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Structural analysis of the hinge region of the Islay Anticline

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Structural analysis of the hinge region of the Islay Anticline.

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Abstract: The hinge region of a major anticlinal fold structure in the SW Scottish Highlands was located in the eastern part of the Isle of Islay. The structure plunges gently NNW, with the hinge line measuring 02/026. The hinge region was located by mapping a 2km² area comprised of deformed Neoproterozoic metasedimentary and metacarbonate rocks, and plotting the measurements on stereograms.

The data collected was also analysed to attempt to assess evidence of refolding, and it is suggested in this thesis that the area displays evidence of at least one subsequent refolding event.

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1. Aim:

In this thesis I aim to locate and map the hinge region/s of the parasitic folds that comprise the Islay Anticline, and by using these data I aim to determine the geometry of folding, and assess evidence of refolding.

2. Introduction:

The Islay Anticline is a regional scale recumbent fold located on the Isle of Islay, which lies off the coast of SW Scottish Highlands approximately 40 km north of Ireland.

The anticline dips to the south east, and is bounded to the east by the Loch Skerrols Thrust, and to the west by the Bein Bhan Thrust. The rocks that are present on Islay are mainly Dalradian rocks of Mid-Neoproterozoic age, and are comprised of mainly clastic sedimentary rocks, although also include carbonate and volcanic units.

These rocks have all been deformed and metamorphosed during the early Caledonian orogeny (namely the Grampian event).

Several of the rocks that crop out in the Islay Anticline, such as the Port Askaig Tillite Formation, are rocks that were deposited during the Neoproterozoic, and have in correlation with other tillite units worldwide been cited as evidence of global (or “Snowball”) glaciation events (Anderton 1985).

The Port Askaig Tillite was one of the first rock types to provoke paleoenvironmental interpretation, which was done as early as 1871, when Thomson classified it as a glacial deposit. (Anderton 1985, Thomson 1871).

One of the strongest points of evidence for these worldwide glaciations is the $^{13}\text{C}/^{12}\text{C}$ ratio, the reasoning being that such a mass extinction event as a global glaciation ought to cause an extreme negative excursion in the $^{13}\text{C}/^{12}\text{C}$ ratio. This means that isotopic data recovered from these units could possibly effect our interpretation of Neoproterozoic climate. (Rothman et al, 2003)

This can however be troublesome to interpret correctly in metamorphosed rocks. This is due to the possibility of $\text{H}_2\text{O}/\text{CO}_2$ isotopic exchange with metamorphic fluid that is produced by syn-metamorphic dehydration reactions. This means that care must be taken to analyse if the $^{13}\text{C}/^{12}\text{C}$ is to be explained by syn-depositional processes, or if it is due to exchange with metamorphic fluids (partly or completely). (Skelton et al., in press)

However, not all metamorphic fluids are created through syn-metamorphic dehydration reactions. It is quite common for meteoric and or basinal fluids to infiltrate rocks during basin inversion, a process most commonly recorded in veins.

As shown by previous workers, such as Pitcairn et al, 2010, metamorphic fluid flow has been abundant in the Neoproterozoic carbonate rocks present in the axial region of the Islay Anticline.

Although the relationship between deformation and the structural focus of fluid flow has been a focus of research within the petrology community for several decades (Bickle et al, 1987; Bowman et al, 1994; Ramsay, 1980; Skelton et al, 1995) prior to the study conducted by Pitcairn et al (2010), the relationship had not been investigated within the area of the Islay Anticline, or its limbs.

Pitcairn et al showed that the metacarbonate rocks had experienced complete isotopic homogenization from their original $\delta^{18}\text{O}$ ratio to silicate values in parasitic fold structures, localized anticlinal structures, and in the axial region – indicating that fluid fluxes and flux were enhanced and focused in these areas. (Pitcairn et al, 2010)

As fluids are an integral part of orogenesis, investigating the relationship between rocks and metamorphic fluids could possibly provide important insight about orogenic processes, and by extension, metamorphic processes.

Given coupling between metamorphic fluid flow and folding the attempted mapping of any fold hinges in the axial region of the Islay Anticline (or if possible, the hinge of the entire anticline) would greatly aid in any future research within the subject.

3. Geological background:

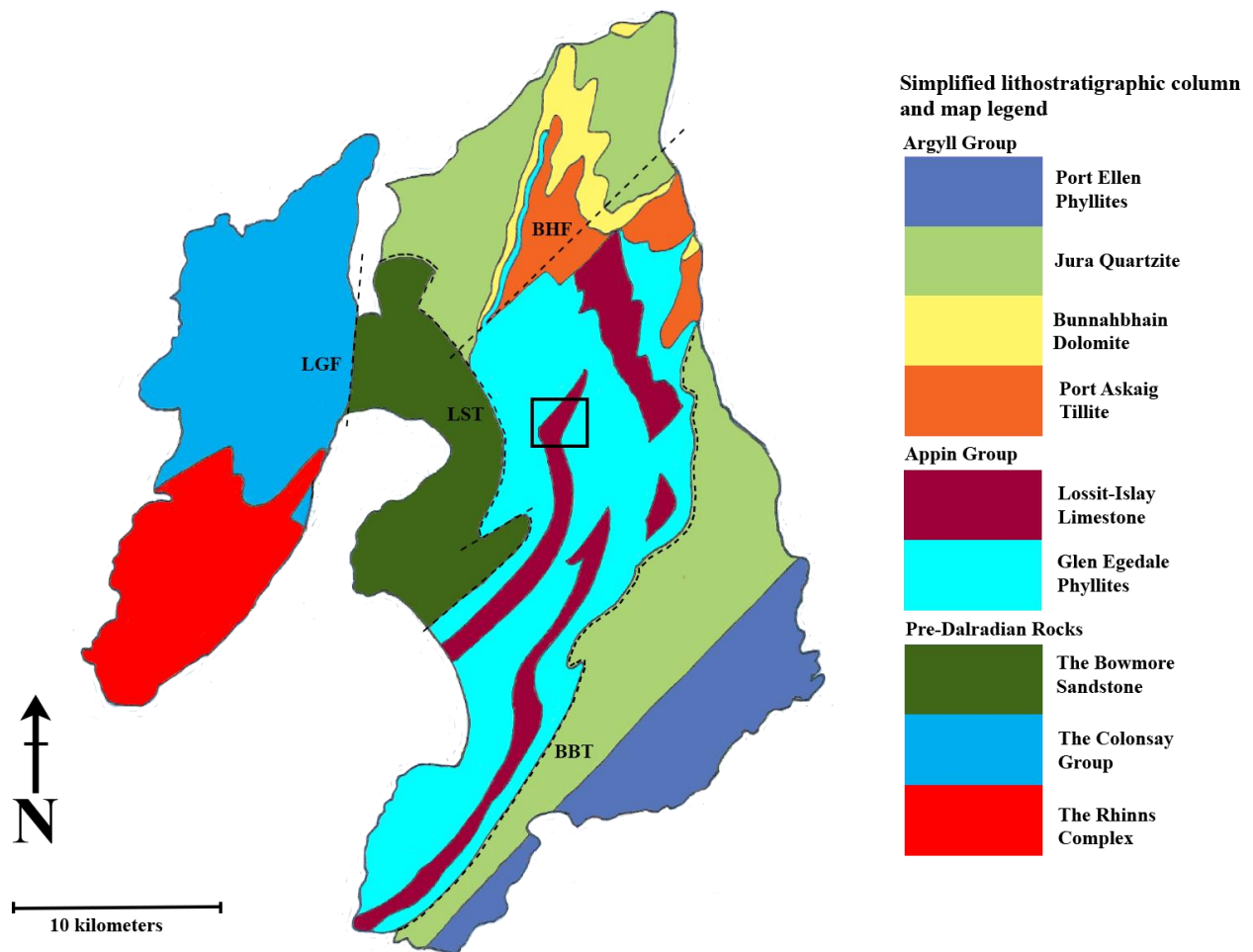


Figure 3.1: Geological map of Islay showing regional rock distribution, location of major faults, and a simplified lithostratigraphic column. The square indicates the location of the field area. Map and lithostratigraphy adapted from Stephenson et al (2012), and Pitcairn et al (2010). LGF = Loch Gruinart Fault, LST = Loch Skerrols Thrust, BHF = Bunnabhain Fault, BBT = Beinn Bhan Thrust.

The geology of Islay differs greatly between the East and the West part of the island. The south-western part is comprised of the Rhinns Complex, which is succeeded by the Colonsay Group to the north. The Colonsay Group is tectonically separated from the Rhinns Complex by the Kilchiaran Shear Zone.

The west part of Islay is separated from the east by the Loch Gruinart Fault. The Loch Gruinart fault also separates the Colonsay Group from the Bowmore Sandstone that lies directly to the east of it. The Bowmore Sandstone is in its turn separated from the Dalradian succession on the eastern part of Islay by the Loch Skerrols Thrust.

The parts of the Dalradian Supergroup that we see on Islay belong to the Argyll Group, with the Appin Group cropping out in the central parts of the island.

Below follows a brief description of Dalradian lithostratigraphy, its basement, and the depositional history of the Dalradian succession, and a discussion regarding the folding and tectonics of the area. Extra attention has been put towards the groups and subgroups which are present on Islay, but all Dalradian rocks relevant to this paper will be briefly discussed.

There are also two units of rock present on the Isle of Islay whose stratigraphical affinity is still uncertain. Therefore, although I have chosen to include them here, they will be discussed separately from the Dalradian Supergroup.

The basement of the Dalradian Supergroup.

The basement on top of which the Dalradian sequence was deposited is of Proterozoic age, and is comprised of two units; the Rhinns Complex and the Badenoch Group.

The Dalradian basement is thought to underlie much of the Grampian Terrane, although there are currently only a few known outcrops; the Rhinns Complex crops out on the islands of Colonsay and Islay, while the Badenoch Group crops out in the northern parts of the Grampian Terrane.

The Rhinns Complex:

The Rhinns Complex is comprised of amphibolite-facies granitic and syenitic gneissose rocks.

The Rhinns Complex was previously regarded a part of the Lewisian Gneiss Complex, and therefore the Herbridean Terrane, but is now regarded to be a part of the same Palaeoproterozoic crust that comprises the Scandinavian Svecofennian Belt and the Ketilidian belt of Southern Greenland. (Tanner et al, 2013).

This conclusion is supported partly by dating of the Rhinns Complex using U-Pb zircon ages and partly by recent stable-isotope studies. Dating the Rhinns Complex has yielded an age of 1782 ± 5 Ma, which has been interpreted as crystallization age of the protolith (Marcantonio et al, 1994), and the stable-isotope studies have indicated that the Rhinns is comprised of primarily juvenile mantle material (Muir et al, 1993). This means that although the Rhinns Complex is contemporaneous with the tectonothermal reworking of the Archean crust that comprises the Lewisian Gneiss Complex, the fact that it is comprised of juvenile mantle material dismisses any direct correlation between the two. (Muir et al, 1993, Stephenson et al, 2012).

The actual reach of the Rhinns Complex is still uncertain, as we are limited to a few outcrops on Islay and the neighbouring island of Colonsay, and a few outcrops on the island of Inishtrahull off the northern coast of Ireland. Isotopic measurements indicate that the Rhinns Complex might underlie much of the Grampian Highlands, but geophysical evidence indicates a different, lower density basement under the south-eastern part of Grampian, and yet another, higher density basement to the north-east (Trewin, 2002). This in combination with the fact that the area is bounded by major slip-strike faults such as the Loch Gruinart fault and the Great Glen fault, has led to some workers (Bentley et al, 1988) suggesting that the area of Colonsay and western parts of Islay might be a part of a small, allochthonous terrane (aptly named the Colonsay-western Islay terrane), likely to have been displaced somewhere between 620-540 Ma (Bentley et al, 1988).

The Colonsay Group, and the Bowmore Sandstone:

The Colonsay Group and the Bowmore Sandstone Group are both fairly monotonous metasedimentary units; the Colonsay Group consists of one formation that is comprised of highly deformed metapelites and metapsammities with some calcareous beds, which have been metamorphosed at greenschist facies conditions.

The Bowmore Sandstone Group is comprised of two formations - the Laggan Sandstone formation: a more fine to medium-grained sandstone, and the more coarse-grained Blackrock Grit Formation. In contrast to the Colonsay Group, the Bowmore Sandstone is only slightly metamorphosed, although the Group is still tightly folded. (Stephenson et al, 2012).

The Colonsay Group is located on the western side of Islay, and the Bowmore Sandstone is located on the eastern side. They are tectonically separated from each other, and all the rocks of the Dalradian succession by faults, thrusts, and shear zones. (Stephenson et al, 2012).

The Colonsay Group was for many years correlated to the Torridonian Sandstone due to its stratigraphic placement on top of the Rhinns Complex, which at the time was thought to belong to the Lewisian Gneiss Complex (Bailey 1917) but based on geochemical analysis it has been argued to correspond to the Ballachulish Limestone (Rock, 1985). This is further substantiated by the fact that the upper part of the Colonsay formation has a strong lithological resemblance to the middle part of the Appin Group – or more precisely – it is similar to the sequence that starts with the Leven Schist, and ends with the Appin Quartzite.

McAteer et al (2010) have, on the other hand, correlated the Colonsay Group to the lowermost part of the Grampian Group based on the U-Pb ages of detrital zircons (Tanner et al, 2013; Stephenson et al, 2012).

The Bowmore Sandstone has been correlated with both the Torridonian Sandstone and the Crinan Grit formation. The distinction between the two is (as opposed to the Colonsay Group) not based on dating or geochemical data – instead it is mainly based on differing definitions regarding the Loch Skerrols Thrust.

The thrust separates the Bowmore Sandstones from the overlying Dalradian, and has been argued to be a regional structure, possibly comparable to the Moine thrust (Roberts and Treagus, 1977). It has also been argued that it is a shear zone of only local importance (Fitches and Maltman, 1985). If the Loch Skerrols Thrust is a regional structure, this would indicate a correlation between the Bowmore Sandstones and the Torridonian (Stephenson et al, 2012). A local structure, however, would indicate a correlation between the Bowmore Sandstone and the Crinan Grit. (Stephenson et al, 2012; Fitches and Maltman, 1985).

3.1 Dalradian lithostratigraphy:

Appin Group:

The oldest Dalradian rocks that crop out on Islay belong to the Appin Group. The Appin Group is divided into three Subgroups; Lochaber, Ballachulish, and Blair Atholl. All three Subgroups show evidence of low-energy shelf to tidal shelf depositional environments, with the inclusion of anoxic basin environments and are comprised of pelites, semi-pelites, quartzites, metacarbonates, and calcisilicate rocks. (Anderton, 1985)

The Argyll Group tends to show a rapid alternation of facies, which indicates rapid changes between the different depositional environments, something that Anderton (1985) has attributed mainly to slow subsidence and transgression.

The Appin Group crops out in the central parts of Islay (Pitcairn et al, 2010; Anderton 1985; Stephenson et al, 2012), and all three Subgroups are represented in the core of the Islay anticline – the lowest member being the Glencoe Quartzite of the Lochaber Subgroup (Stephenson et al, 2012).

Argyll Group:

The Argyll Group has been divided into four Subgroups; Islay, Easdale, Crinan, and Tayvallich.

The Islay Subgroup is comprised of the Port Askaig Tillite, Bonahaven Dolomite, and Jura Quartzite formations.

The Port Askaig Tillite is a highly conspicuous lithological unit which is comprised of metapsammites, metaconglomerates, metadiamicrites, and clasts up to two metres in diameter (Stephenson et al, 2012), and has as such been widely used as a lithostratigraphic marker.

The limestone clasts present in the Port Askaig tillite are likely to have been eroded from exposed parts of the underlying Lossit Limestone, but the upper part of the member is unique within the

Dalradian Supergroup, as it contains extrabasinal granitic and gneissose clasts. (Anderton, 1985; Stephenson et al, 2012).

The Port Askaig Tillite is overlain by the Bonahaven Dolomite Formation, which consists of a carbonate succession containing metamorphosed mudstones, metapsammites, and stromatolites. Most of the Bonahaven Dolomite Formation crops out on the north-east of Islay, where the total thickness of the formation reaches approximately 350 metres.

The largest member of the Islay Subgroup is the Jura Quartzite. It is comprised of coarse-grained, pebbly sandstone, and has been interpreted to be of deltaic and shallow-water shelf origin. The Islay Subgroup marks the end of the more stable shelf conditions that were present during the deposition of the Appin Group, and the start of the rapid basin subsidence and basin deepening present during the deposition of the Easdale and Crinan Subgroups (Anderton, 1985; Stephenson et al, 2012).

A sharp contact between the Jura Quartzite and the Jura Slate marks the beginning of the Scarba Conglomerate Formation, the lowermost member of the Easdale Subgroup.

The lower parts of the Easdale Subgroup are comprised of much finer grained graphitic rocks that show structures characteristic of deep-water sedimentation. Some of the rocks show evidence of turbidity currents.

The upper part of the subgroup is on the other hand characterized by rock types that are representative of shallow water deposition - such as metacarbonates, and calcareous pelites and psammites, such as the Port Ellen phyllites – which indicates a return to the same depositional environment as most of the Islay Subgroup. However, the coarser-grained, pebblier Laphroaig Quartzites that overlie the Port Ellen Phyllites indicate a higher energy flow.

This coarse-grained pebbly quartzite marks the end of the Easdale Subgroup, and the beginning of the Crinan Subgroup. It gradually shifts to turbiditic pelites and semi-pelites as one moves toward the upper boundary of the sequence, and they together form the formation known as Crinan Grit.

The depositional environment changed quite drastically between the Easdale and the Crinan Subgroup. The subsidence and basin deepening that started during the deposition of the Islay Subgroup had on many levels been mitigated by basin filling, but that changed at the beginning of the Crinan Subgroup, when the depositional environment through rapid shelf deepening and basin forming events changed from tidal shelf/flat or low energy shelf conditions to a submarine fan.

The last of the Easdale Subgroup, and thus the last of the Dalradian rocks to crop out on Islay, are the Ardmore Grit and Ardmore Conglomerate formations.

Further deepening of the basin took place between the Crinan and the Tayvallich Subgroups, until the turbidite basin that is the depositional environment of the limestone and slate make up large parts of the Tayvallich Subgroup. Volcanic sills and basic volcanic rocks are also present in this subgroup, and are likely to have intruded the sedimentary package due to localized rifting of the basins.

3.2 Folding and deformation of the Islay Anticline.

The rocks on Islay were metamorphosed during the earliest part of the Caledonian Orogeny, known as the Grampian Event, or the Grampian Episode.

The actual Caledonian Orogeny lasted approximately 150 Ma, but the Grampian Event was, geologically speaking, a fairly short event – lasting from approximately 480 to 465 Ma (Oliver, 2001).

The Grampian orogeny was initiated by the closure of the Iapetus Ocean.

When the oceanic crust of the Iapetan seafloor ruptured, it initiated the south-eastward subduction of the North American plate beneath an island arc. This subduction created an island arc that then moved forward, and eventually collided with the passive margin of the Laurentian.

As the arc moved forward, parts of the oceanic crust and the Laurentian margin were obducted, and the turbidite basins that had been created as the crust progressively stretched during the opening of the Iapetus were inverted.

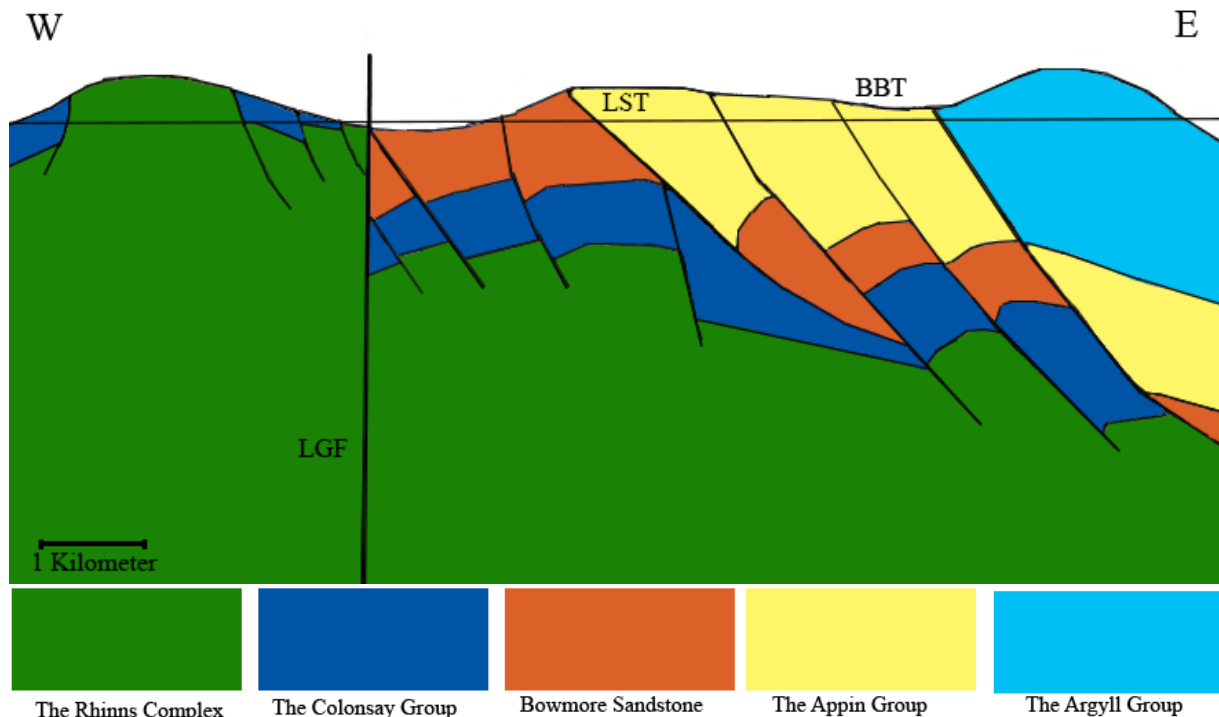


Figure 3.2: West to East cross-section of the Islay Anticline showing the main structural features, and the stratigraphical positions of the rock types in the area. Adapted from Anderton (2015).
LGF = Loch Gruinart Fault, LST = Loch Skerrols Thrust, BBT = Beinn Bhan Thrust.

The deformation of the Dalradian rocks is usually divided in to three or four major phases of deformation. D1 and D2 used to be considered completely separate events, but most workers these days agree that D2 is almost continuous with D1, and that they are part of one single progressive event, with a high simple-shear component. (Stephenson 2012; Grahame H.J Oliver, 2001).

It is however important to remember that even if D1-D2 are considered to be one continuous progressive event, the structures developed during the initiation of crustal shortening (D1), are still likely to have been refolded by the second phase of deformation, and it is therefore still important to separate the two phases.

The simple shear during D1-D2 deformation contrasts with the D3 and D4 phases of deformation, as they show proof of mainly co-axial, pure shear. (Mitchell, 1978)

D1-D2 is usually pointed to as the point in time when the regional deformation started. D1-D2 is usually classified as the point of formation of the Tay Nappe, and D2-D3 as the point of peak deformation. The age between D1 and D2 is thought to be only about 1-2Ma, and this is point where the island arc collides with the Laurentian margin, and the seafloor is obducted. (Tanner, 2013)

These phases created mainly major tight folds, and almost all large-scale features such as the Islay Anticline and the Tay Nappe originate from these early stages of deformation (Oliver, 2001; Stephenson et al 2012; E.B Bailey 1917).

Metamorphism never reached beyond greenschist facies until the D3 deformation phase, and even then it only reached lower-to-middle amphibolite facies (Oliver, 2001, Stephenson et al 2012).

The D4 phase of deformation was quite noticeable less intense, and also occurred quite a bit later than the D1, D2, and D3 phases of deformation. D4 deformation was most likely due to late-orogenic isostatic uplift. (Oliver, 2001, Stephenson et al 2012)

Some workers consider the Islay Anticline to be a compound D2-D3 structure (Fitches and Maltman, 1985), while yet others consider it to be a D1-D2 structure (Pitcairn et al, 2010). This paper will adhere to the convention established by Borradaile, 1979, and the Islay Anticline will therefore be considered a compound D1-D2 structure.

