdery rotten rock” of Coles’s (1898) description. Groom noted that the foliation of the schists is parallel to the surface of the quartzite and to what is apparently bedding in it, and that the schists essentially resembled those formed by “dynamo-metamorphism” in the Malverns. He described the superposition of the diorite and schists on the quartzite as the most remarkable feature of the section. The readiest explanation, he concluded, was that the quartzite is interstratified with the igneous rocks. However, he then goes on to say that the quartzites interfoliated with gneissic and schistose rocks seen on a limited scale in the Malverns are quite different from the Martley quartzite in being metamorphosed quartz schists. The Martley quartzite is a “typical sedimentary rock”, with a microscopic structure similar to the Cambrian quartzite of the Malverns. Groom’s illustrations show a section about 2.9 m long and 2 m high comprising diorite at the top, overlying schists which surround quartzite forming a corrugated anticlinal structure. The foliation of the schists is drawn as parallel to the corrugations of the quartzite surface and to internal structures within the quartzite which Groom interpreted as bedding. A sketch plan of the pit shows the quartzite forming a central domal area surrounded by schists dipping quaquaversally off it.

Groom (1898), while agreeing with Coles’s general description, maintained that the quartzite forms a plicated anticline or anticlinal dome and the thickness of the bed was stated to be about 42 in. He believed the powdery rotten rock of Coles to be a greenish schist formed by dynamo-metamorphism, like others in the Malvern chain, but agreed that it separated the quartzite from the overlying igneous rock, which he called diorite (the syenite of Coles) and ascribed to the Malvernian group of Pre-Cambrian rocks. Groom rejected the possibility that the quartzite may be interstratified with the Malvernian rocks in favour of the hypothesis that the diorite has been thrust over the quartzite, the green schists having been formed from the former by shearing during the thrusting. The anticlinal form of the quartzite was explained by later folding of the thrust-plane. Callaway

(1898) wrote a letter in support of Coles's description of the syenite as an altered Malvern diorite, comparing it with examples in the Malvern Hills. He also agreed that the quartzite is very like similar rocks of Cambrian age in the Midlands.

In a section across the Archean rocks, Groom (1900, p. 163) showed the quartzite to be separated from the overlying Archaean by a thrust-plane with shearing of the older rocks above the fault. These rocks, together with the neighbouring Old Red Sandstone, were believed to have been folded at a later date along a north-south axis; subsequently Coal Measures (now classed as Halesowen Formation) were deposited on the Archaean rocks and then Triassic strata. Groom's section shows the Old Red Sandstone faulted down against the Archaean on the west of the exposure and the Triassic with similar relationships on the eastern flank.

Brooks (1968) interpreted the Precambrian basement to be at probably over 1000 m depth near Martley. He suggested that the axis of the major fold of the Malvern axis (responsible for the Malvern Hills) lay east of Martley in Armorican (Variscan) times and was subsequently lowered by movements along the East Malvern Fault. In this interpretation, he concluded that the Martley inlier may comprise material thrust westward from the axial zone of the major fold prior to the formation of the Triassic Worcester Basin. On this basis the structure at Martley was closely comparable to that of Herefordshire Beacon and Chase End Hill in the Malverns.

Barclay and Rathbone (1990) summarised the geology of the site and presented a revised detailed geological map, as well as an interpretative cross-section invoking a series of thrusts in the footwall of the East Malvern Fault, splaying from the latter at depth below the site.

8.2 Structure revealed by the trenching

The trenching revealed the presence of a previously unknown steeply dipping to vertical fault zone named the Martley Rock Fault (MRF; Barclay et al., 2012). This is exposed in Trench 2 to a depth of about 1 to 2 m; elsewhere, in trenches 5, 7 and 8, it is only seen at rockhead and represented by zones of sheared meta-igneous and quartz arenite debris. Over most of the inlier, this fault separates two different successions, with the Malvern Quartzite Formation confined to its west and the Malvern Complex confined mainly to its east. In Trench 2, the fault comprises a complex zone of tectonised quartz arenite and meta-igneous rock. There is little evidence of the low-angle folded thrust between the two units and plicated anticline recorded by Groom (1898) except for one example (Plate 4), which lies in the backwall of the old pit and may have been the exposure on which

Groom based his interpretation. To the south-west of the MRF in Trench 2, the Malverns Complex is thrust over the Malvern Quartzite Formation by a flat-lying thrust. This structure superimposes much fractured quartz arenite of the Malvern Quartzite Formation on clays of the Halesowen Formation.

Trenches 1, 6, 7 and 11 proved that the Malvern Quartzite Formation exposed in the inlier comprises a newly discovered, flat-lying WNW-directed thrust sheet overlying the Halesowen Formation. The eastern boundary of the Malverns Complex, as seen in trenches 1, 4 and 9, is interpreted as an east-facing, west-directed thrust with the overlying thrust sheet comprising mudrocks of the Halesowen Formation. Small steps in the thrust plane may represent small-scale extensional normal faults related to the East Malvern Fault very close to the east. The junction between the Halesowen and Moor Cliffs formations, the latter present in a narrow strip in the immediate footwall of the East Malvern Fault, is also interpreted as a tectonic one, with east-facing, west-directed thrusting producing a complex of inter-sliced red (Moor Cliffs Formation) and grey (Halesowen Formation) clays.