4. Method:

All structural measurements were made in the field using a compass-clinometer during the first week of June 2015.

Field sketches were made of every outcrop. These sketches contained the parameters: height and width, rock types found, inclusions and veins (if applicable), grid reference, where on the outcrop the measurement was taken, and an arrow denoting north.

Errors, and error minimisation:

As always when one is working with structural measurements, there are going to be a certain degree of possible error, which here has been estimated to ± 10 -15 degrees.

This is based on the standard compass deviation, which here is accepted to be ± 2 degrees (van der Pluijm and Marshak, 2004) in addition to the human factor, which here is estimated to be ± 10 degrees. As the dip direction and dip are known to vary slightly as one moves along an outcrop, measurements were taken in several spots.

Error was minimized by replicating each measurement. Two measurements were taken and logged in the field. The average was then calculated and is what has been reported in this thesis.

All measurements were also studied as a group while still on location to ensure that one could return to specific locations if any errors were apparent. Unfortunately, structural geology does not have the advantage of “blanks” – clean samples often used in other fields, such as geochemistry, to control for contamination. However, hinge measurements taken in the field have been used in this thesis as an indicator of the validity of the calculated hinges.

Exposure:

The anticline is quite poorly exposed, and at times heavily eroded – so eroded that Fitches, W. R., and A. J. Maltman hypothesised in their 1985 paper that part of the irregular trace of the anticline is likely to be due to glacial erosion rather than tectonic activity. This makes it harder to find viable outcrops, which may also make the measurements more biased.

Data processing:

All structural measurements have been plotted as poles-to-bedding using Visible Geology’s Stereonet application. (Cockett, 2012)

The hinges were calculated using best-fit great circles based on the poles-to-bedding plotted field measurements. To obtain the best-fit great circles, the average of all the dip and dip direction data for each structure was used.

5. Results:

A complete set of structural data, and stereograms for each locality can be found in the appendix. All data present in the appendix, and in this thesis will be presented according to the convention of dip/dip direction.

405 measurements were made during the study, of which 393 were bedding measurements, and 12 were hinge measurements.

Plotting these bedding measurements as poles to bedding on a stereogram shows that the structure of the area is dominated by one large fold (figures 5.1, 5.2), but there are also smaller folds with dip directions differing from the general trend (figure 5.3 - 5.5).

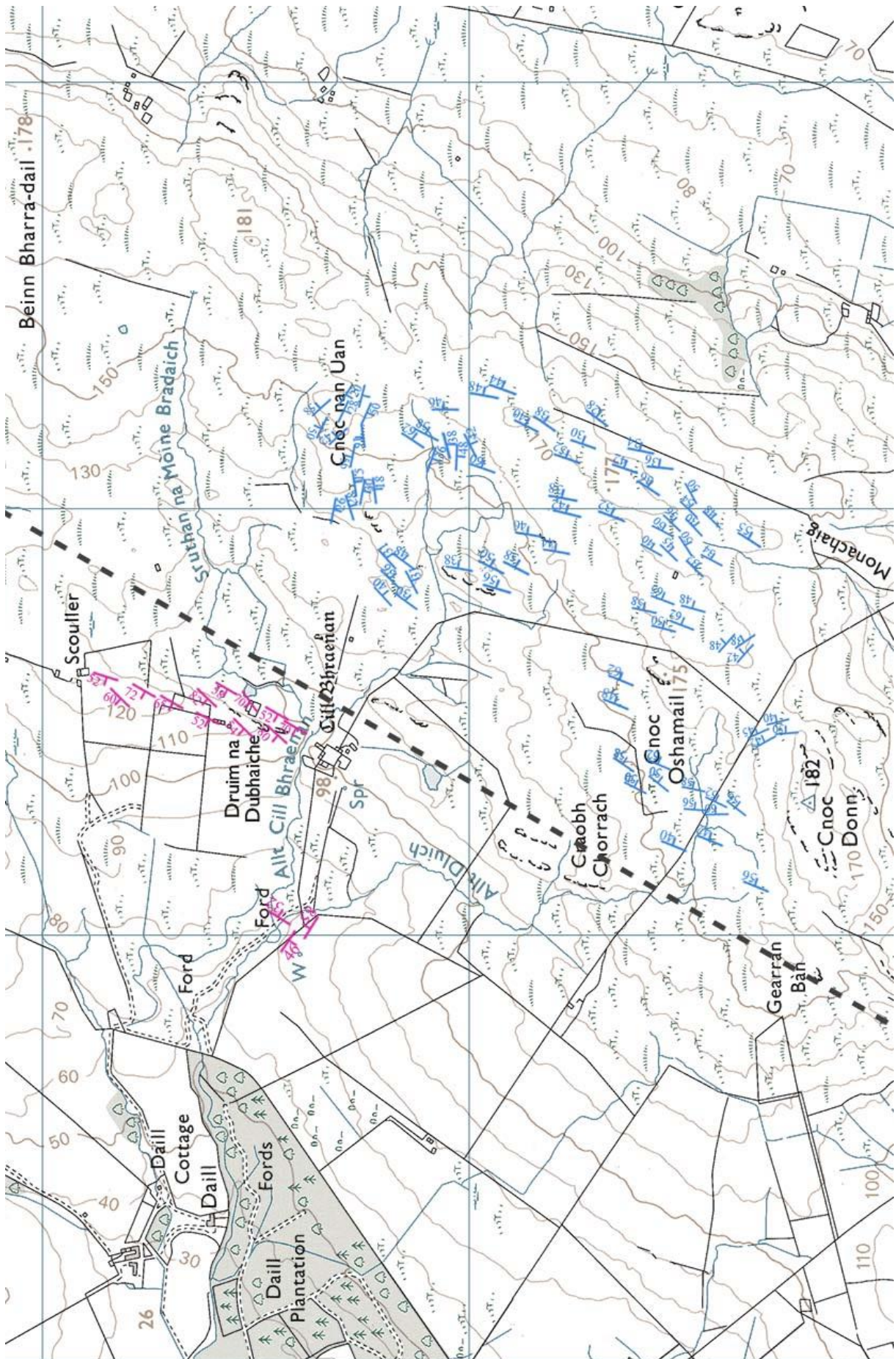


Figure 5.1: Map of the field area with the proposed hinge represented by the dashed black line, and both limbs of the fold represented by plotted structural measurements. The plunge of the hinge (00/023) is based on calculations made from the stereogram containing the measurements plotted as poles-to-bedding. The location of the hinge is an approximation based on the change in dip directions of the outcrops visible in the field area.

5.1 The larger structure

Calculating a best-fit great circle within the data of the larger structure, and then using that to calculate the hinge gives a fold hinge plunging NNW (00/023). This hinge is shown on the map in figure 5.1, and on the stereogram in figure 5.2.

The calculated hinge is deemed to be within the margin of error based on the 12 hinge measurements that were taken in the field. These hinges range from 01/004 to 05/019, and are also shown on the stereogram in figure 5.2.

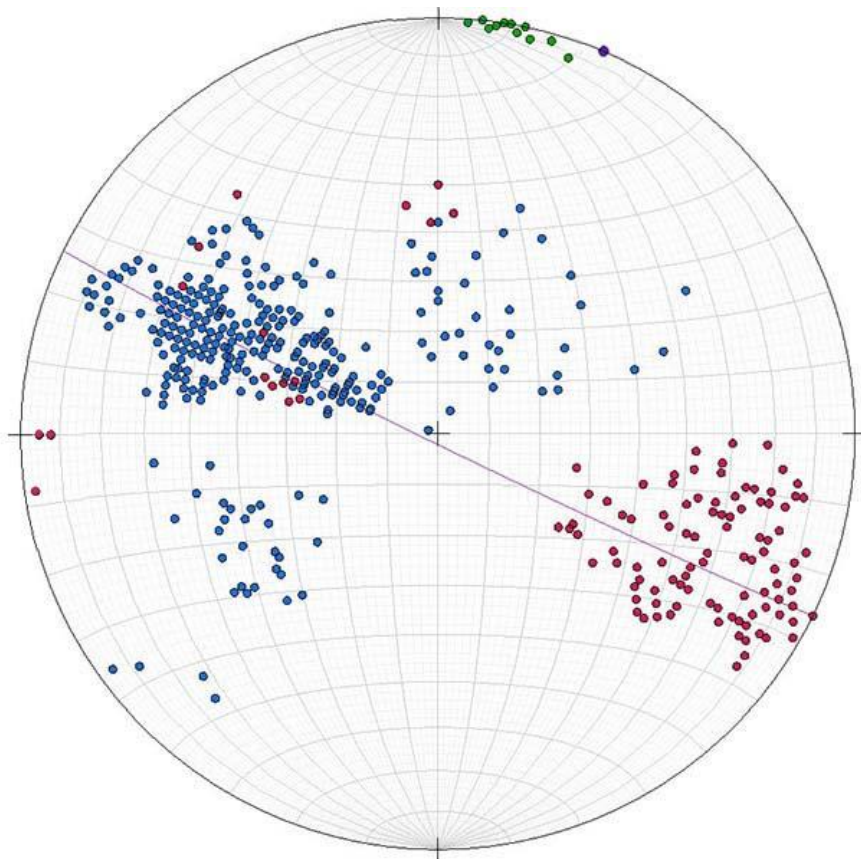


Figure 5.2: Stereograms showing all measurements plotted as poles to bedding, the hinges measured in the field area, and the calculated best-fit hinge. Measurements from the NE limb are shown in blue, and the measurements from the SW limb are shown in red. The hinges measured in the field are shown in green, and the interpolated best-fit hinge is shown in purple.

The measurements from the eastern side of the mapping area dip west south-west, in a range of 110-140 degrees. The measurements from the western side of the mapping area dip east north-east, in a range of 270-310 degrees.

5.2: Areas with differing dip directions.

The north-east plunging fold confirms quite nicely to the structure of one large fold, with the data showing that the bedding layers dip west on the eastern side and east on the western side, respectively. The localities discussed below, however, differ from the rest of the field area in appearance, dip direction, or both.

Locality 2 is an especially good example of this.

While the data that indicates the larger structure was gathered in outcrops comprised of seemingly undeformed, tilted bedding with some minor (millimetre to centimetre scale) veining and pyrite inclusions, locality 2 is mainly comprised of highly deformed, veined (centimetre to decimetre scale) metacarbonate rocks.

The top part of the outcrop is comprised of south-east dipping metapelites, which is followed by a three meter high sequence of highly deformed metacarboneates, which in its turn is followed by another set of metapelites, this time dipping south-west. The metacarboneates contain a large amount of the smaller folds, but they are completely absent within the metapelites. The dip direction of the metapelites, however, shifted approximately 90 degrees between the top and the bottom member.

Interestingly enough, the dip directions of both the top (128-140 degrees) and bottom (205-230) pelites roughly corresponds to the limbs of the small folds present in the metacarbonate.

This pattern of highly deformed metacarbonate and seemingly untouched metapelites continue throughout the field area, although in no other locality is it as well exposed as locality 2.

The relationship between highly deformed metacarbonate and seemingly untouched metapelites is likely to be due to the contrasting mechanical properties of the rocks. In contrast to carbonates, which tend to behave plastically during deformation and therefore develop visible folds, the clay minerals of the metapelites align during deformation to form foliation which effectively absorbs the deformation.

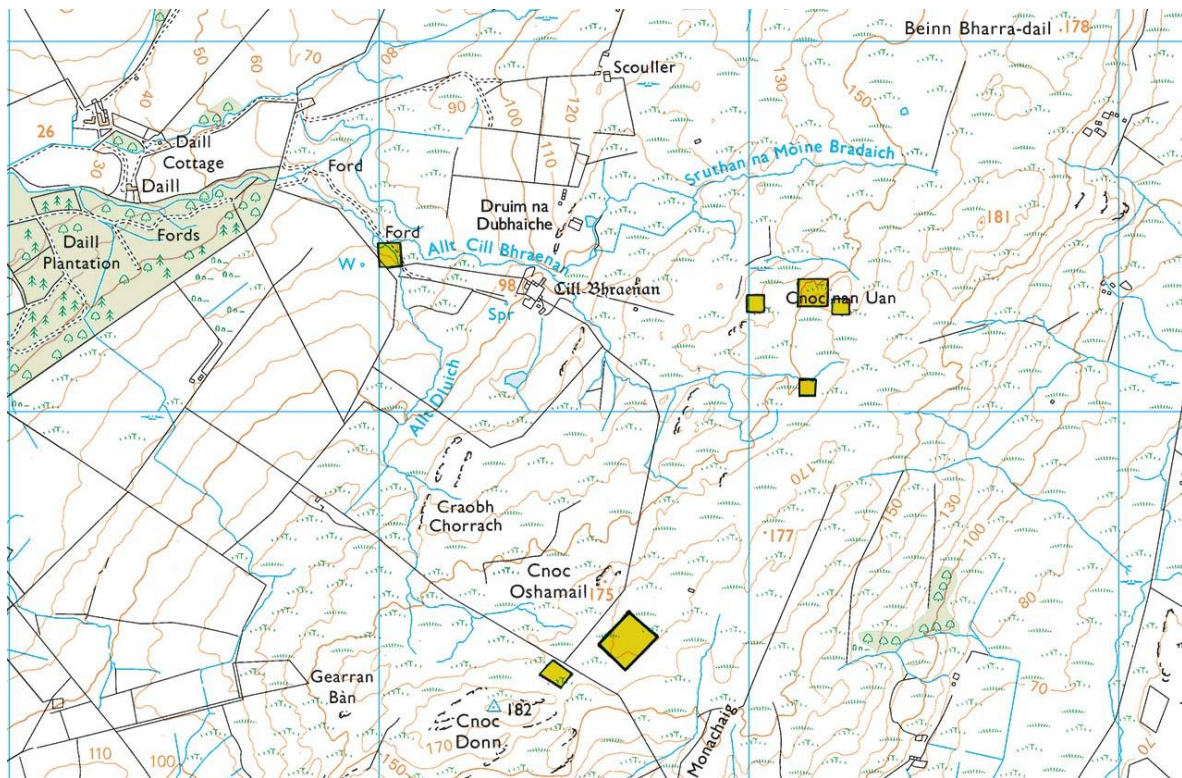


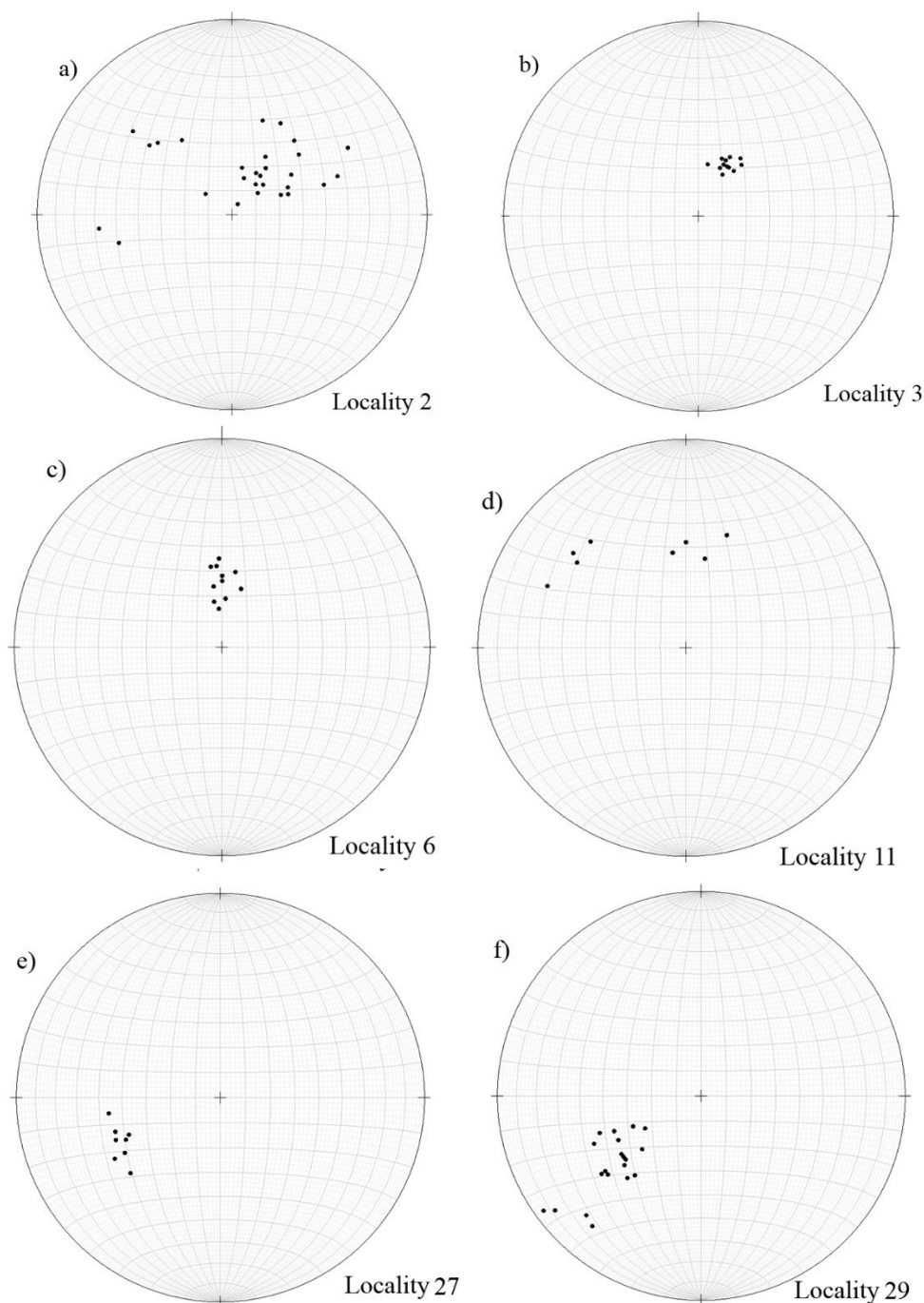
Figure 5.3: Map of the field area with the areas displaying differing dip directions highlighted in yellow. The size and boundaries of the areas are interpolated based on the outcrops where the data was gathered.

Locality 42 displays the same deformation pattern as locality 2. The dip directions of the fold limbs range from 082 to 184, over four different areas of the same outcrop. Area A ranges from 102 to 110, area B from 120 to 140, area C from 172 to 184, and area D from 084 to 090. This relationship indicates that even though the hinges are not visible in this area, the outcrop is comprised entirely of the smaller folds that were discussed regarding locality 2.

Locality 3, 6, 11, 27, 29 also display dip directions differing from the general trend of the larger structure. Locality 26, and 28 are comprised of deformed metapelites, while locality 3, 6 and 11 are comprised of deformed metacarbonate.

Locality 3 and 6 has a range of 202-220 and 170-198 respectively, and could thus represent a south-western dipping limb. Locality 11 has wider range (114-138 and 172-200), which is likely due to a large fold in the middle of the outcrop.

The dip direction of locality 26 range from 040 to 072, and locality 28 range from 050 to 082. This, and the quartzite (dipping at range of 035-040 degrees) that is present between Neriby and Cnoc Donn are the only representation of this north-eastern dip direction outside of the smaller folds found in locality 42.



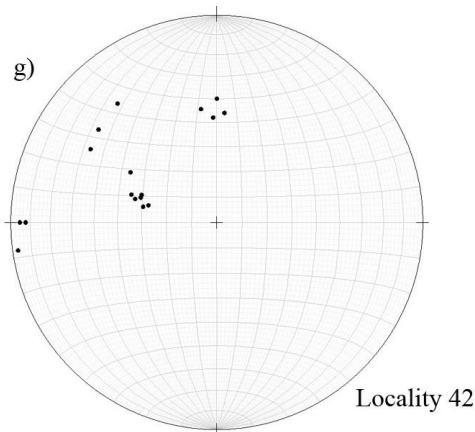


Figure 5.4: Stereograms showing the measurements taken at localities 2, 3, 6, 11, 26, 28, and 42 plotted as poles-to-bedding.

As presented above, the smaller folds have a large range of dip directions. When plotted together as poles-to-bedding on a stereogram, they loosely follow a great circle.

However, the many outliers makes it harder to calculate a reliable best-fit great circle and subsequently a reliable hinge. The best-fit circle and hinge in figure 5.5a below was calculated using all the data, while the best-fit circle and hinge in figure 5.5b was calculated while excluding the outliers.

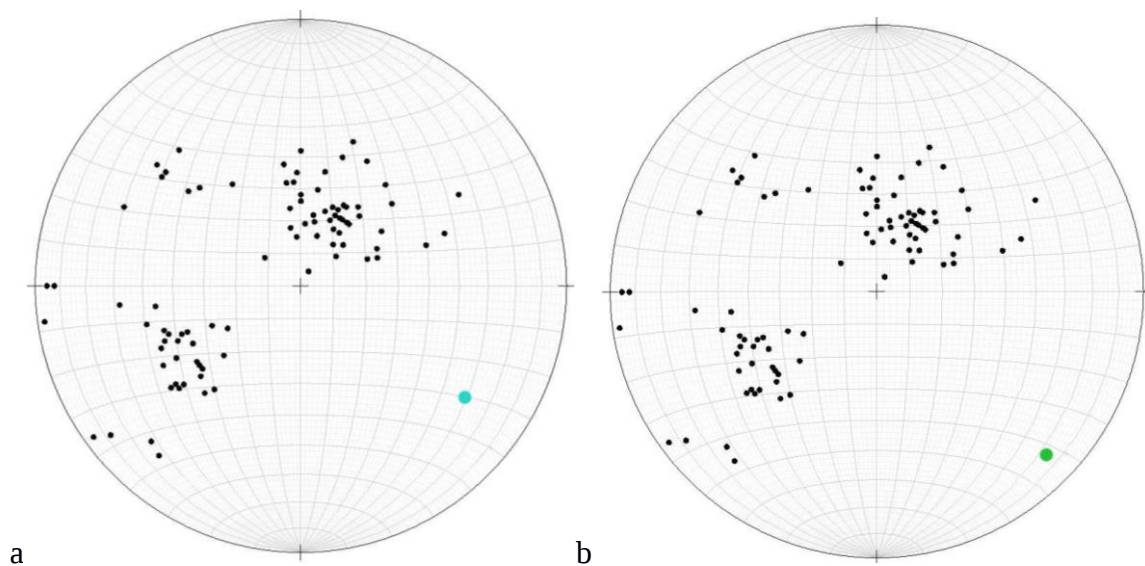


Figure 5.5: Stereogram showing the measurements from only the areas with differing dip directions, and the two different hinges Figure 5.5a displays the hinge based on all the data (26/120), 5.5b displays the hinge as calculated while excluding the outliers (08/131).

As can be seen in figure 5.5 above, both hinges are fairly similar despite the possibly skewing effect of the outliers. This indicates that they are at least a good indicator of where one would find the hinge in a larger, more comprehensive set of data.

5.3 Geometry of the field area.

As shown on figure 5.1 the north-western limb is significantly smaller than the south-eastern limb.

The geometry of the fold is better visualized using figure 5.6, which show a cross-section of the structure drawn approximately at level of Daill Cottages.

The image clearly shows the size difference between the two limbs.

The north-western limb is only spans an area of approximately 300 meters, while the south-eastern limb spans approximately 1000 meters.