The trenching has accurately pinpointed the location of the East Malvern Fault, as proved in Trenches 1, 4, 5, 9, 10 and 13. The fault was shown by seismic studies (Chadwick, 1985; Chadwick and Smith, 1988; Barclay et al., 1997) to be one of a series of Variscan transpressional thrust faults reactivated as a Permo-Triassic extensional basin-margin fault

8. A footwall short-cut thrust model

In a regional context, the Martley inlier lies on the Malvern Axis, in the footwall of the East Malvern Fault (EMF). The EMF forms the western boundary of the Permo-Triassic Worcester Basin. The Malvern Axis exposes Precambrian meta-igneous rocks of the Malverns Complex in its type locality of the Malvern Hills to the south of Martley, as well as Silurian strata of Llandovery to Pridoli age. Close to the north, the Abberley Hills expose Silurian (Wenlock to Pridoli) strata, arranged in a series of stacked thrust sheets separated by steeply dipping reverse faults named by Mitchell et al. (1962) named the Cockshot Hill Thrust, Penny Hill Thrust and Rodge Hill Thrust. These (the Malvern Axis thrusts of Chadwick and Smith, 1988, Figure 2b), converge southwards in the vicinity of Martley. Compressive, contractional stress, resulting in folding and thrusting along the Malvern Axis, is summarised in Worssam et al. (1989) and Barclay et al. (1997). Structures include the Herefordshire Beacon Thrust, parts of the West Malvern Fault, the Storridge Anticline and the Ankerdine Thrust.

Brooks's model was confirmed by the British Geological Survey's Kempsey Borehole (Whittaker et al., 1980) and subsequent seismic studies (Chadwick, 1985). Chadwick and Smith (1988) proposed a structural model based on the seismic work. They noted that the precise timing of the compression and reverse displacements on the Malvern Axis is difficult to assess, but suggested that early Palaeozoic (Caledonian) episodes may have been initially responsible. This is supported by the marked thickness changes in the Cambrian strata of the Malverns, attributed by Brooks (1970) to pre-Llandovery tectonism. However, a significant component of Variscan (late Carboniferous) compression is clear, both from the seismic and field evidence. Chadwick and Smith (1988) commented that whereas the Caledonian (?Acadian) compressive stresses were probably oriented NW-SE, and that the Variscan stresses were oriented roughly N-S, movement on the N-S ('Malvernoid') Malvern Axis and East Malvern Fault were likely to have had a considerable oblique strike-slip, transpressive component. That none of the structures have been imaged to great depth in the seismic studies suggests that they are relatively steep, supporting a model of a major flower structure that produced Palaeozoic uplift of a tract now underlain by the Worcester Basin. Permo-Triassic extension and negative inversion of this tract resulted in the Worcester Basin.

Barclay and Rathbone (1990, Figure 3a) sketched a thrust model for the Martley inlier. The new trenching data has provided refinement of this model. McClay and Buchanan (1994) illustrated experimental laboratory models, as well as actual examples, of the effects of compressive inversion of an extensional sedimentary basin. In both laboratory modelling and actual examples, whilst much of the compressive stresses are taken up by reverse movement on the basin-margin fault (e.g. the East Malvern Fault in the case of Martley), a footwall short-cut thrust or fan of short-cut thrusts can splay off the main fault. This provides a mechanism and model for the thrust faulting seen at Martley in the footwall of the East Malvern Fault (Figure 5). Subsequent Mesozoic (Permo-Triassic) rifting and extension was taken up principally by this fault, to form the western margin of the Worcester Basin.

9. Conclusions

The Neoproterozoic/Cambrian Martley inlier lies on the Malvern Axis, in the immediate footwall of the East Malvern Fault. This is one of the major basement structures of southern Britain with a history movement dating back at least to continental accretion in the Late Precambrian. Palaeozoic inversion and contraction produced reverse faulting on the structure, with tensional rifting in the Mesozoic focussed on it to form the western boundary of the Worcester Basin. Although the stratigraphy of rocks and strata of the inlier has been broadly known since the early work of Phillips (1848) and Groom (1898, 1900), and confirmed by later work by the Geological Survey, the recent trenching work has provided refinement. It has also greatly improved the accuracy of the geological map, as well as providing important new information on the nature and positioning of the geological boundaries and the structure of the inlier. The most important discoveries and conclusions are:

1. The presence of a steeply dipping thrust fault zone (the Martley Rock Fault); structures described by Groom (1898) in the backwall of a former pit in the inlier are likely to have been within this zone.

2. The Neoproterozoic Malverns Complex of the inlier is entirely fault-bounded, by the Martley Rock Fault in the west and by an east-facing, west-directed thrust in the east, which is overlain by the Carboniferous Halesowen Formation.

3. An acritarch from the quartz arenite of the inlier suggests that it is of Cambrian age and correlatable with the Malvern Quartzite Formation of the Malvern Hills.

4. The Malvern Quartzite Formation forms a west-directed, low-angle thrust sheet overlying the Late Carboniferous Halesowen Formation.

5. The Halesowen Formation has been shown to lie unconformably on the Late Silurian Moor Cliffs Formation on the wset side of the inlier (east of the Malvern Rock Fault), but the latter is in thrust contact with the former on the east side of the inlier (See Conclusion 2).

6. The inlier is interpreted as a thrust complex, the thrusts being shortcut thrusts in the footwall of the East Malvern Fault, propagated during Variscan transpression.

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Figures

1. Location of the Martley inlier and generalised bedrock geology

2. Plan showing the trenches and their geology

3. Geological map of the Martley inlier

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2. Tectonised quartz arenite of the Malvern Quartzite Formation, Trench 2.

3. Tectonised, shattered quartz arenite of the Malvern Quartzite Formation thrust over clay of the Halesowen Formation, Trench 1.

4. Sheared meta-igneous rocks of the Malverns Complex overlying and faulted against quartz arenite of the Malvern Quartzite Formation in the Martley Rock Fault Zone, Trench 2.

5. Colour-bedded mudrocks of the Halesowen Formation unconformably overlying red clay of the Moor Cliffs Formation, western end of Trench 1.