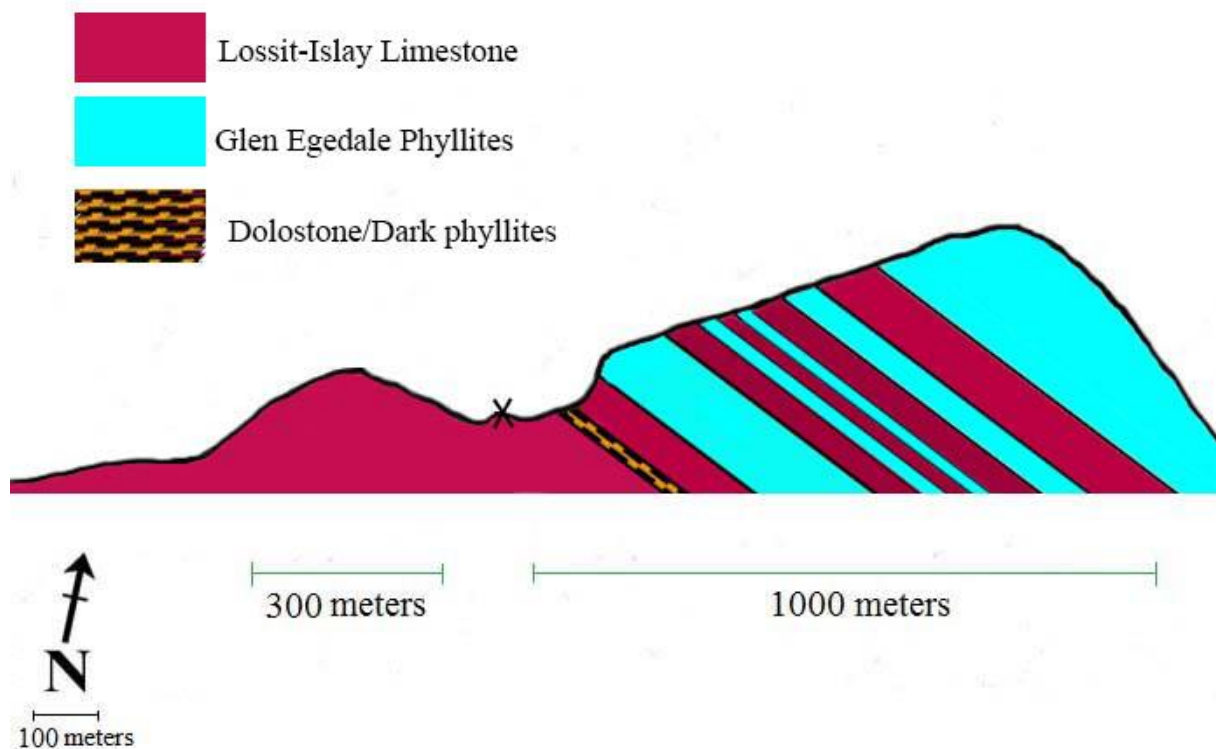


Figure 5.6: Cross-section of the field area, showing the width of the fold limbs, and the approximate location of the hinge. The green lines indicate the widths of the fold limbs, which have been interpolated based on the location of outcrops found in the field, and the black “X” indicates the approximate location of the hinge. The location of the hinge is, as in figure 5.1, an approximation based on the change in dip directions of the outcrops visible in the field area.

6. Discussion:

Based on the data gathered in the field the area displays evidence of two different phases of folding.

The first phase created a larger, asymmetric anticline which plunges gently north-westwards. This larger scale structure is on the scale of hundreds of meters, and is easily identifiable and mappable based on data collected in the field. The hinge can also be interpolated by plotting the measurements on a stereogram, and thereafter obtaining a best-fit great circle which then is used to calculate the hinge.

This structure is discussed in section 5.1, and displayed on figures 5.1, 5.2 and 5.8.

As can be seen in figure 5.1 and 5.8, the westward limb is significantly smaller than the eastern limb, both in height, width, and length.

There are several different definitions of fold symmetry. Some of them involve the steepness and the length of the limbs, while others use the location of the bisecting surface. Ideally one would chose to

use the definition of fold symmetry given by Pluijm et al, which is based on the relationship between the axial plane and the median surface. If the axial surface is anything but perpendicular ($\pm 10^\circ$, Pluijm et al, 2004) to the median surface, the fold is asymmetric, otherwise it is symmetric.

As a rule, one can use axial planar foliation cleavage of minor parasitic folds to interpolate the axial surface of the main fold. Unfortunately, no reliable axial planar foliation measurements were taken during the field work for this thesis. This is due to bad exposure.

However, the asymmetry of the larger structure is apparent even using the more ambiguous definitions. There is a 29° difference in dip angle between the two limbs meaning that they have unequal dip angles which makes the fold asymmetric. The south-eastern limb is significantly larger than the north-western limb, which means that the two limbs cannot be mirror planes of each other. This would also classify the fold as asymmetric.

Figure 6.1 below is a schematic diagram of the fold showing an interpolated shape of the fold, the median surface, and the dip of the fold limbs. The solid lines represent the actual fold limbs as they have been observed in the field, while the dashed black line is an interpolation of the original shape of the fold based on the average dip angle of each limb and the interpolated location of the hinge.

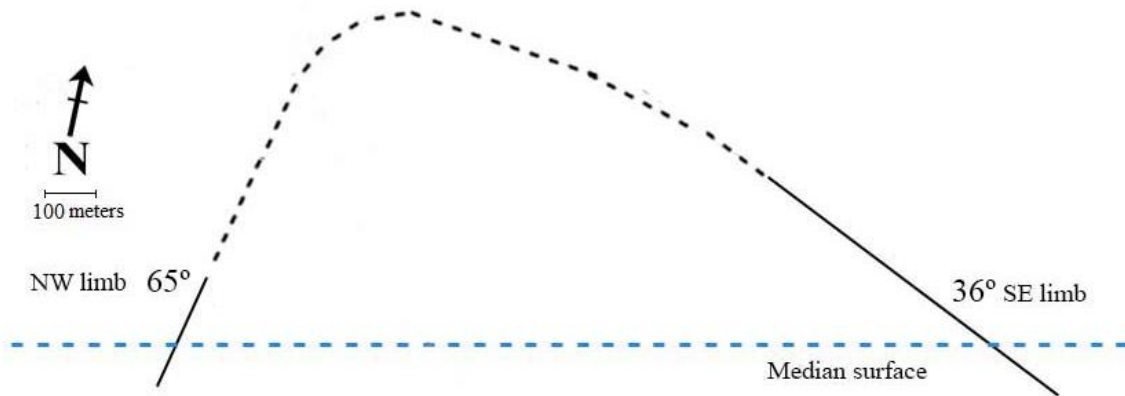


Figure 6.1: Schematic diagram of the fold showing an interpolated shape of the fold based on the dip of the fold limbs, and the location of the hinge. The distance between the two limbs of the fold is based on the distance measured in the field, and is the same as in figure 5.8.

The second phase of folding created the smaller areas with differing dip directions. Based on the west-south-westerly axial planes of the smaller structures resulting from the second phase of deformation, it initiated at approximately 90 to 100 degrees to the larger anticline that was created by the first phase of deformation. This second phase of deformation is also likely to be responsible for the spread in dip directions on the larger structure. This spread is most noticeable on the western side of the larger structure, in localities 13-24. The six different localities that display the differing dip directions are represented in figure 5.7.

The smaller folds with dip directions differing from the general trend could possibly be the result of refolding of the larger structure, the superimposed fold creating a Type 1, or a “dome-and-basin” fold interference pattern.

A Type 1 interference pattern is initiated when one has two generations of folding, where both the axial surfaces and the hinge lines of the two generations are perpendicular to one another – producing a “dome-and-basin” type structure. If later stages of deformation (D3 or D4) caused large scale open folds initiated more or less perpendicular to the Islay Anticline (as in east-northeast to west-southwest rather than north-northwest to south-southeast) a Type 1 fold interference pattern would be the result. (Pluijm and Marshak, 2004)

The small folds correspond most readily to the D4 deformations as described by Fitches and Maltman in their 1985 paper, as they are noted to be “on steep east-west axial planes”, something that conforms to the axial planes of the smaller folds. They also note that “large-scale open folds are influencing the map pattern”, something that would, if they did initiate with the same general direction as the smaller folds, also conform to the Type 1 fold interference pattern.

The highly curvilinear deformations present in the area (figure 6.2) were possibly created either during the second phase of folding, and are in that case due to refolding of parasitic fold hinges of the larger structure during the second phase of folding.

They can also be caused by shear from the nearby The Loch Skerrols Thrust, as differential shear is well known to modify initially symmetrical folds to asymmetrical S- and Z-folds.

It is worth noting that a Type 1 fold interference pattern need not be the result of two separate phases of deformation, but can be the result of a single phase of heterogeneous non-coaxial deformation, or the amplification of pre-existing irregularities.

This means that an alternative scenario for the conception of the areas displaying the differing dip directions could be that they are caused by flow perturbations.



Figure 6.2: Photograph showing locality 18, on the north-western limb. Displayed in the middle of the image is one of the highly curvilinear deformations present throughout the north-western limb.

Passchier et al (2005) define flow perturbations as “the deviation of a heterogeneous flow pattern from the background homogeneous flow”. The model of flow perturbations as proposed by C.W Passchier shows that an isolated rheological heterogeneity (such as an inclusion) can cause perturbations in the velocity field of flow, indicating that the presence of the quartzite veins very well could aid in the formation, or amplification, of the smaller folds.

It is reasonable to believe that one would find well developed north-east plunging folds if the area was not as heavily eroded as it is, as this causes exposure to be very bad in some areas. However, one would be hard pressed to try and find a complete fold in the area at present times.

The low competency of the marble also plays a role in the location of the deformation.

The competency of a rock is a measurement of its resistance to flow. As competency is a relative term, a rock type would be said to have higher or lower competency as related to the surrounding rocks.

A rock with lower competency, such as marble, would be expected accommodate deformation more readily than for example a quartzite.

The metapelites of the area also have low competency, but they are still less likely to show the same type of deformation as a metacarbonate. This is due to the foliation of the metapelites, which often develops in the rock as a first response to stress and/or strain, rather than the folding one would expect to see in the metacarbonates.

This, in addition to the heavy erosion of the area, explains why the smaller, fully developed folds are only readily seen in the metacarbonate rocks.

6.2 Conclusion:

Based on the data reviewed in this thesis, my conclusion is that a large asymmetric NNW-verging anticline on the scale of hundreds of meters pass through my study area. The eastern limb has an average dip/dip direction of 36/114, and the western limb has an average dip/dip direction of 65/292. The anticline shows evidence of at least one subsequent refolding event.

7. References:

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7.1 Images, figures, and software used:

1. Cockett, Rowan. "Online Stereonet Program - Visible Geology." *Online Stereonet Program - Visible Geology*. Rowan Cockett, 1 May 2012. Web.
<http://app.visiblegeology.com/stereonet.html>
2. Adobe, Adobe Photoshop CS6;
<http://www.adobe.com/se/products/photoshop.html>

Appendix.

All measurements are given according to the convention dip/dip direction.

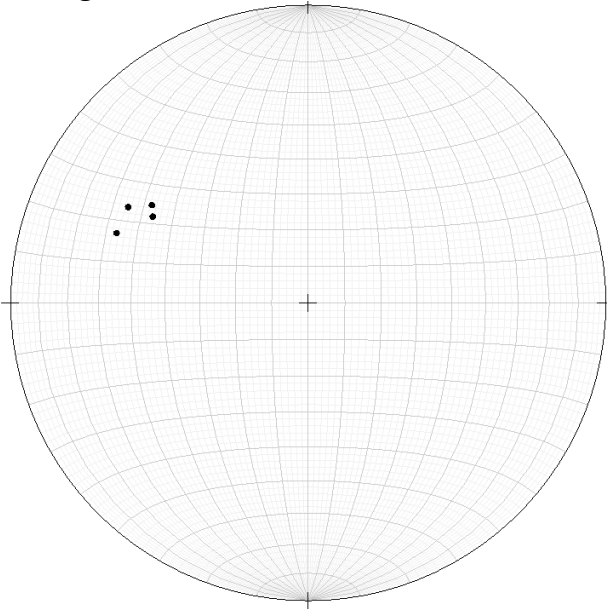
The "x" on the map indicates the location of the locality.

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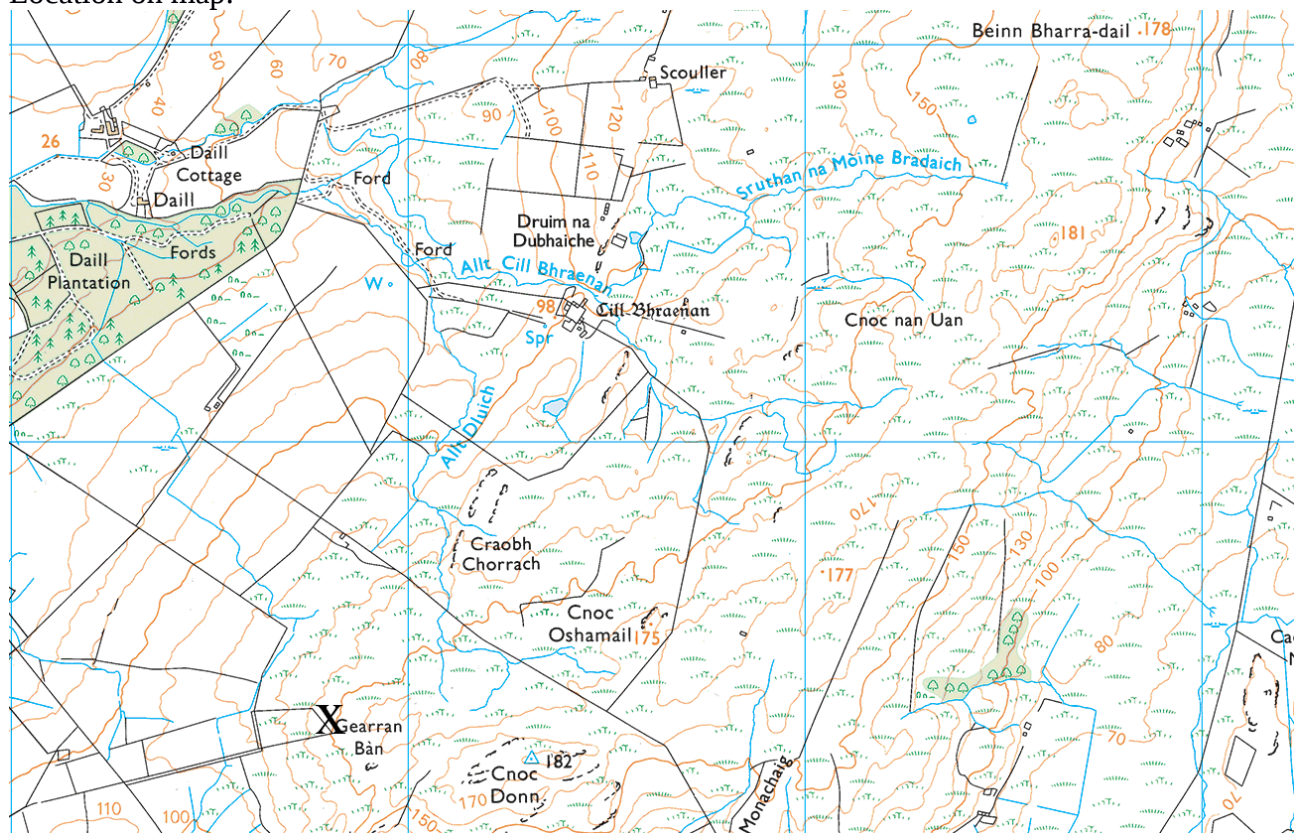
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52/122	58/110

Stereogram:



Location on map:

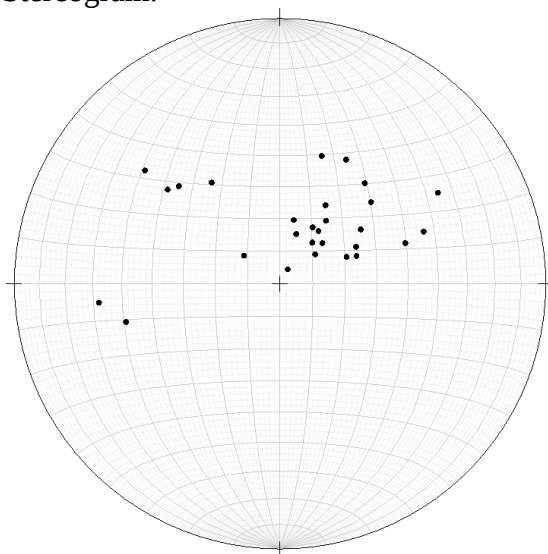


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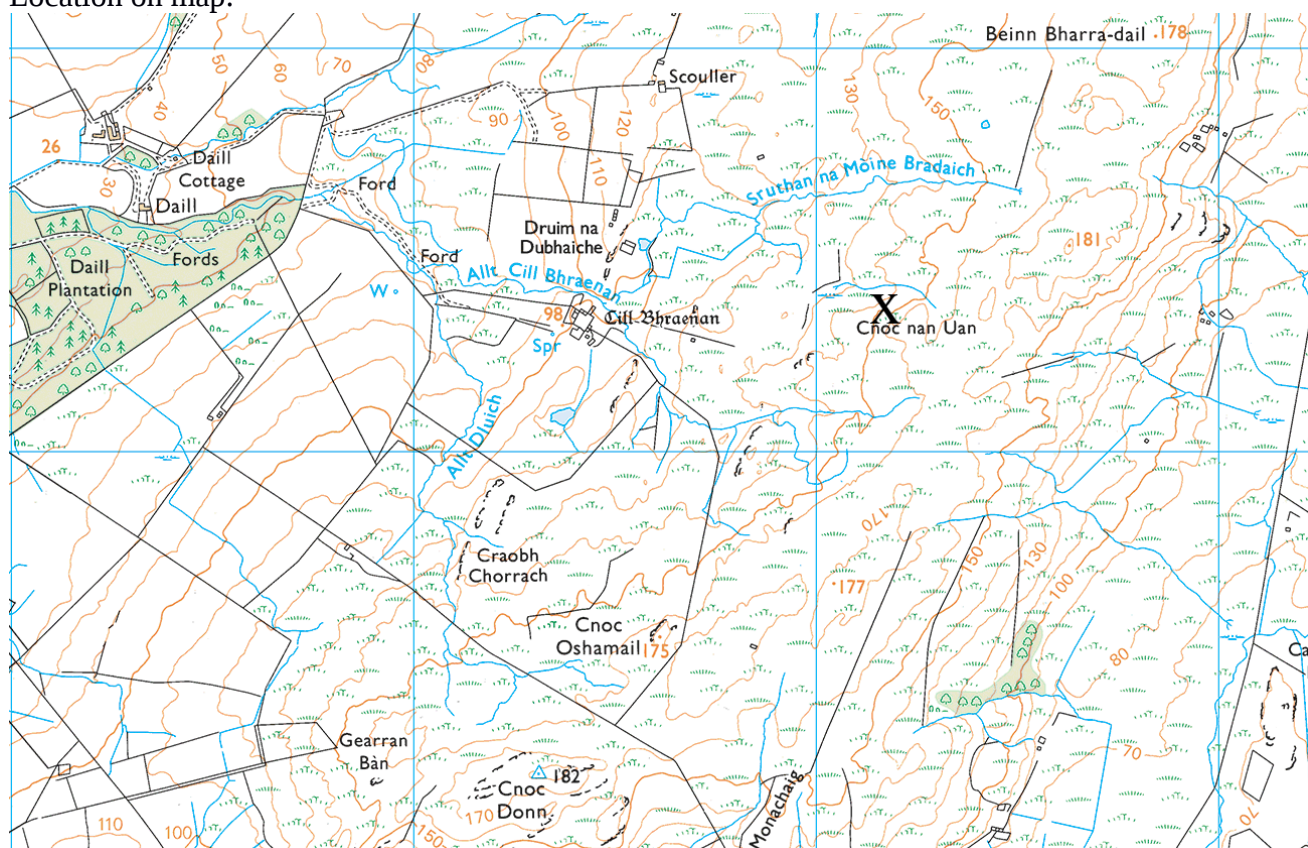
Measurements:

25/250	58/240	41/220	14/230	14/128	41/252
48/250	22/248	38/228	30/236	26/244	24/216
44/134	20/210	5/208	16/198	56/130	38/146
18/226	16/218	20/216	42/198	44/208	58/084
50/076	46/130	20/192	28/210		

Stereogram:



Location on map:

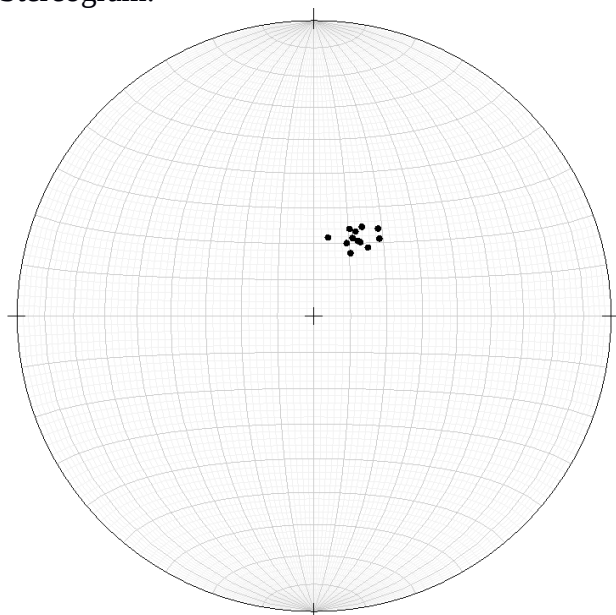


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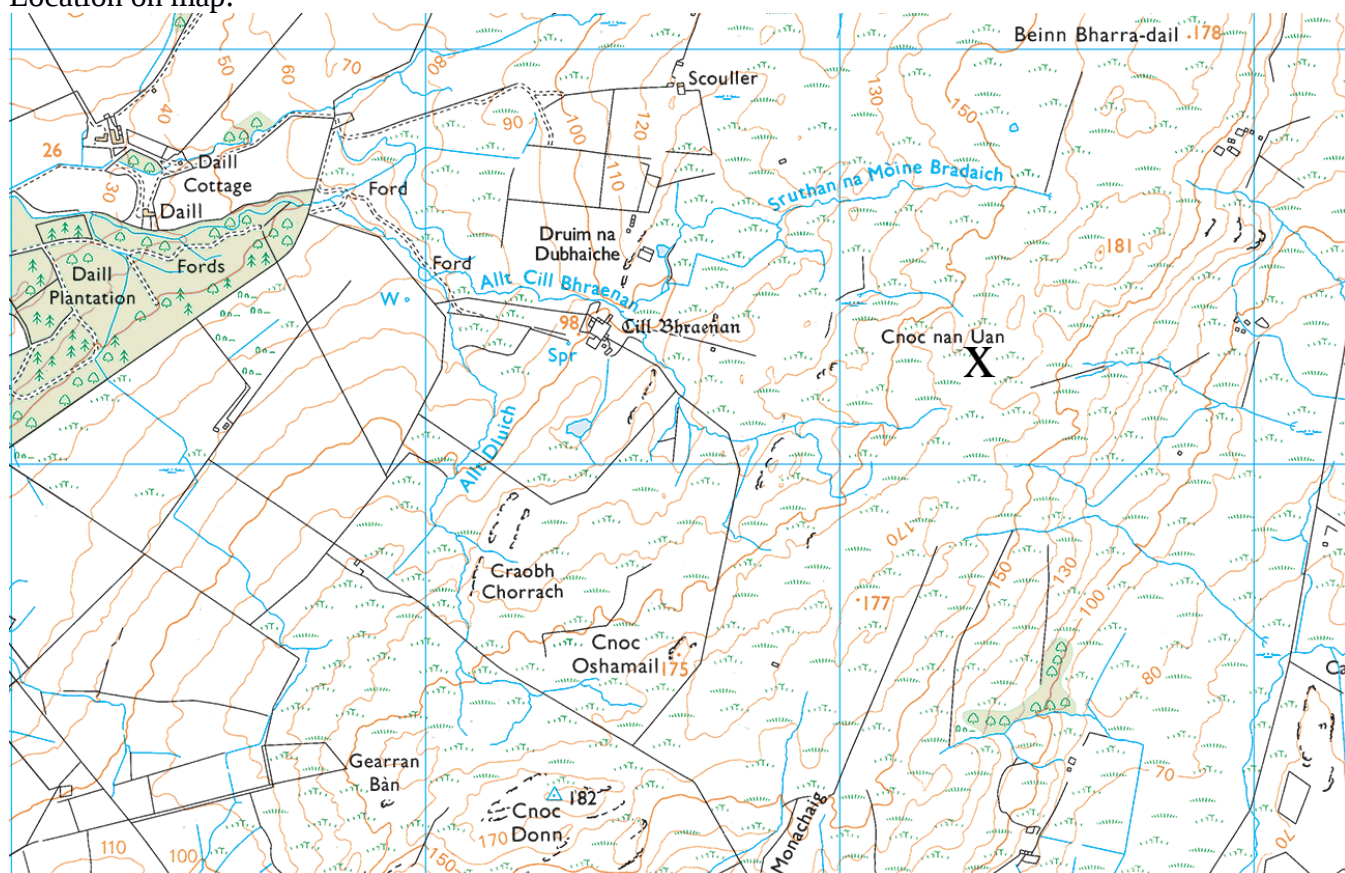
Measurements:

24/218	24/210	28/208	26/206	28/220
30/216	24/212	28/208	22/190	24/206
26/202	22/204	20/210		

Stereogram:



Location on map:

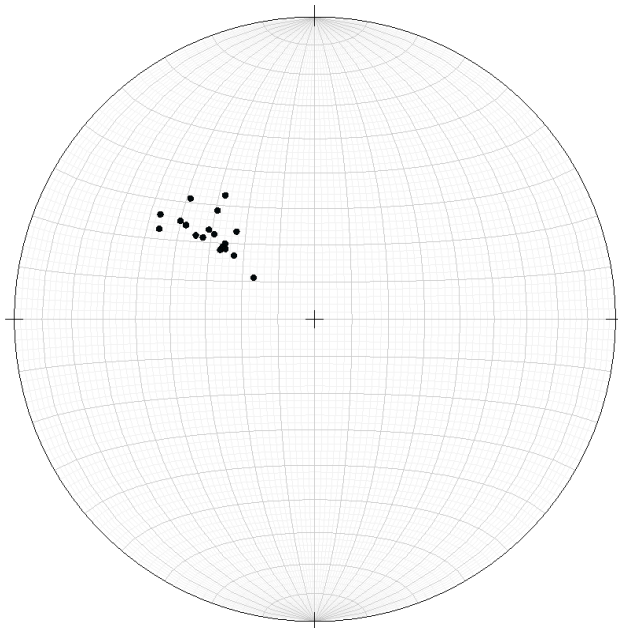


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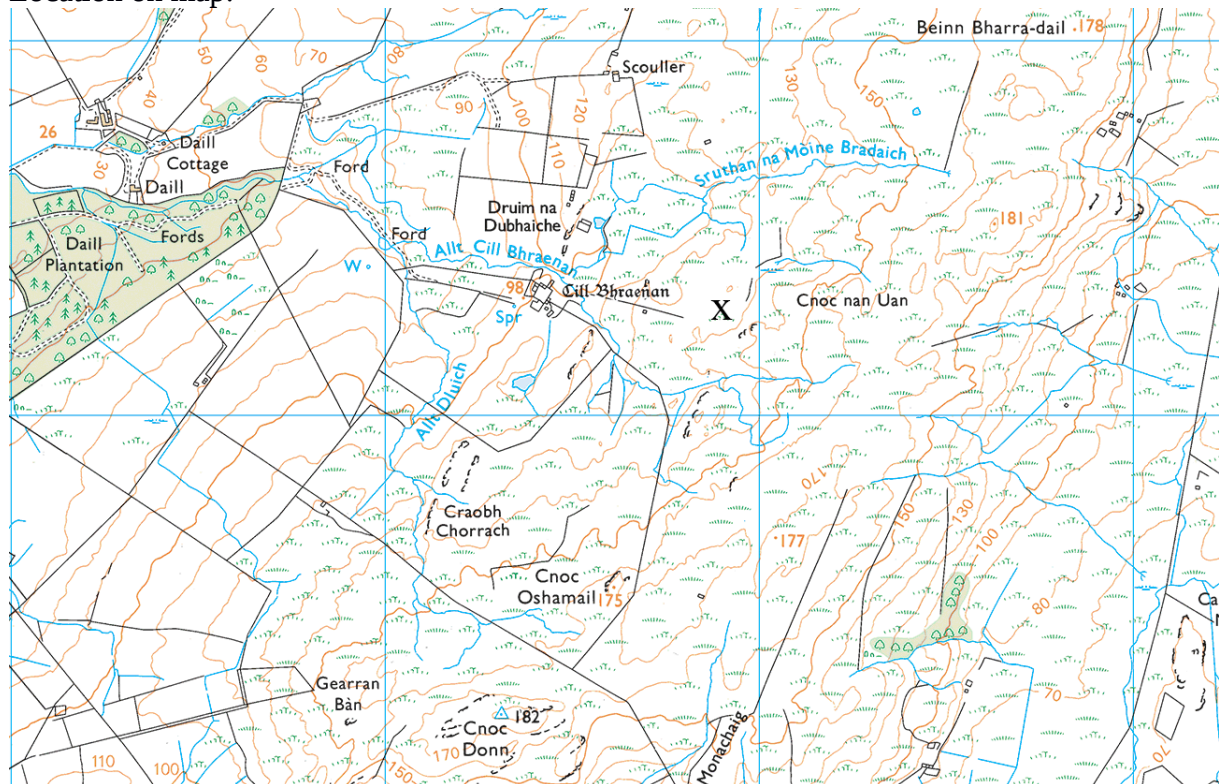
Measurements:

30/132	48/134	40/138	42/144	32/138
31/128	38/130	36/130	28/128	32/128
20/124	40/125	32/126	38/126	44/126
46/126	50/120	52/124		

Stereogram:



Location on map:

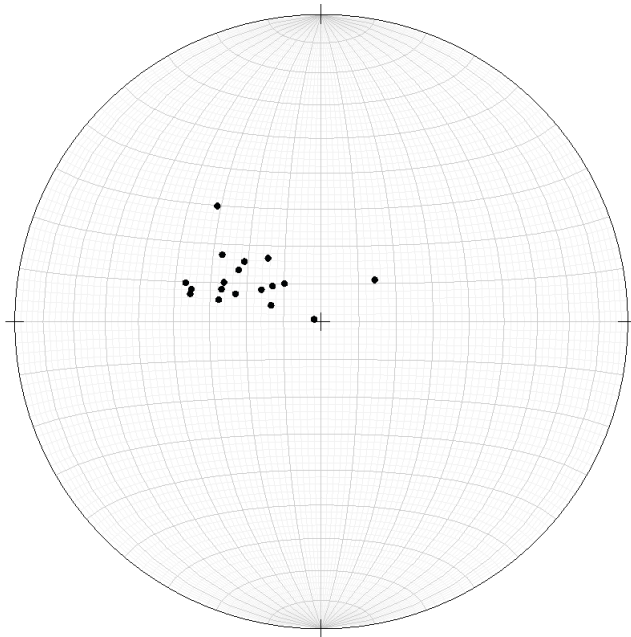


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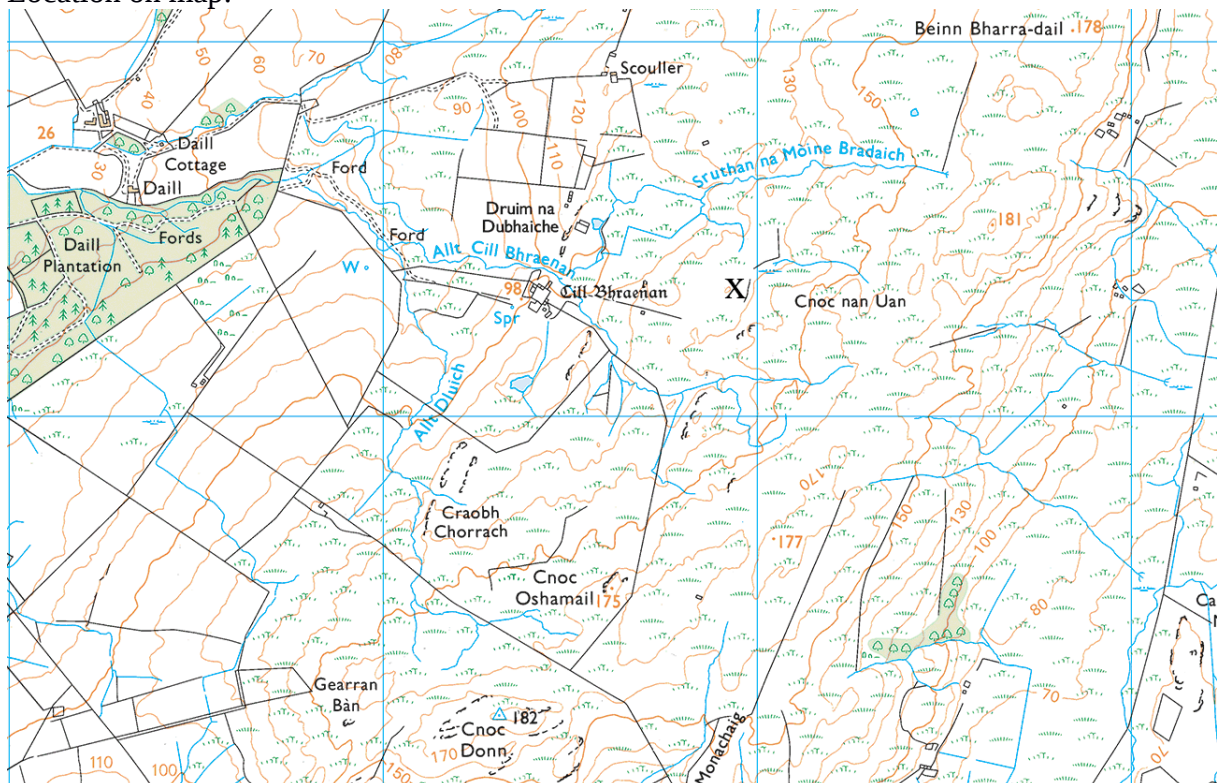
Measurements:

32/124	28/112	27/108	26/122	28/108
22/102	18/118	14/108	38/106	2/108
36/102	22/140	16/136	26/128	42/138
16/126	14/136	22/140	26/104	18/232

Stereogram:



Location on map:

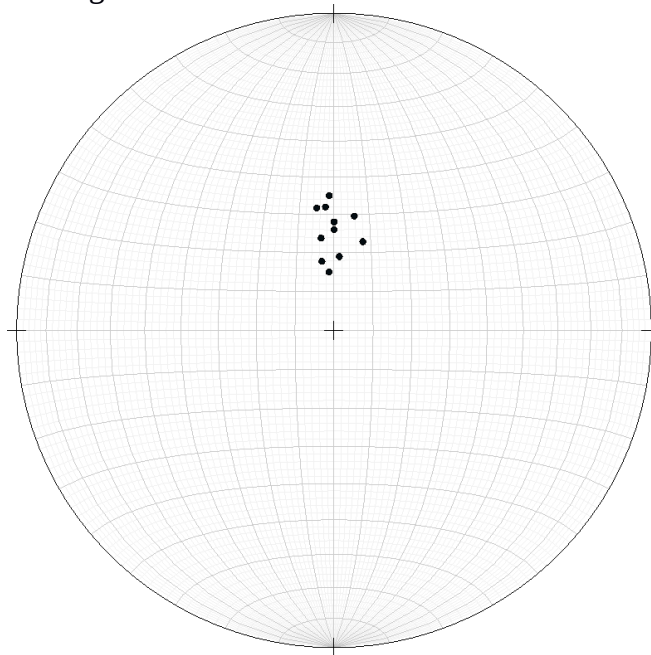


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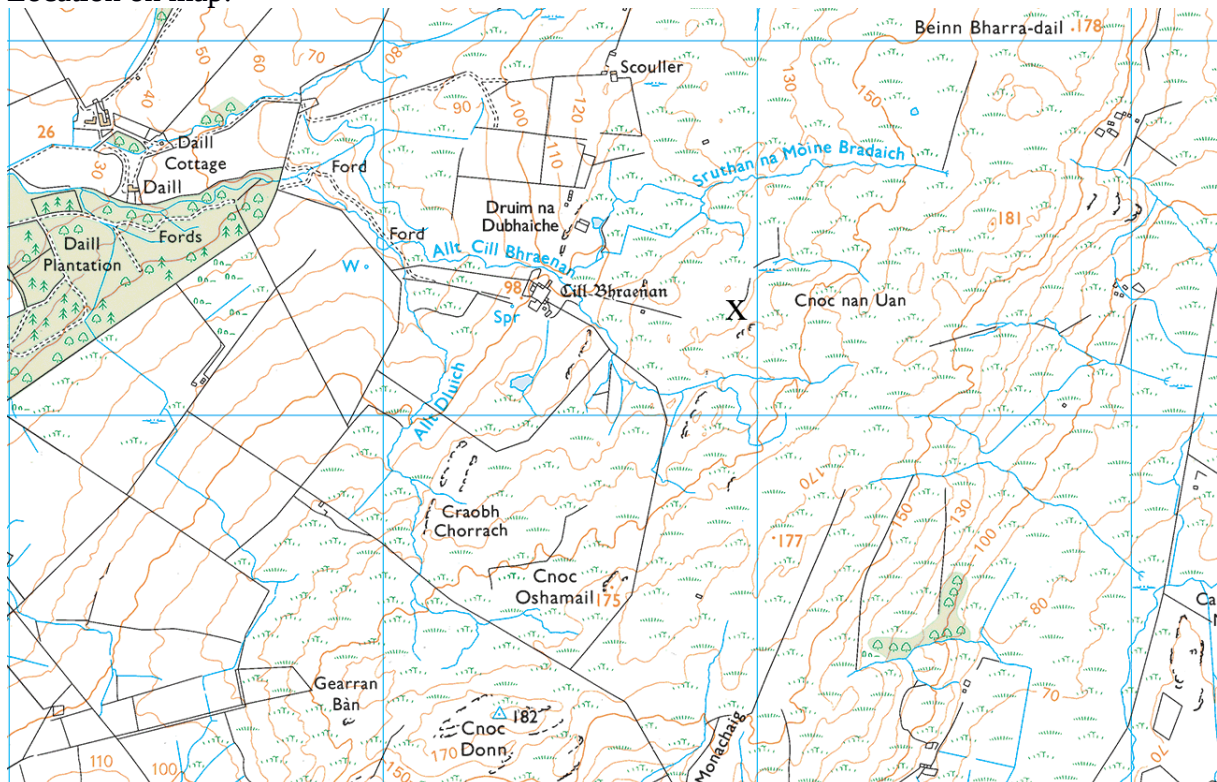
Measurements:

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32/172	32/176	28/180	24/172

Stereogram:



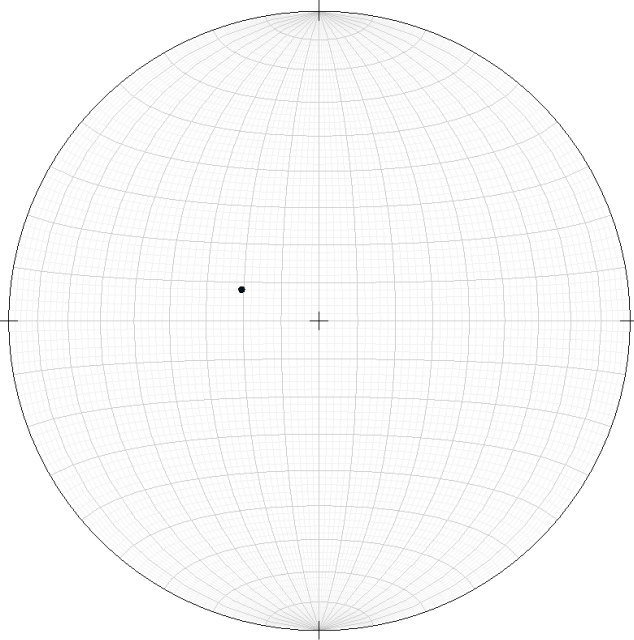
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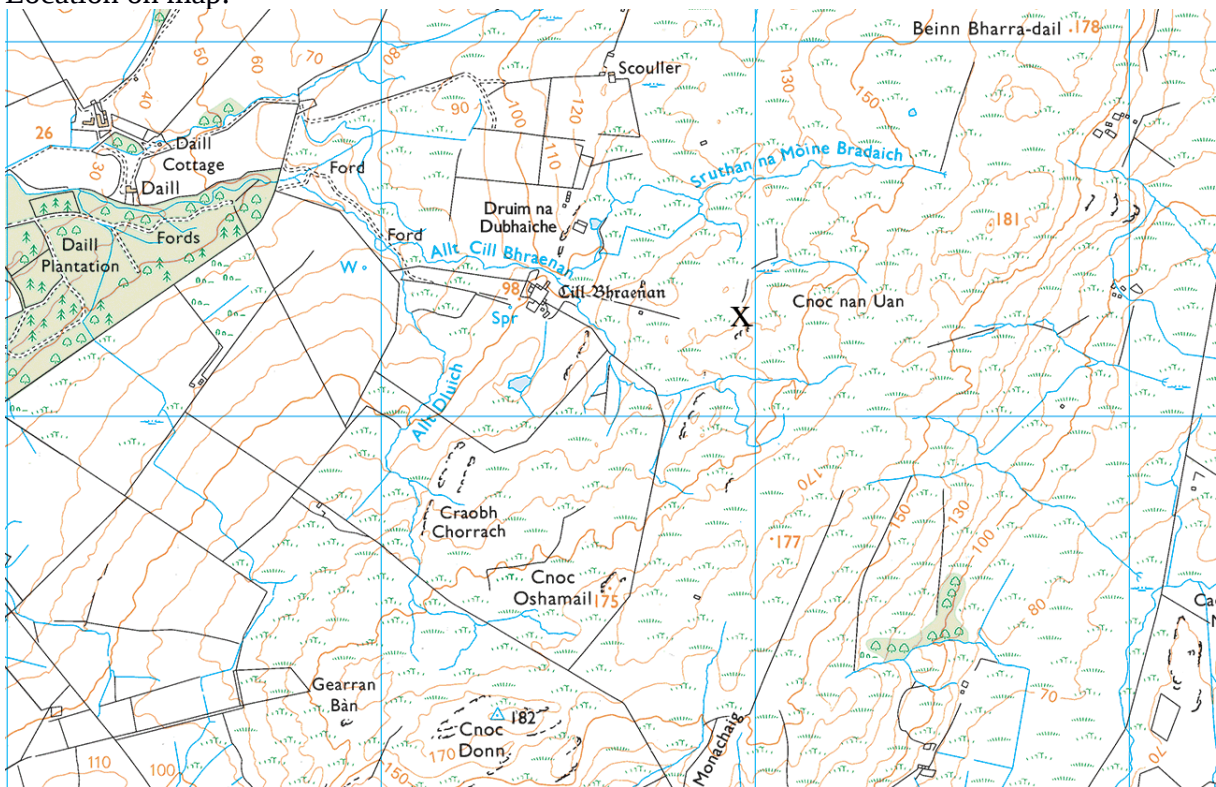
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Measurements:

22/112

Stereogram:



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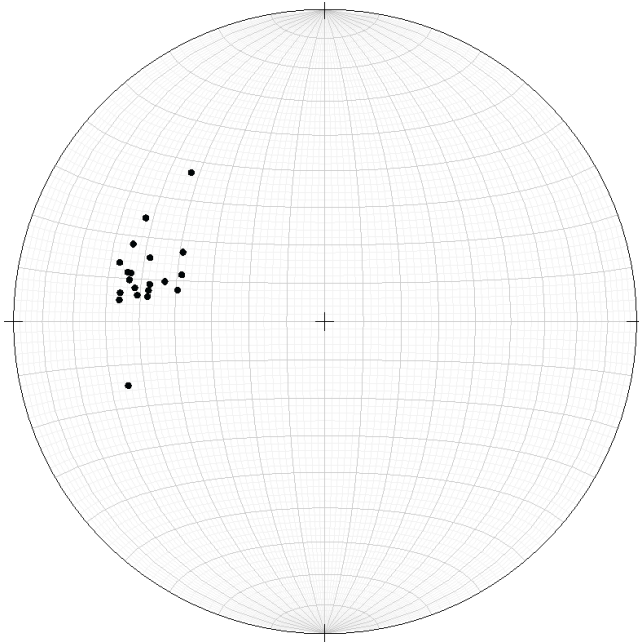


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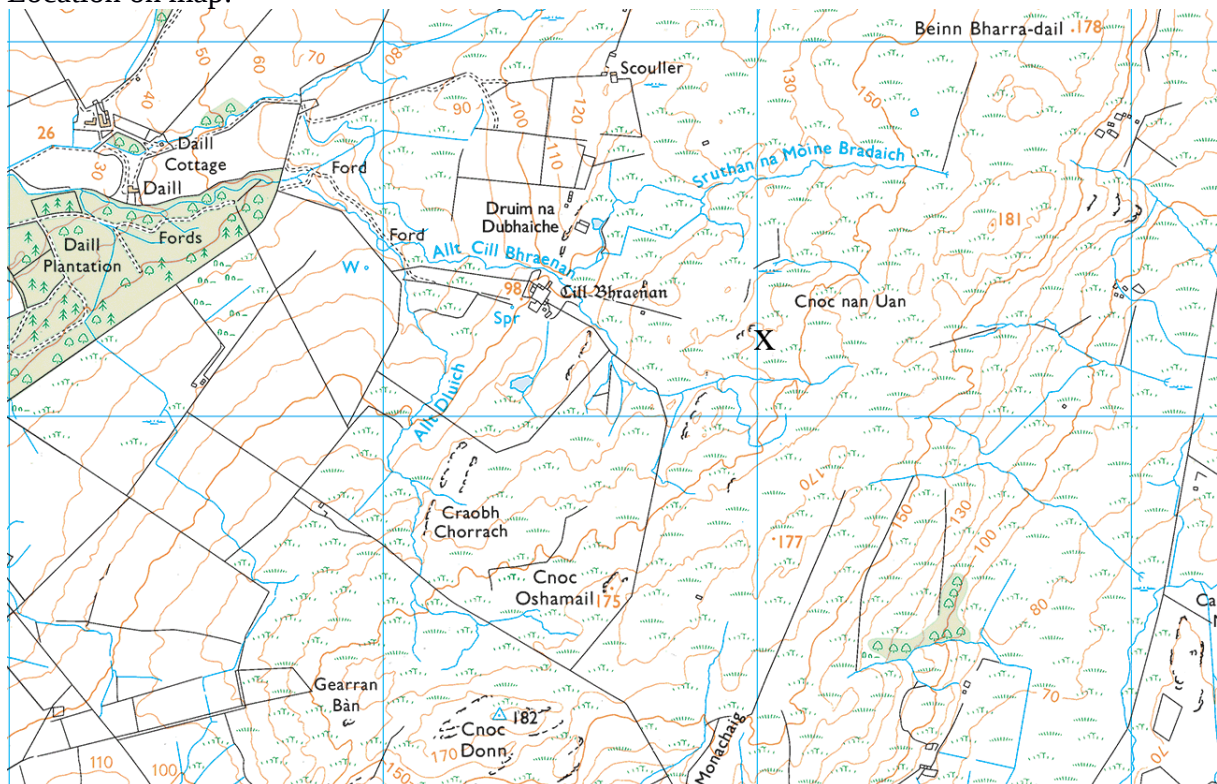
Measurements:

50/110	42/116	40/108	56/112	40/102
48/102	54/104	58/106	52/100	56/098
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51/098	48/098	56/072	56/120	54/138

Stereogram:



Location on map:

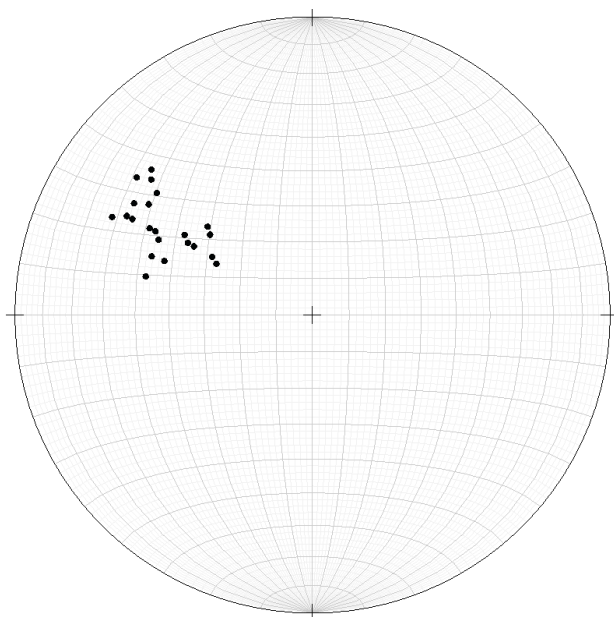


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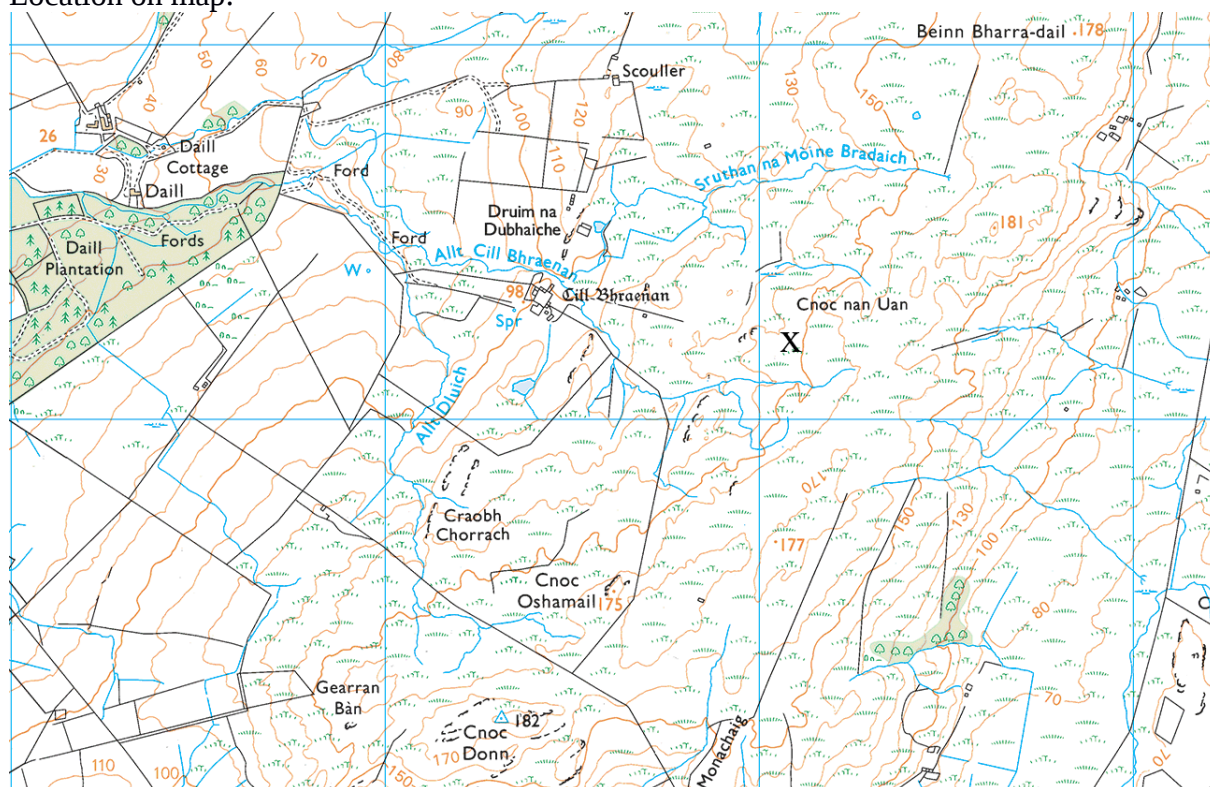
Measurements:

40/120	38/130	36/128	32/120	44/110
48/110	38/120	30/118	48/103	56/124
60/118	60/122	58/118	64/116	64/128
62/132	60/134	56/138	52/118	48/116
50/118	42/122			

Stereogram:



Location on map:

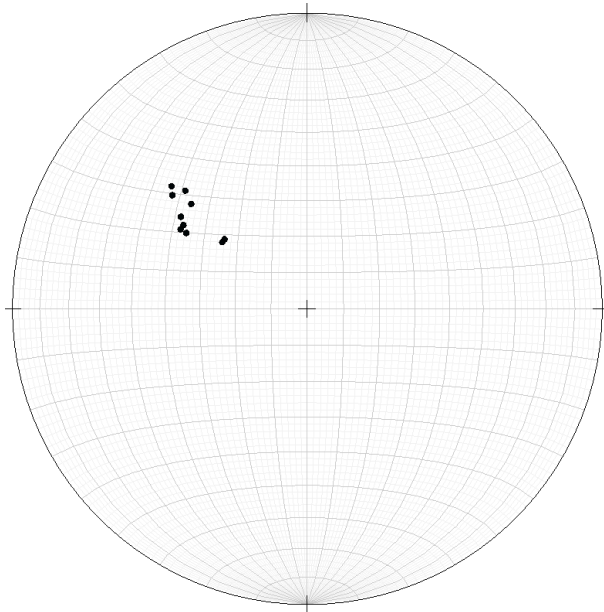


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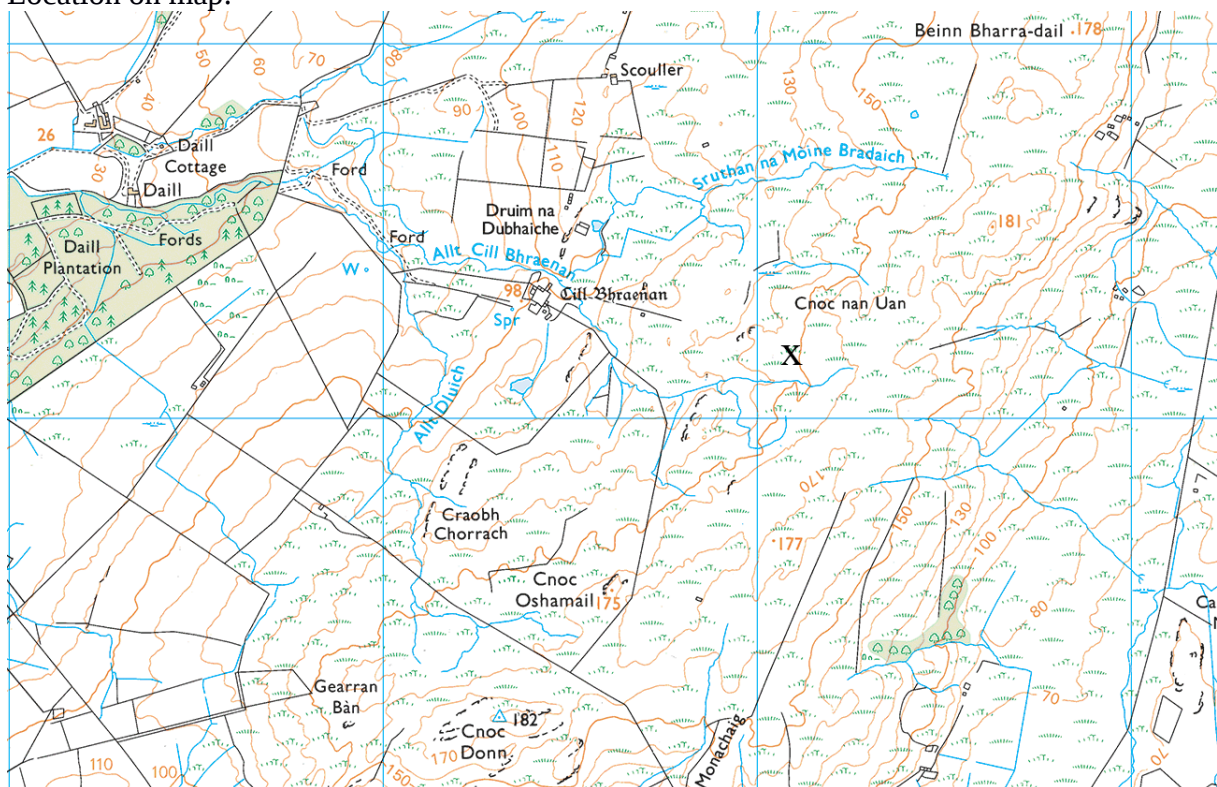
Measurements:

44/126	48/134	50/130	52/132	30/130
30/128	42/124	40/122	44/132	42/122

Stereogram:



Location on map:

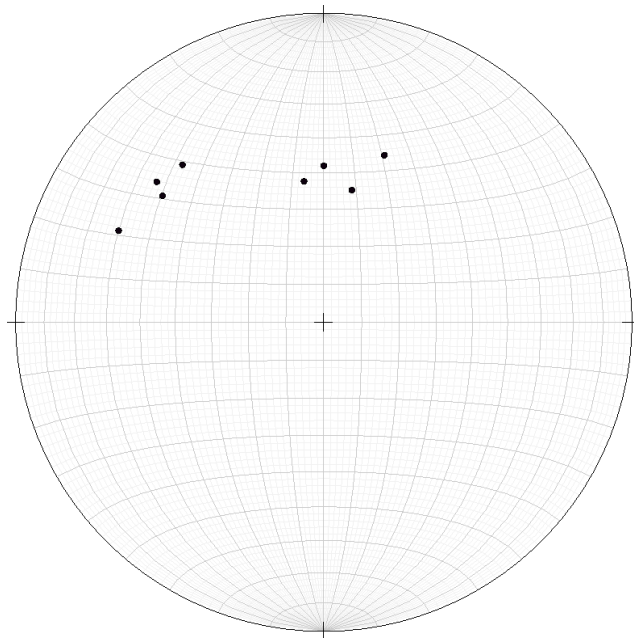


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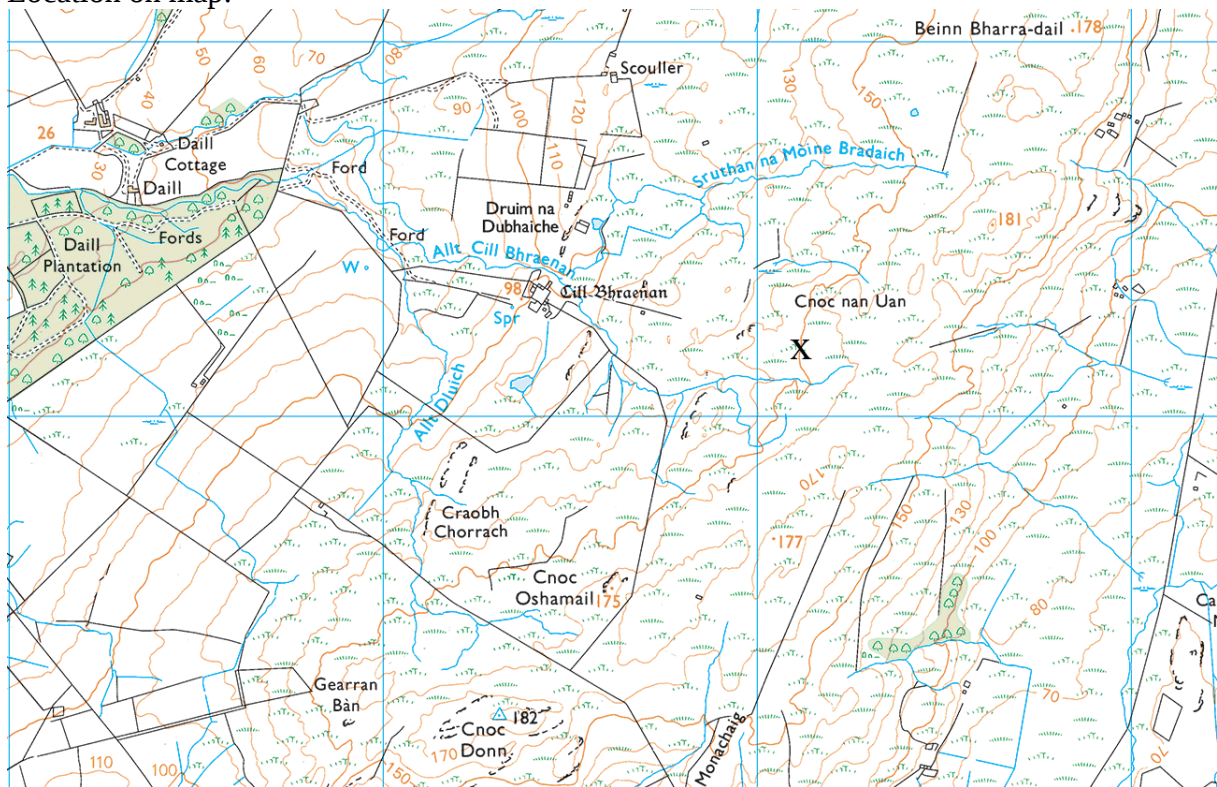
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60/130	62/114	58/138	56/128

Stereogram:



Location on map:



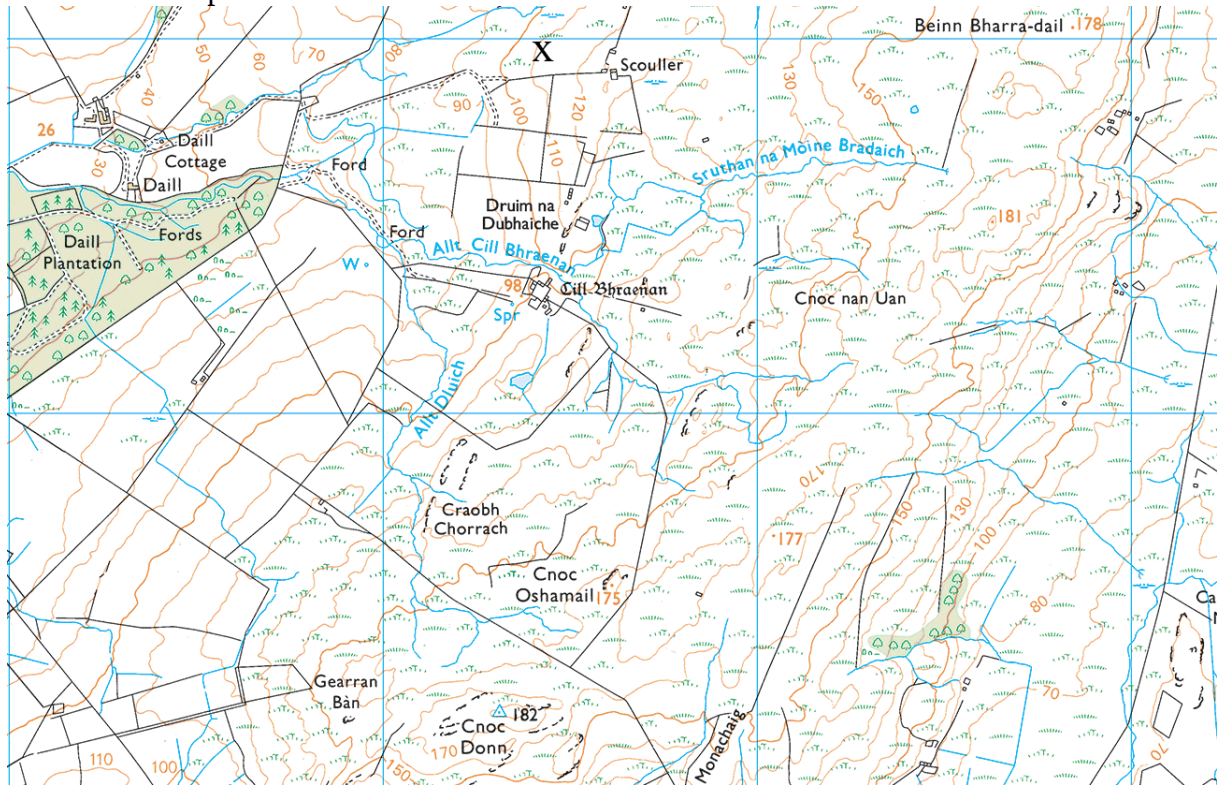
Locality 12:

Measurements:

Axial planar cleavage: 312/70

Stereogram: N/A

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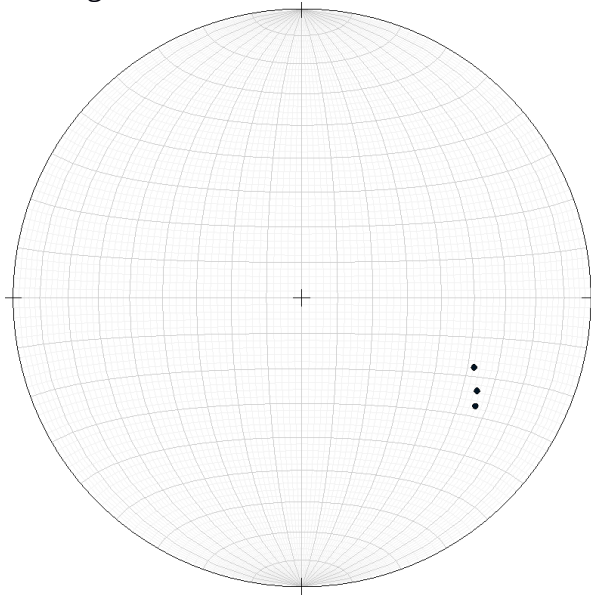


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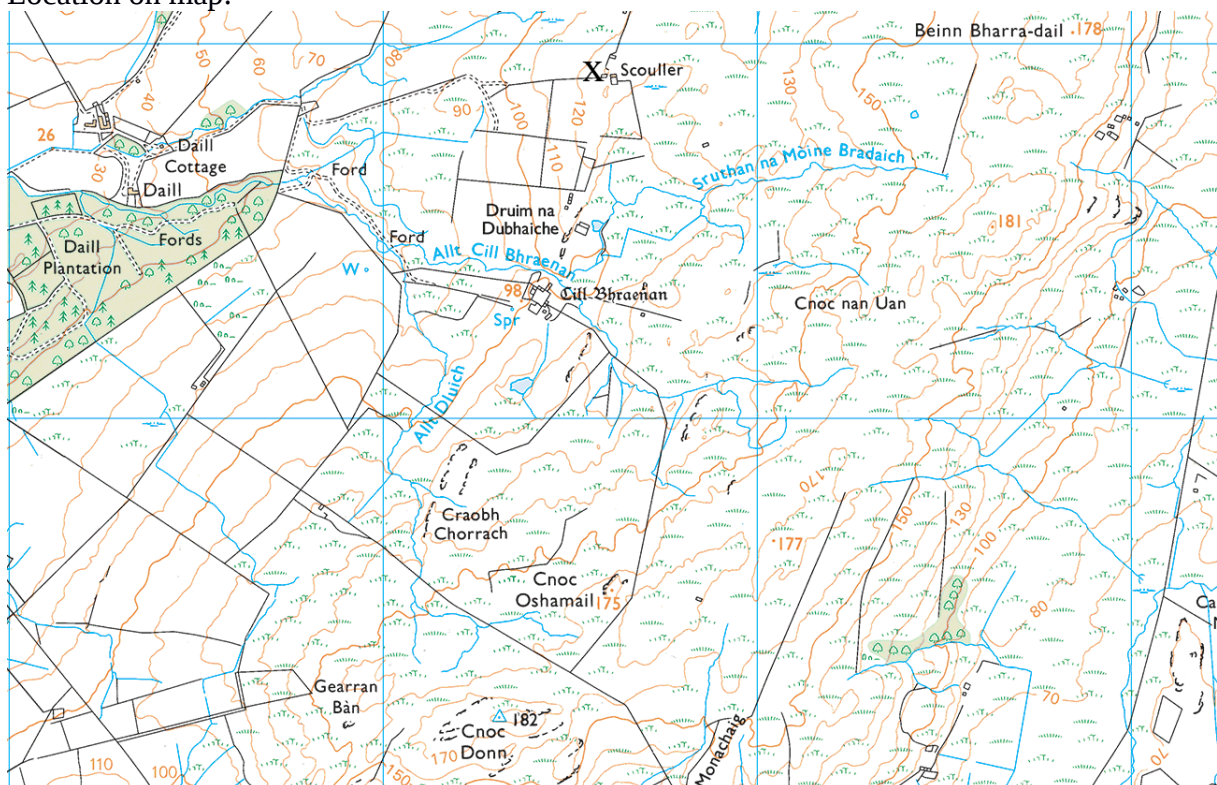
Measurements:

60/302	54/292	58/298
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Stereogram:



Location on map:

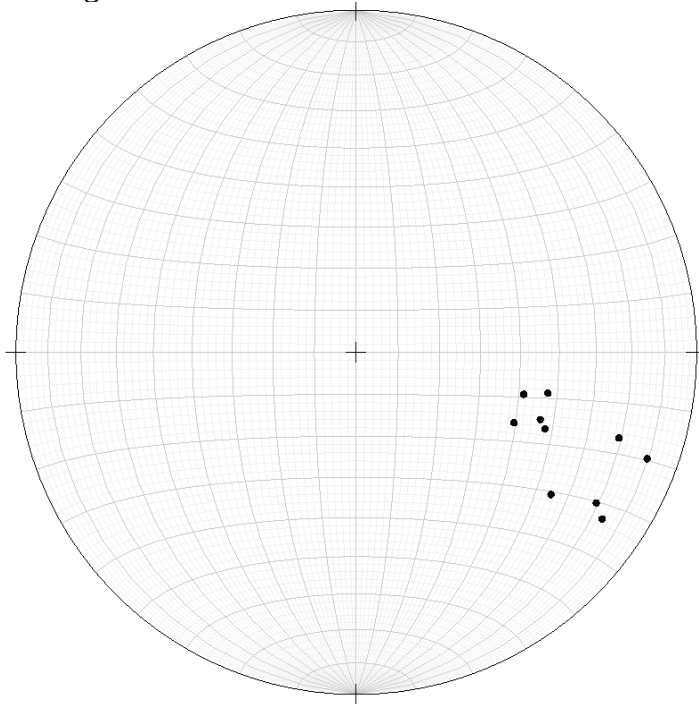


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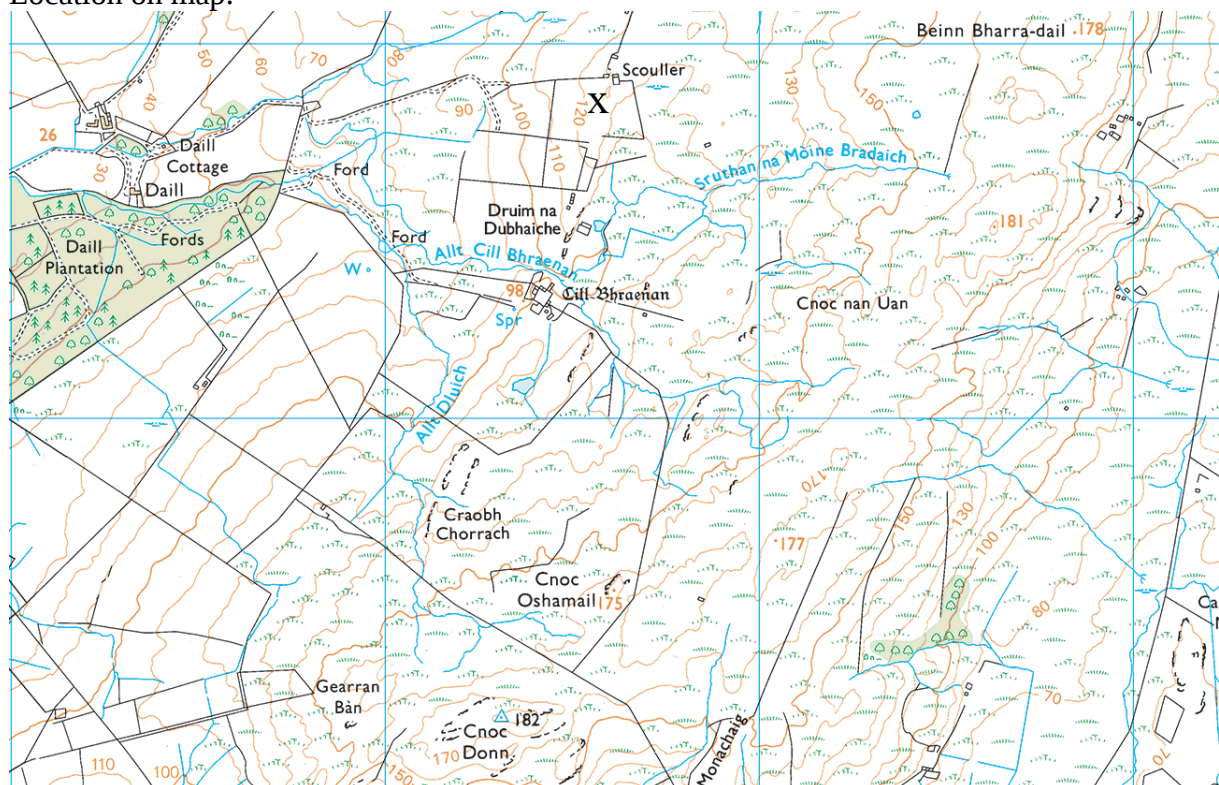
Measurements:

48/290	60/306	42/294	50/292	70/288
80/290	72/302	76/304	42/284	48/282

Stereogram:



Location on map:

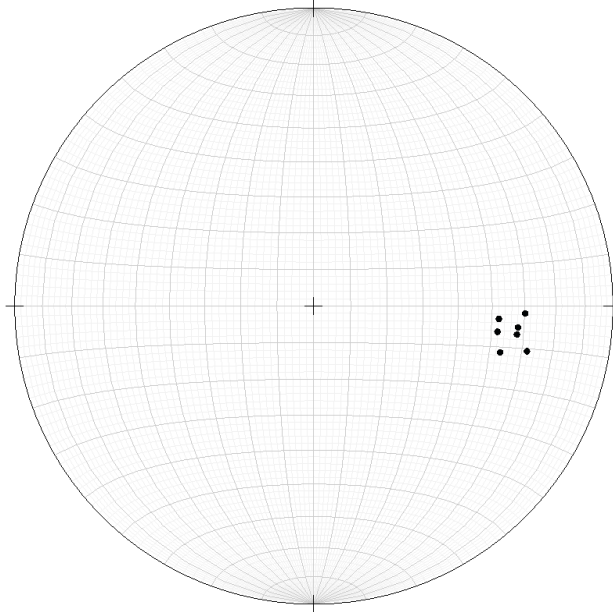


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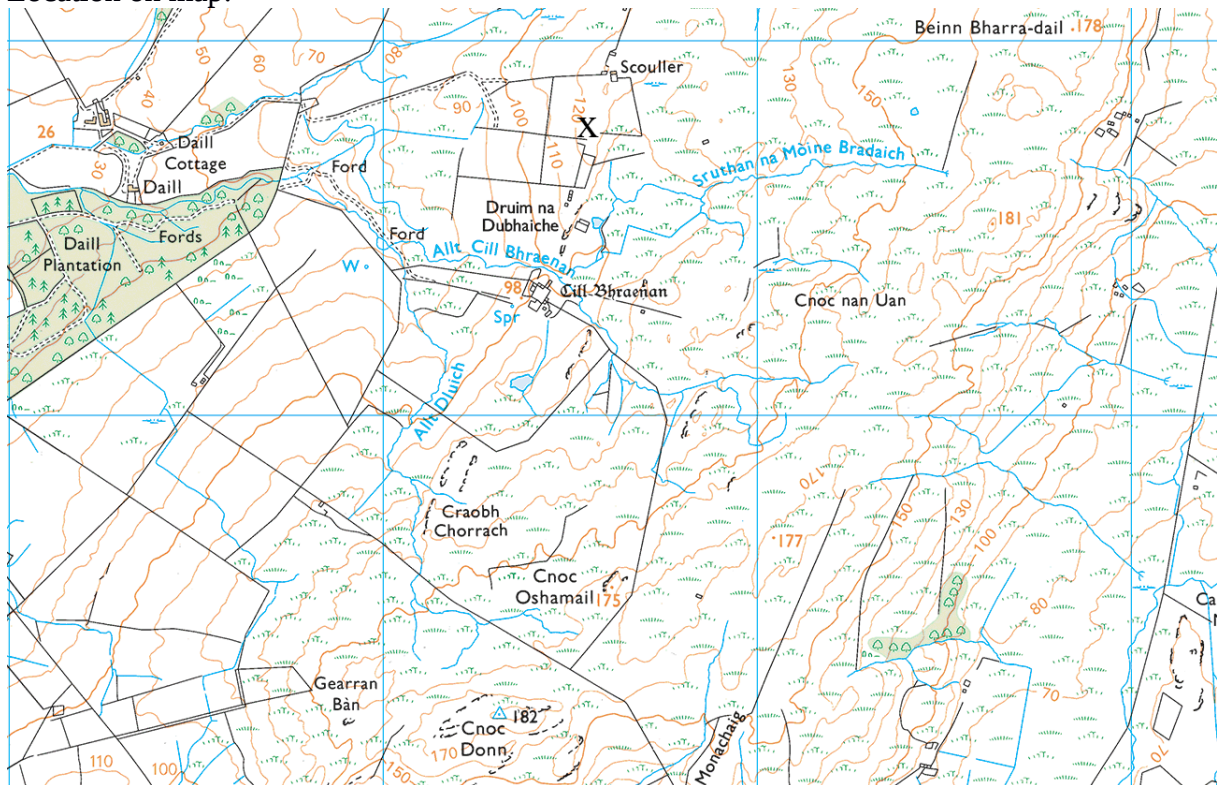
Measurements:

60/272	52/274	58/278	52/278
62/282	58/276	54/284	

Stereogram:



Location on map:

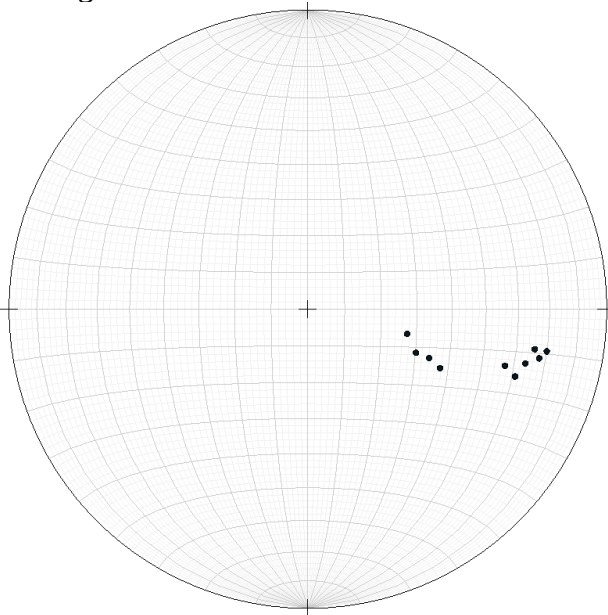


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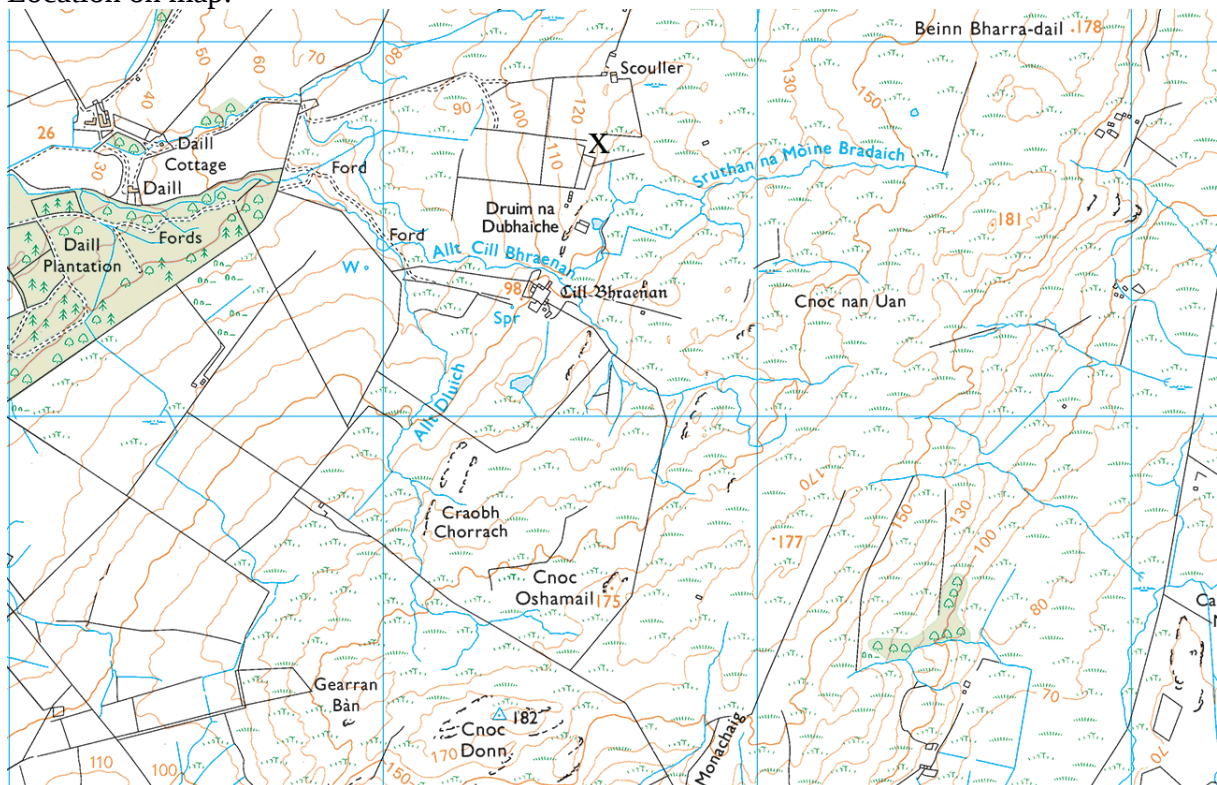
Measurements:

70/280	68/282	64/284	66/280	58/286
62/288	28/284	32/292	40/294	36/292

Stereogram:



Location on map:

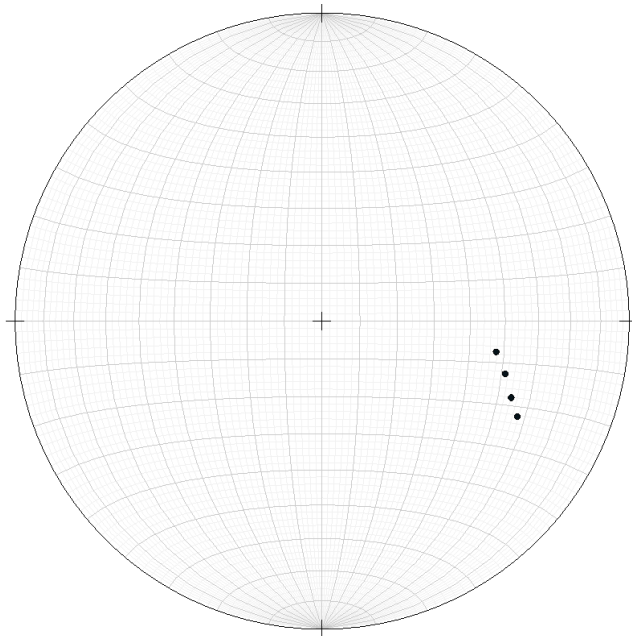


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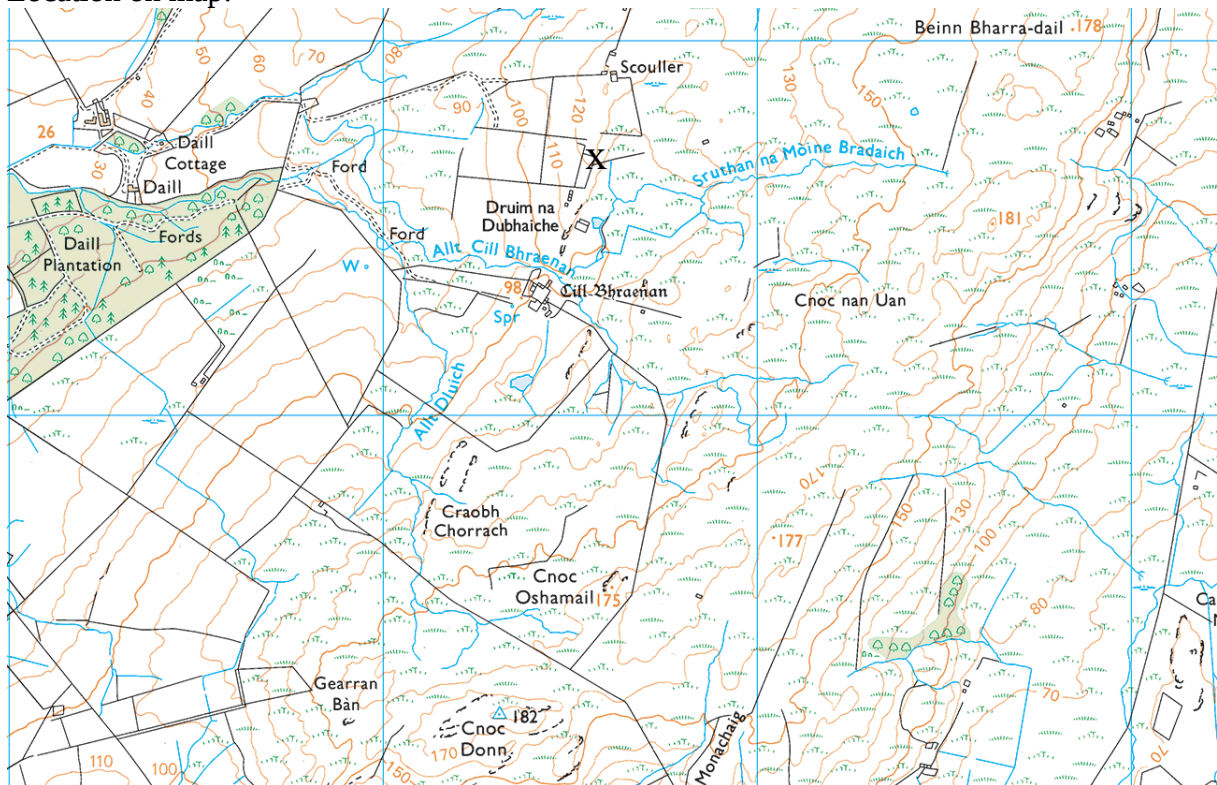
Measurements:

48/280	52/286	56/292	60/296
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Stereogram:



Location on map:

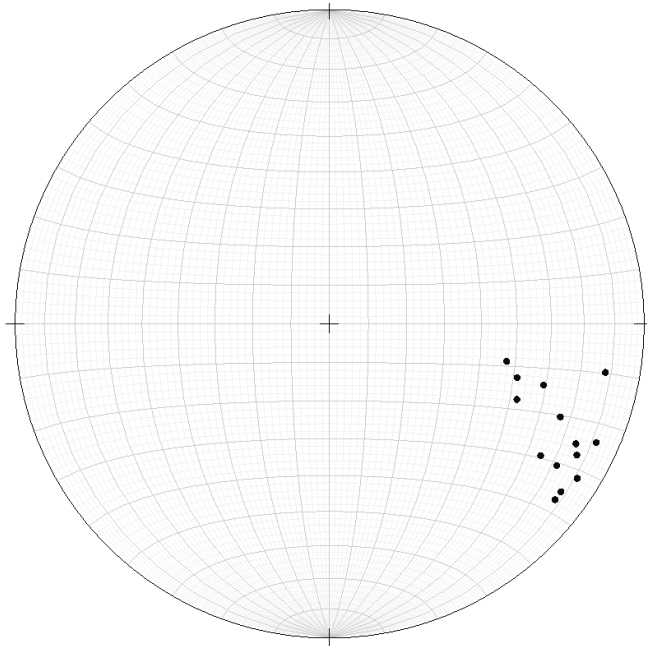


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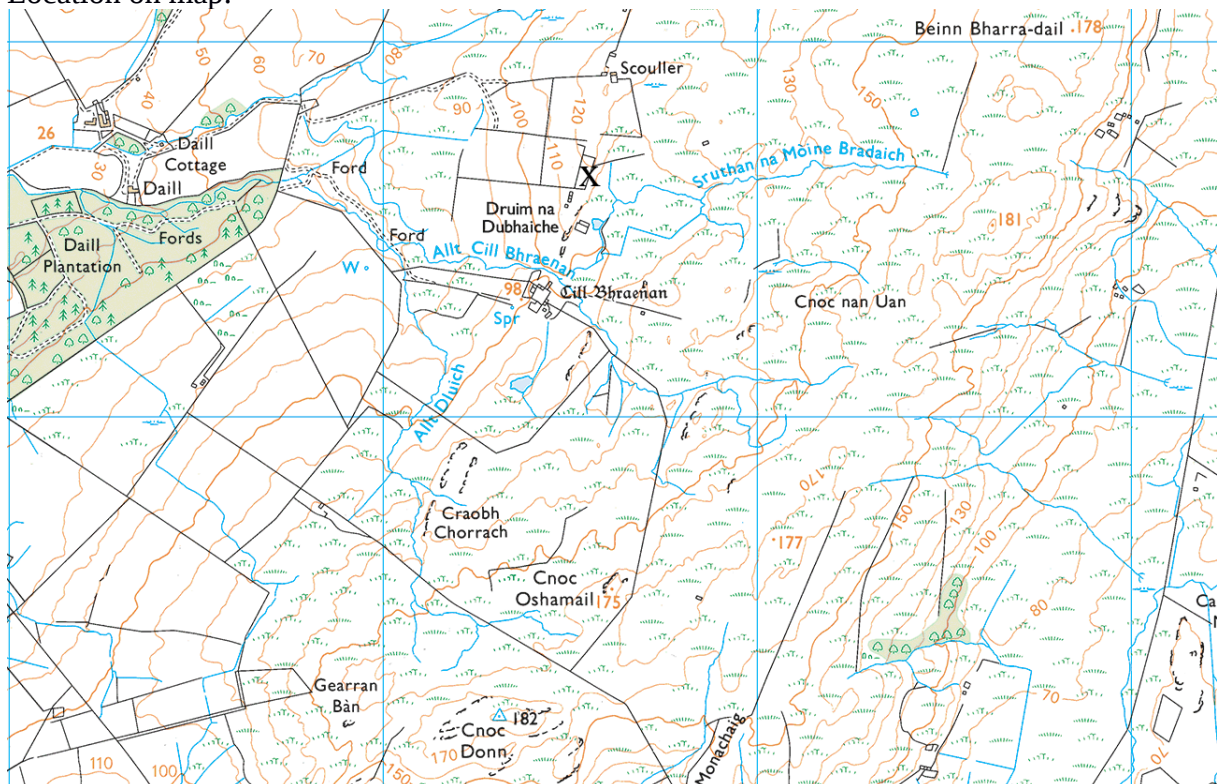
Measurements:

76/296	78/280	82/302	80/306	78/298
82/294	80/308	74/302	68/302	68/292
60/286	52/286	54/292	48/282	

Stereogram:



Location on map:

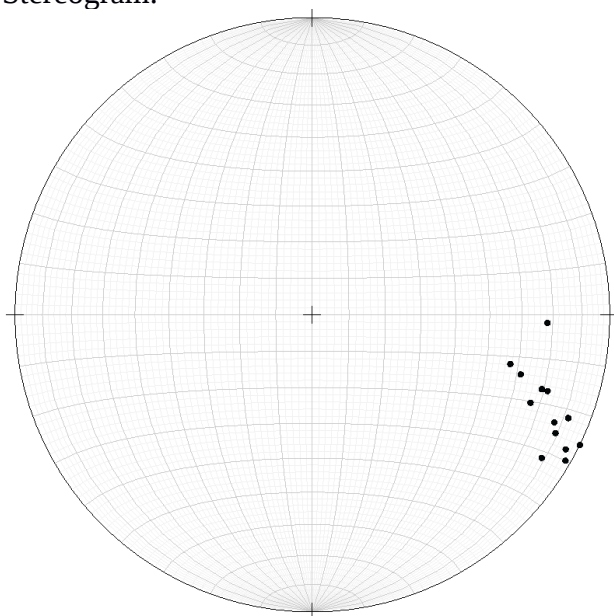


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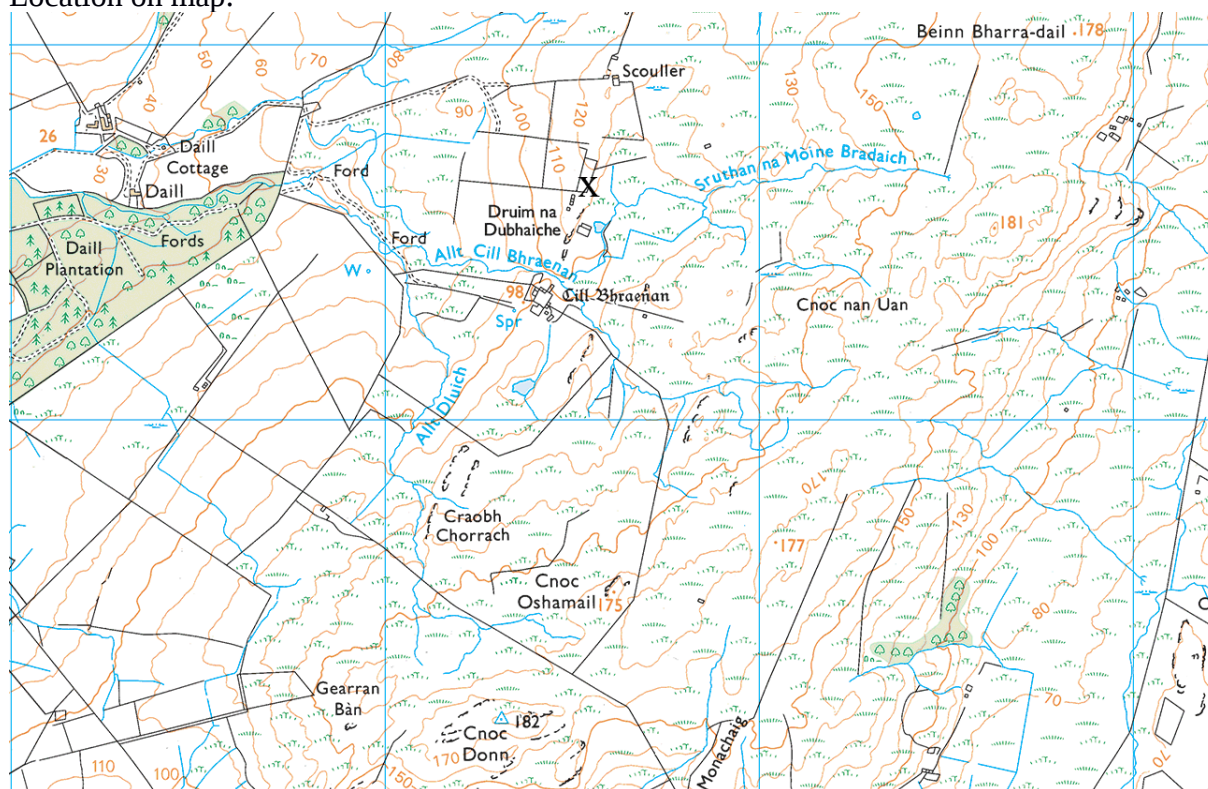
Measurements:

72/288	82/292	80/296	86/298	80/302
88/300	78/294	90/296	68/272	62/286
70/288	68/292	58/284		

Stereogram:



Location on map:



Locality 20:

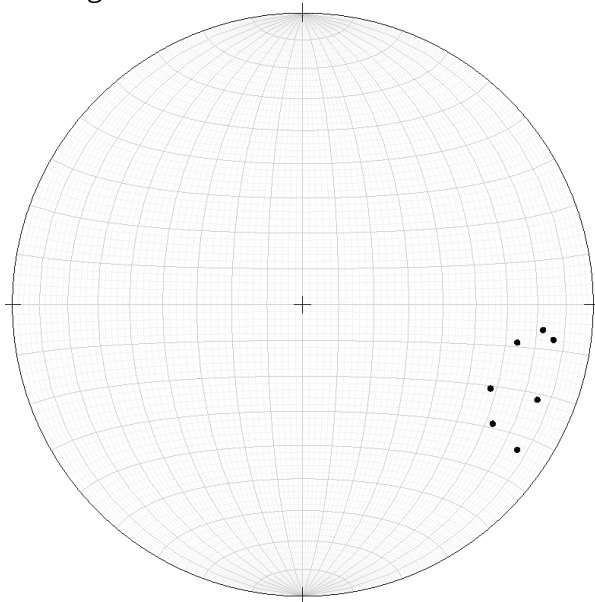
Measurements:

64/280	60/294	66/302	78/304
76/292	76/278	72/276	

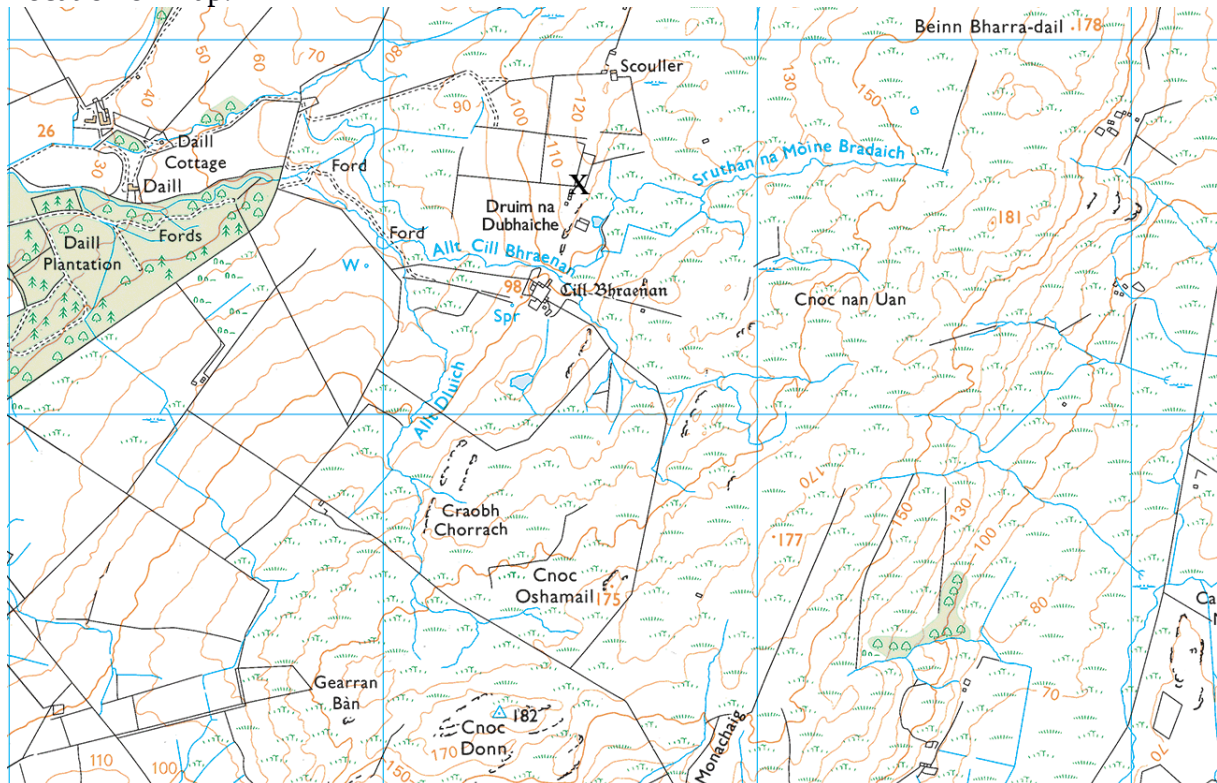
Axial planar cleavage:

312/72	310/70	310/68
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Stereogram:



Location on map:

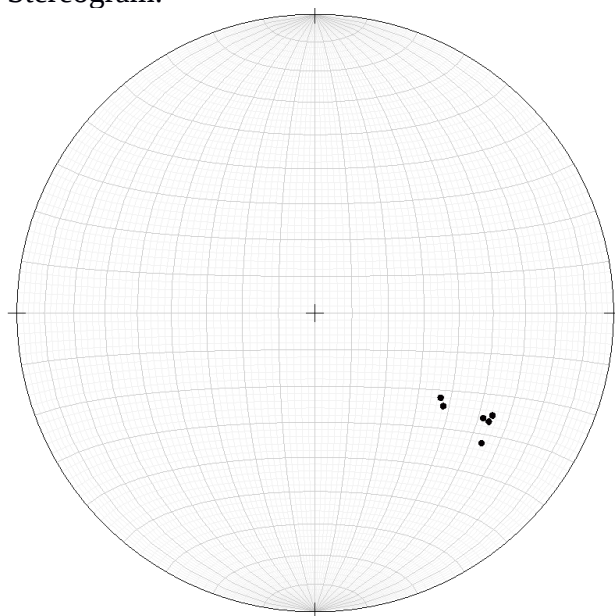


Locality 21:

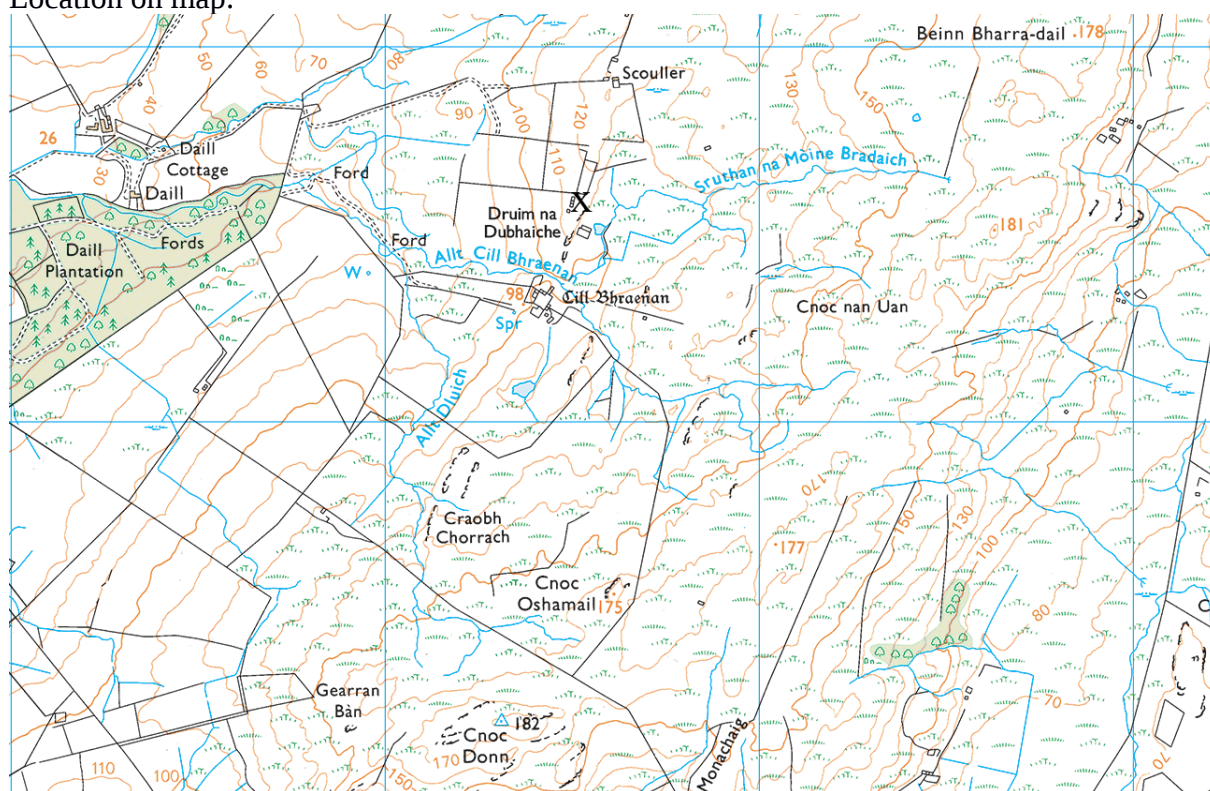
Measurements:

60/308	58/302	58/300	56/302
58/302	44/306	42/304	

Stereogram:



Location on map:

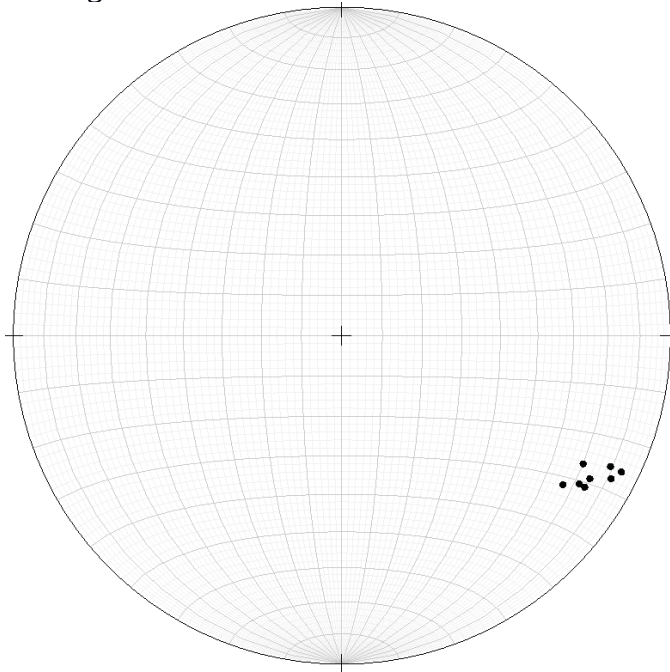


Locality 22:

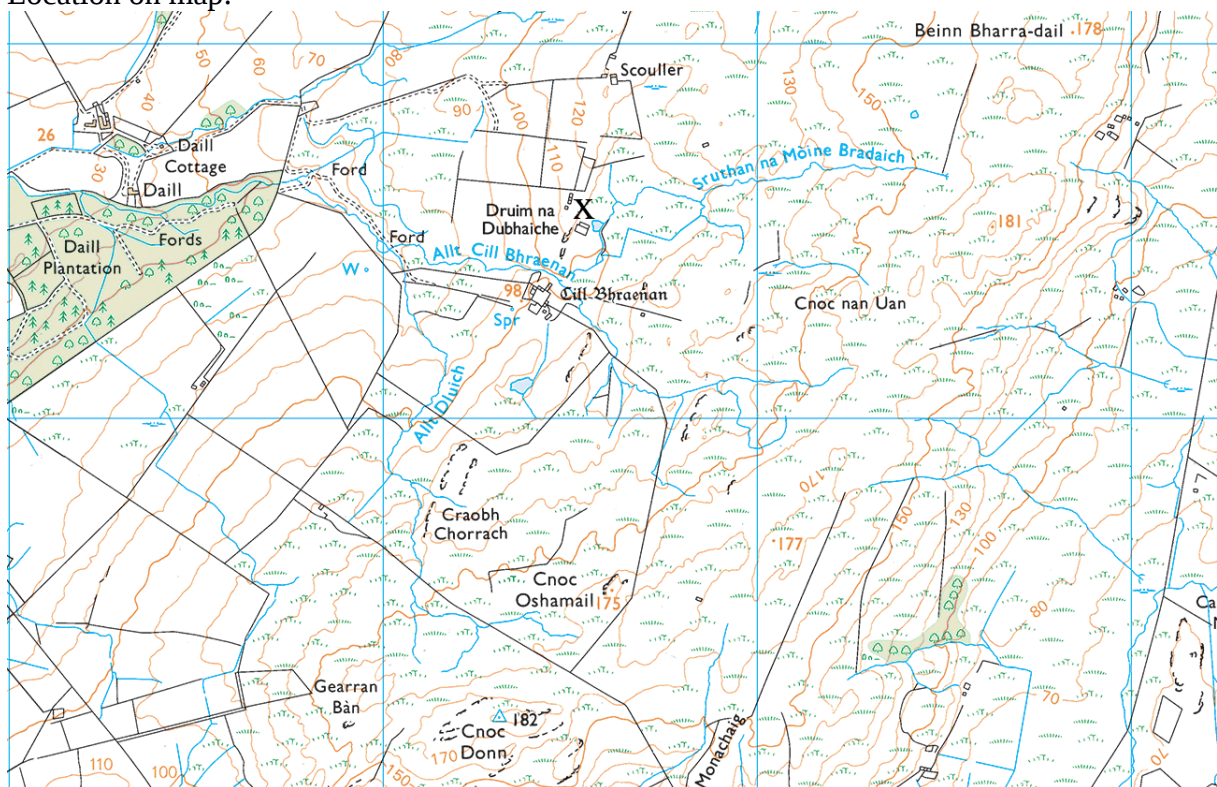
Measurements:

72/298	70/304	74/302	76/300	84/296
76/302	82/298	80/296	70/304	

Stereogram:



Location on map:

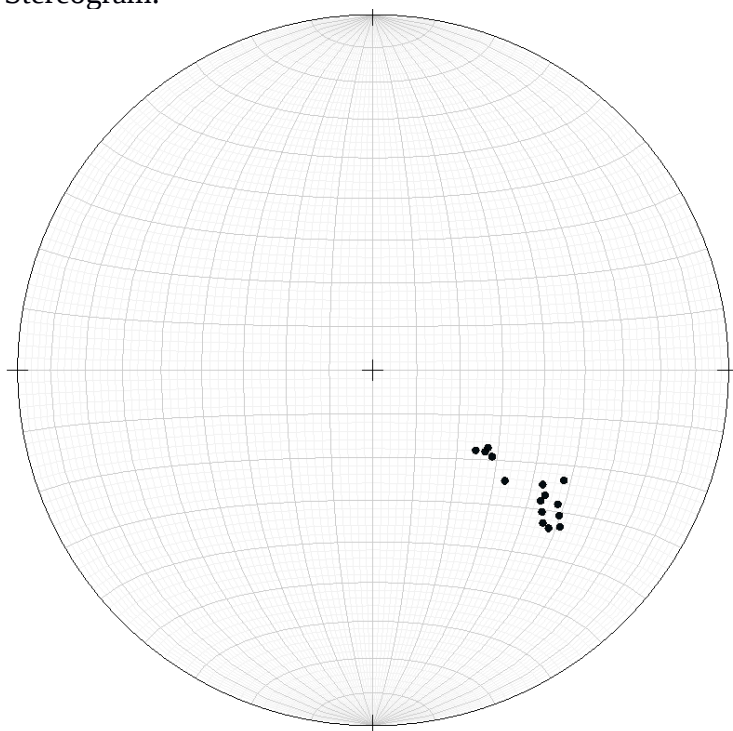


Locality 23:

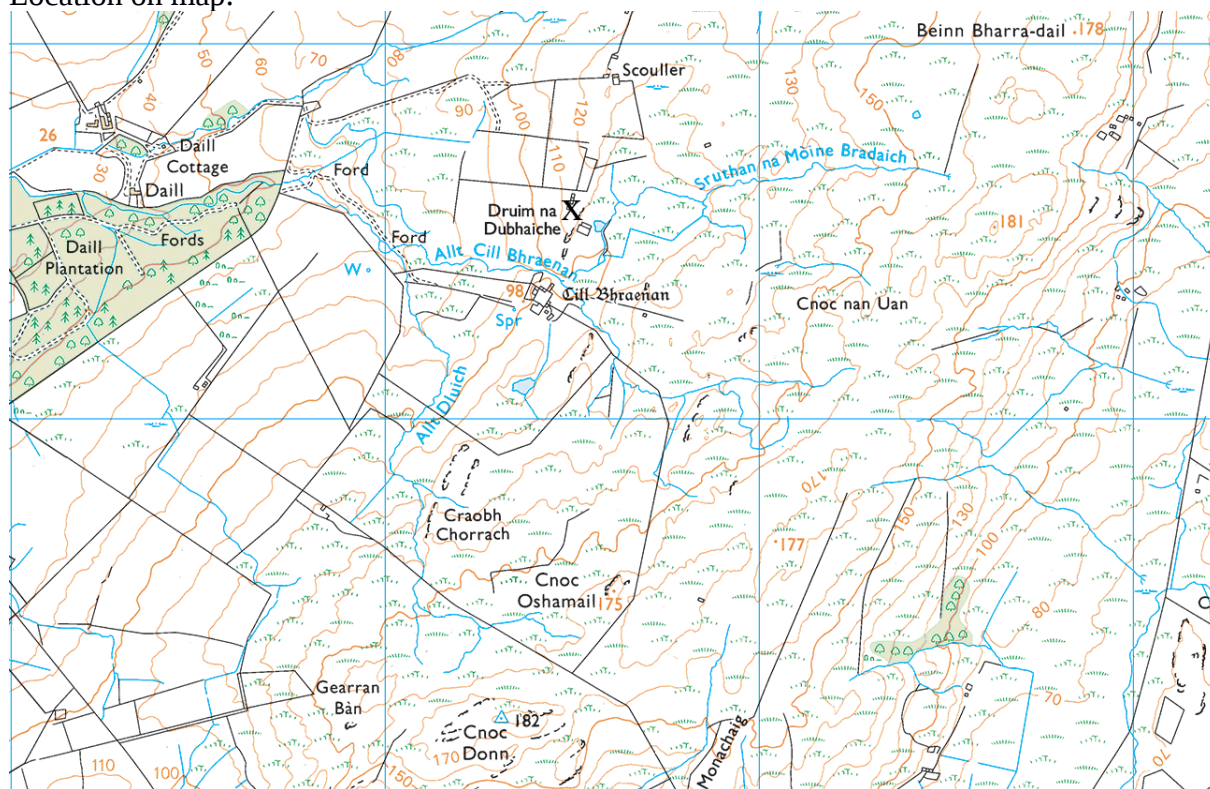
Measurements:

52/300	48/304	56/312	50/306	56/308	58/310
54/312	52/310	50/308	54/306	50/306	40/310
32/306	34/306	32/304	30/308	34/306	

Stereogram:



Location on map:

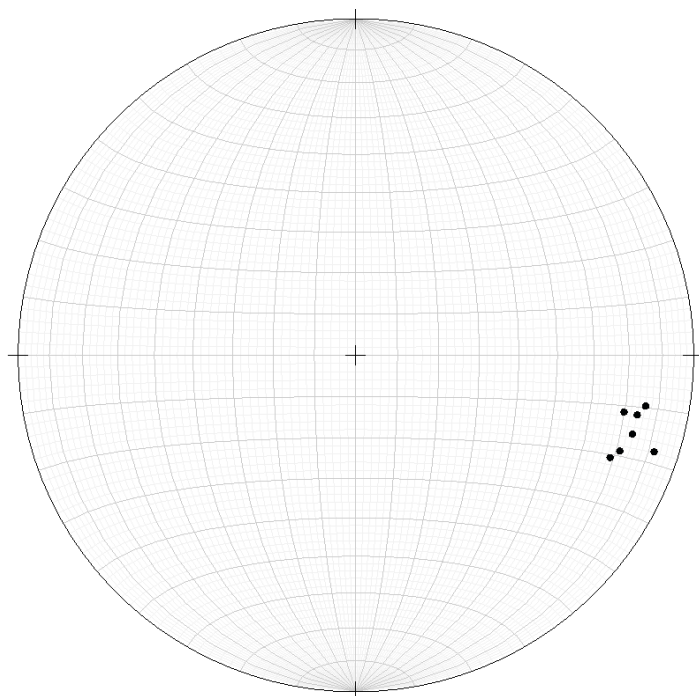


Locality 24:

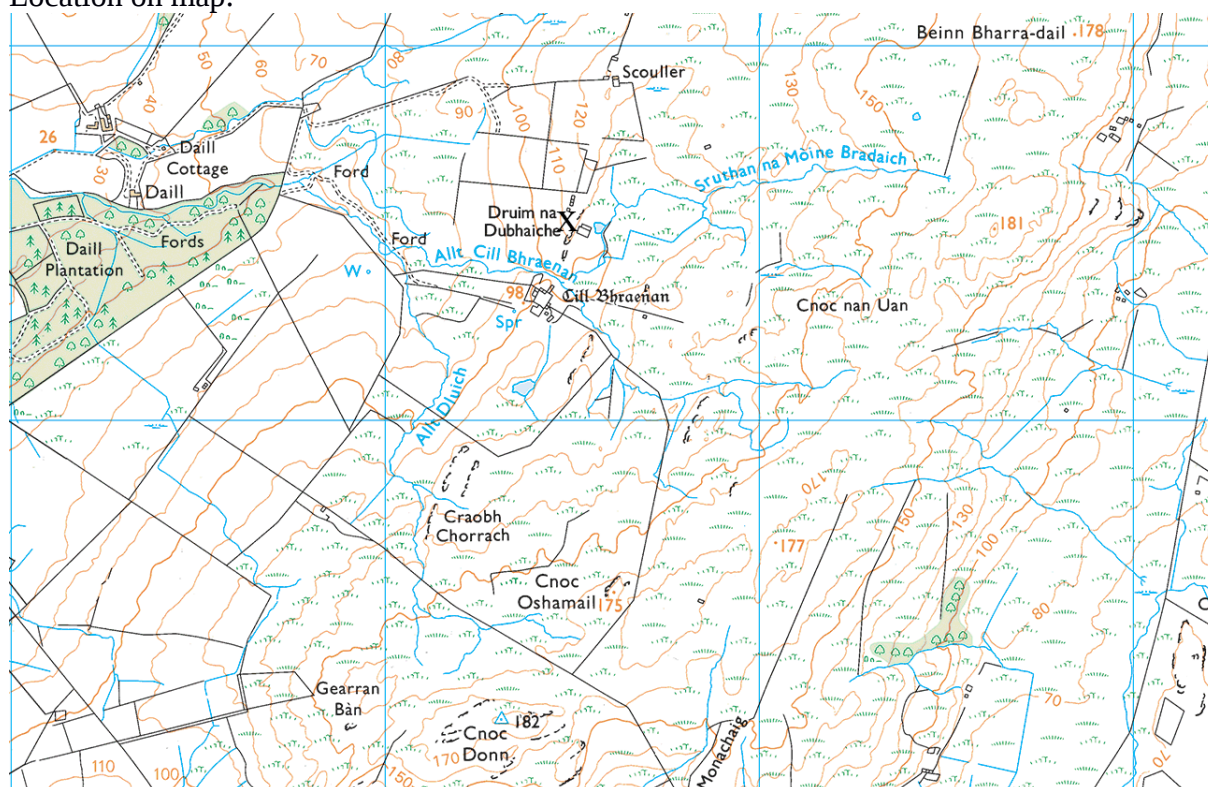
Measurements:

70/292	82/288	74/286	70/282	72/290
74/282	76/280			

Stereogram:



Location on map:

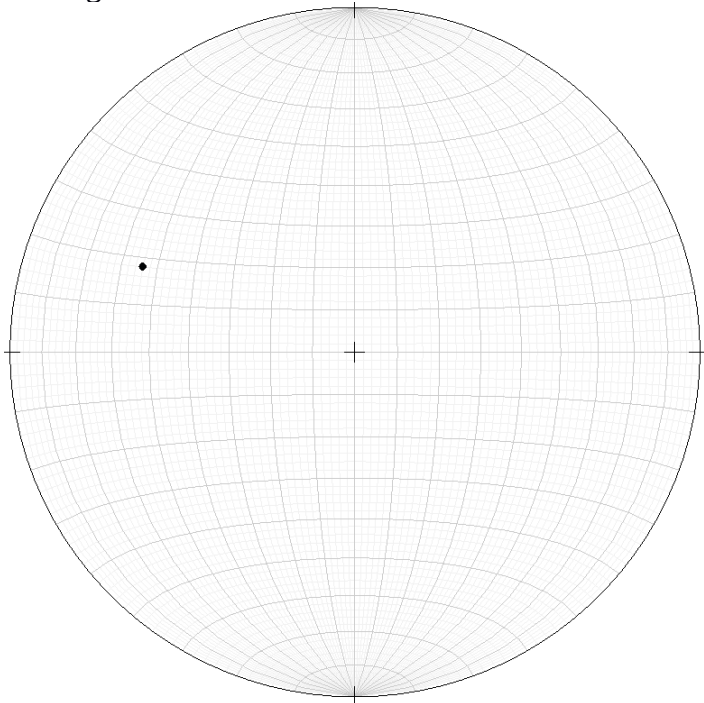


Locality 25:

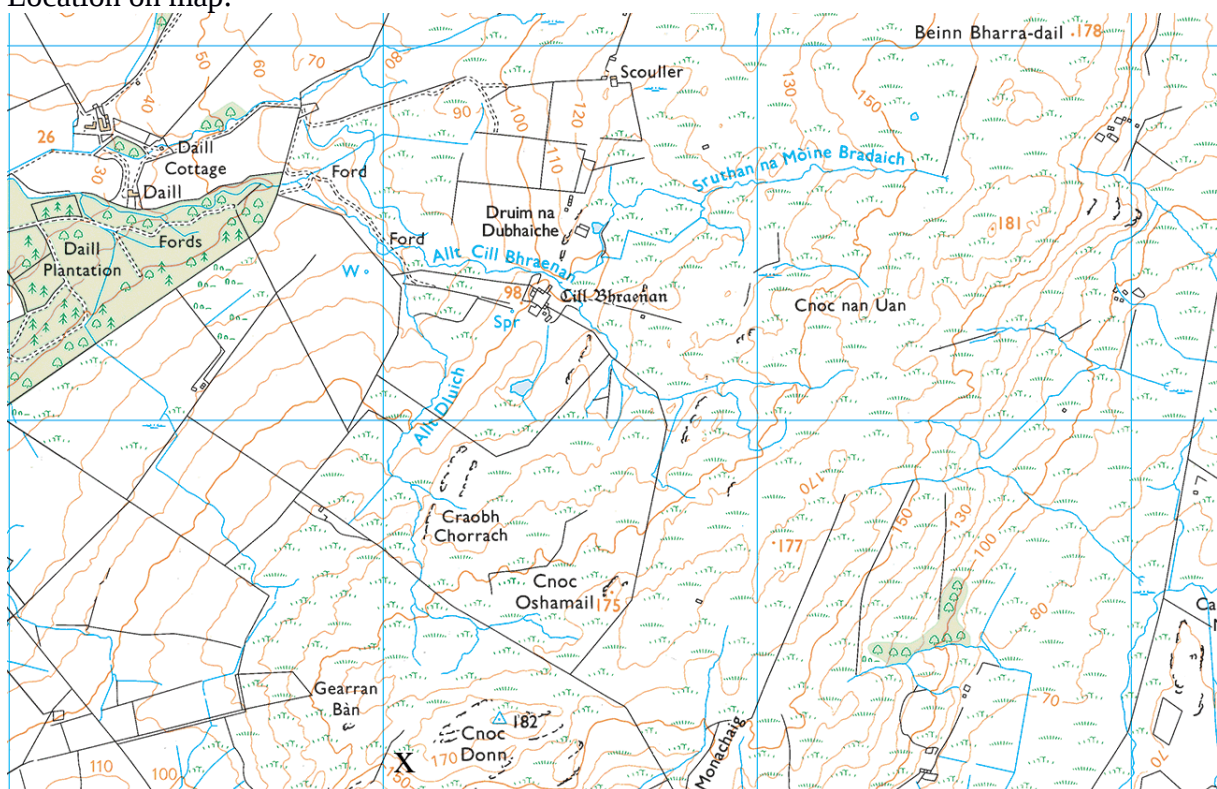
Measurements:

56/112

Stereogram:



Location on map:

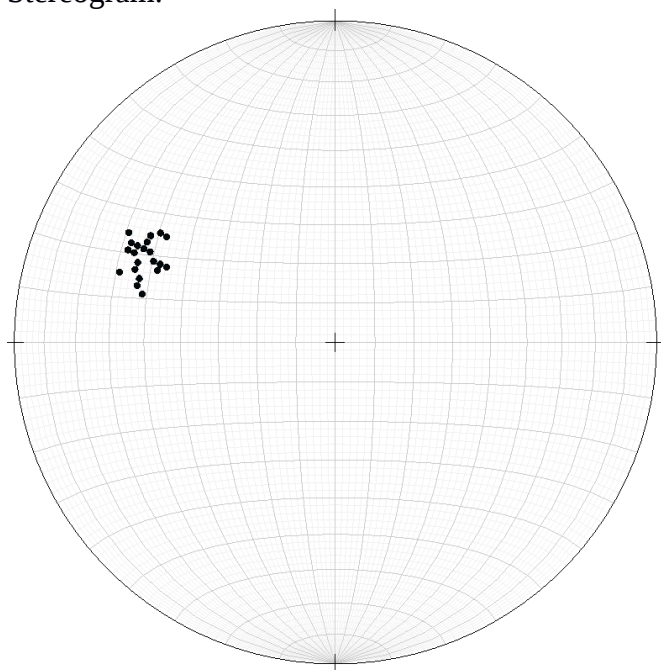


Locality 26:

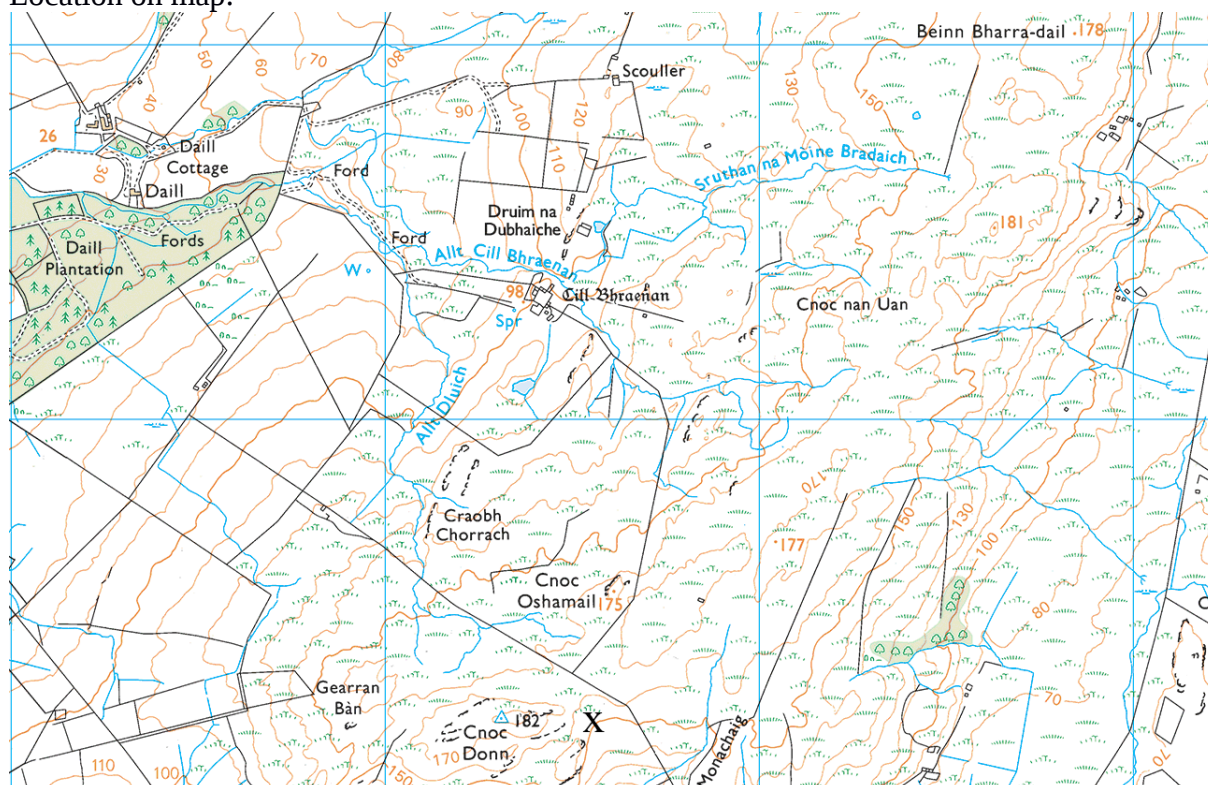
Measurements:

54/116	60/116	62/118	58/116	60/108	56/112
58/114	56/120	50/112	48/114	56/118	54/122
62/118	52/122	52/114	54/116	56/116	60/114
56/110	50/114	54/108	54/106	52/104	

Stereogram:



Location on map:

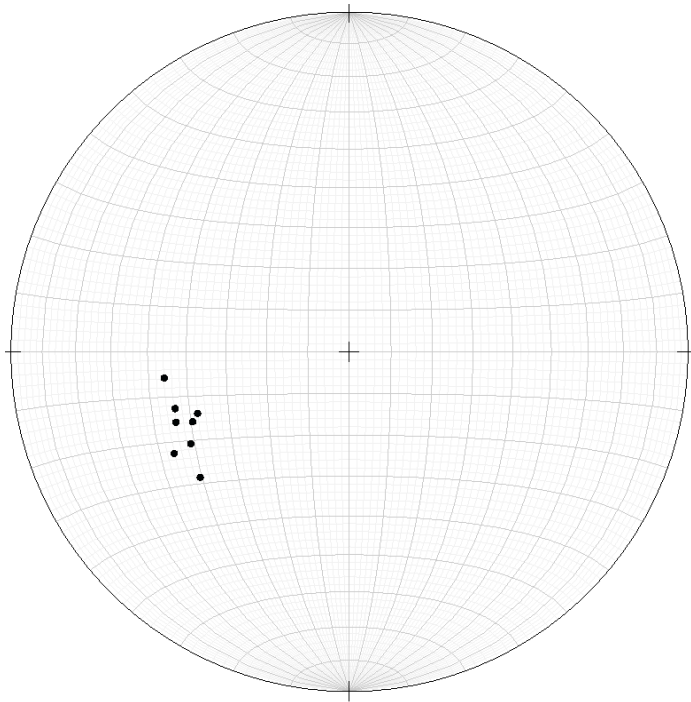


Locality 27:

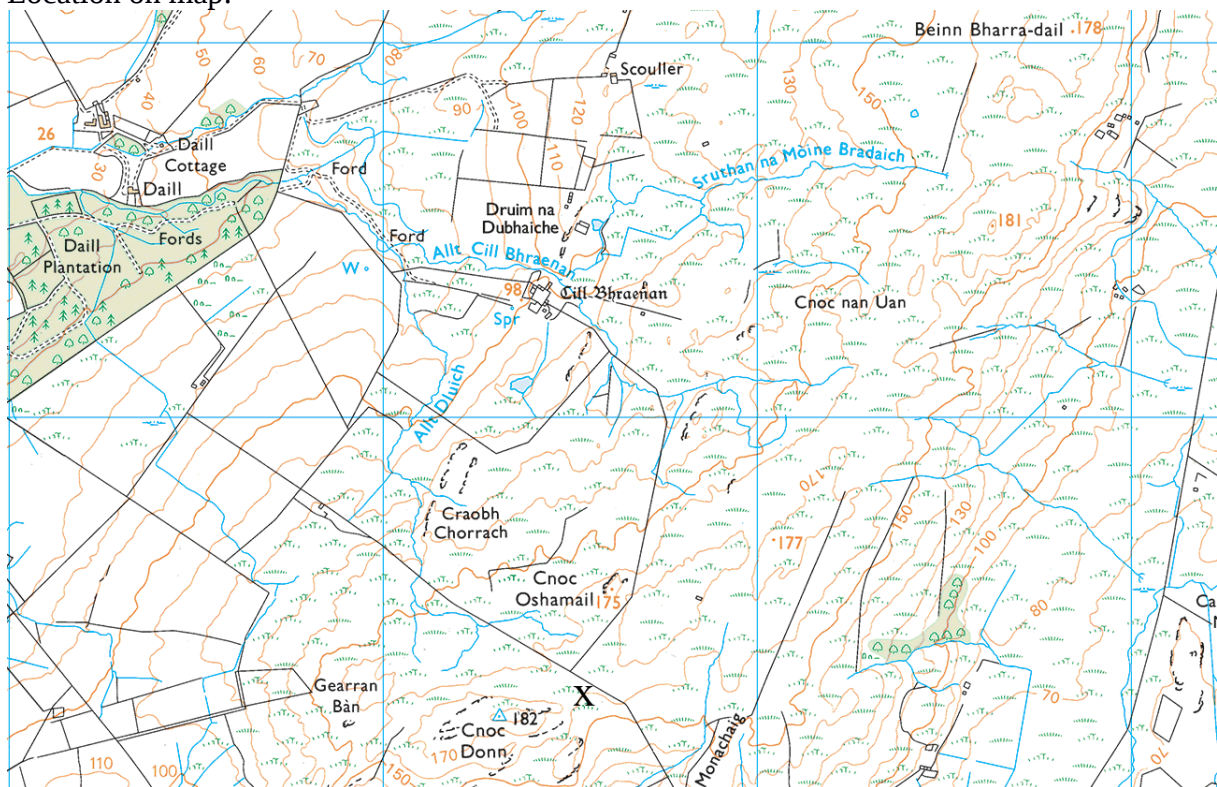
Measurements:

45/060	45/072	42/066	46/068
40/068	46/082	50/060	48/050

Stereogram:



Location on map:

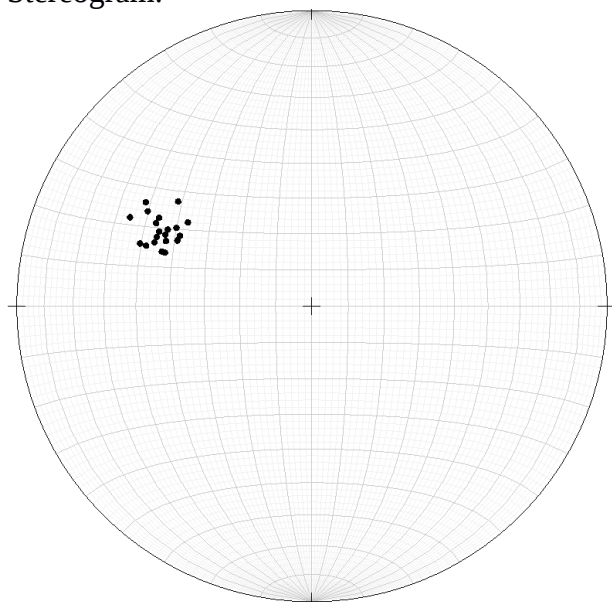


Locality 28:

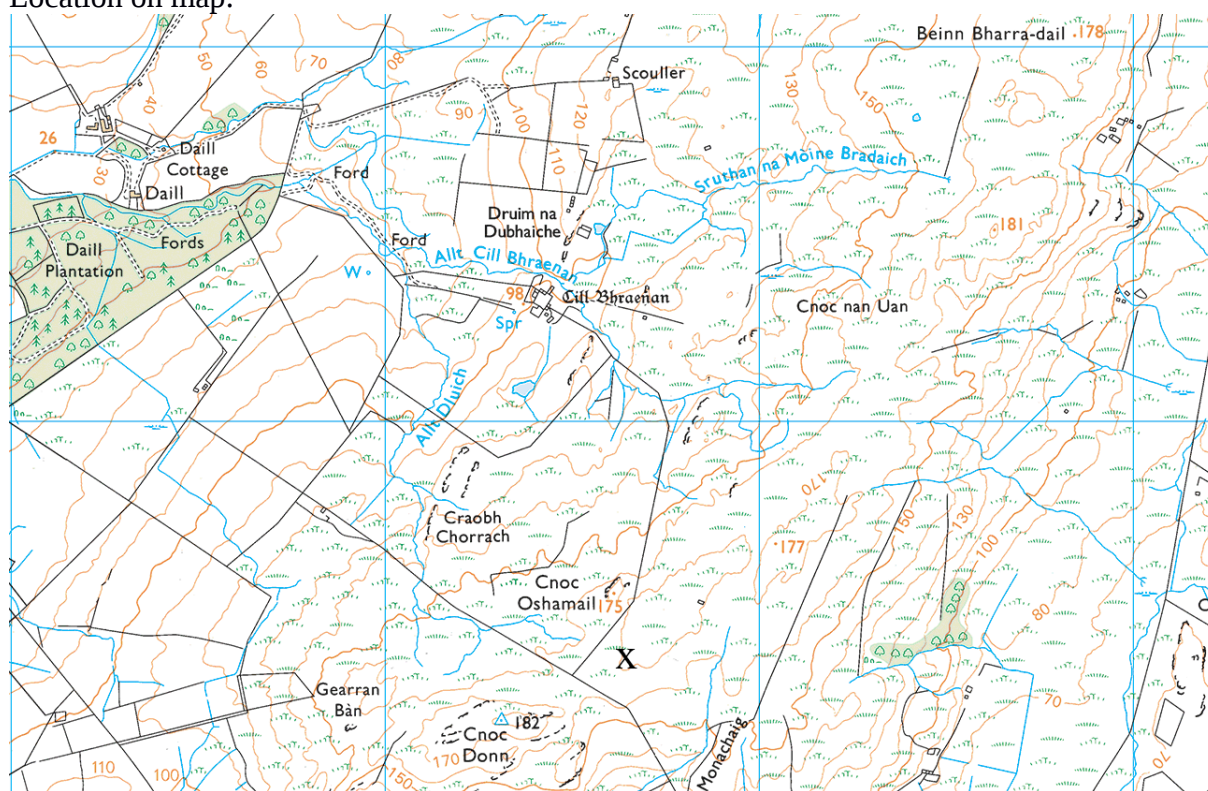
Measurements:

45/110	42/118	45/114	48/116	48/112	50/110
52/110	48/114	46/116	42/116	44/110	48/128
54/120	56/122	42/124	54/120	46/118	50/120
58/116	50/110	48/116	42/118	44/120	50/118

Stereogram:



Location on map:

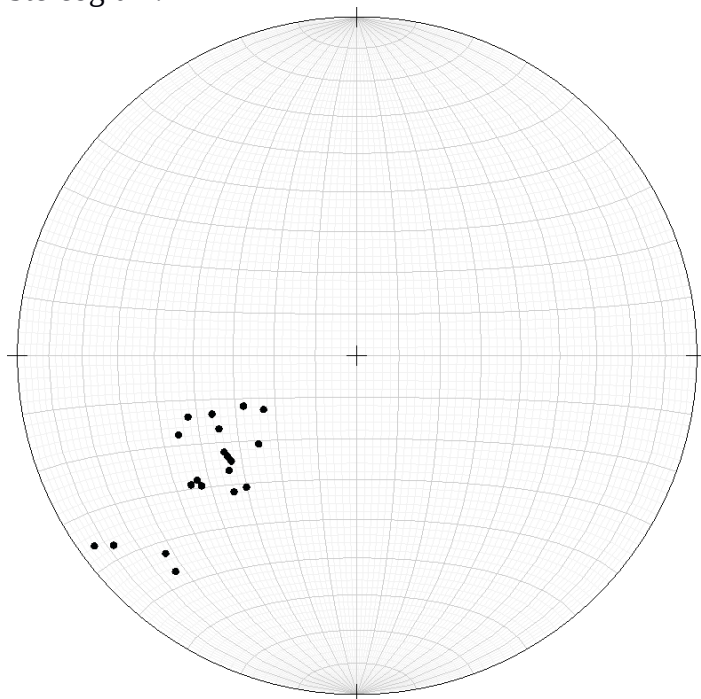


Locality 29:

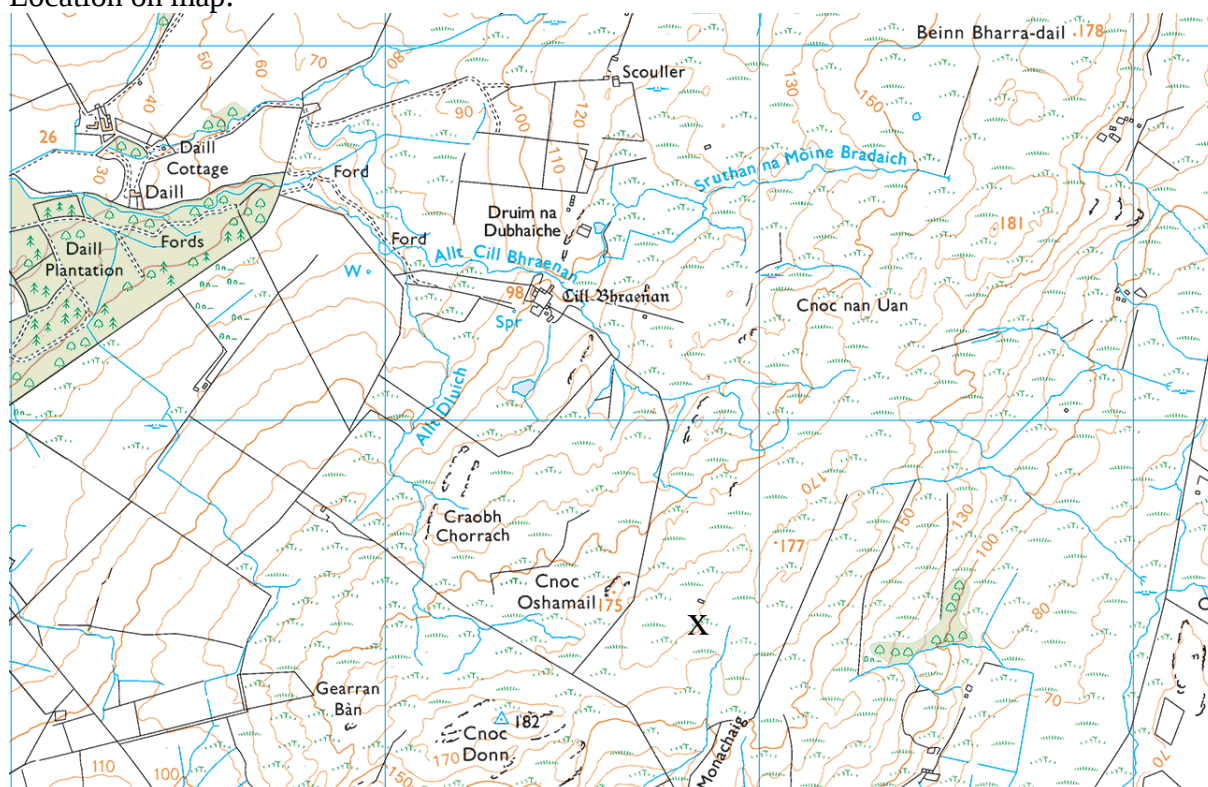
Measurements:

42/040	45/042	40/050	38/068	50/050
44/070	48/066	50/052	70/044	72/040
80/052	86/054	52/052	32/048	40/054
42/048	40/052	38/062	26/060	30/066

Stereogram:



Location on map:

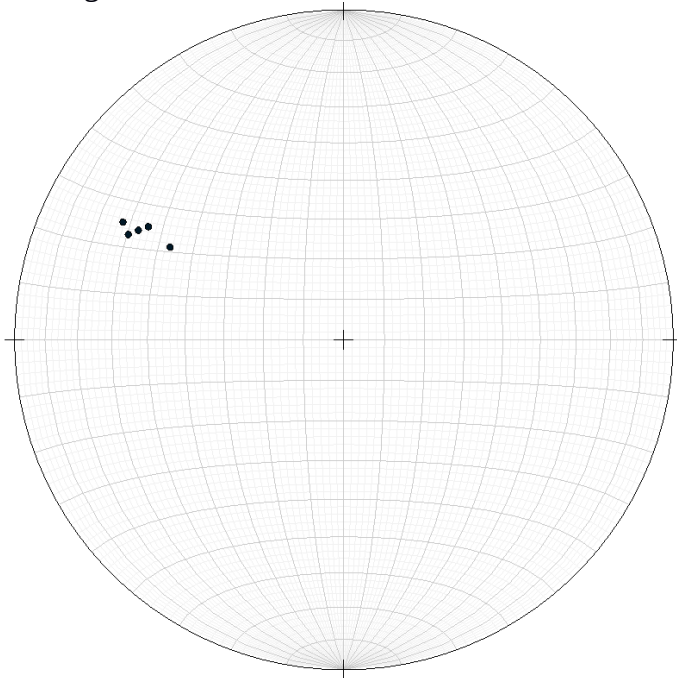


Locality 30:

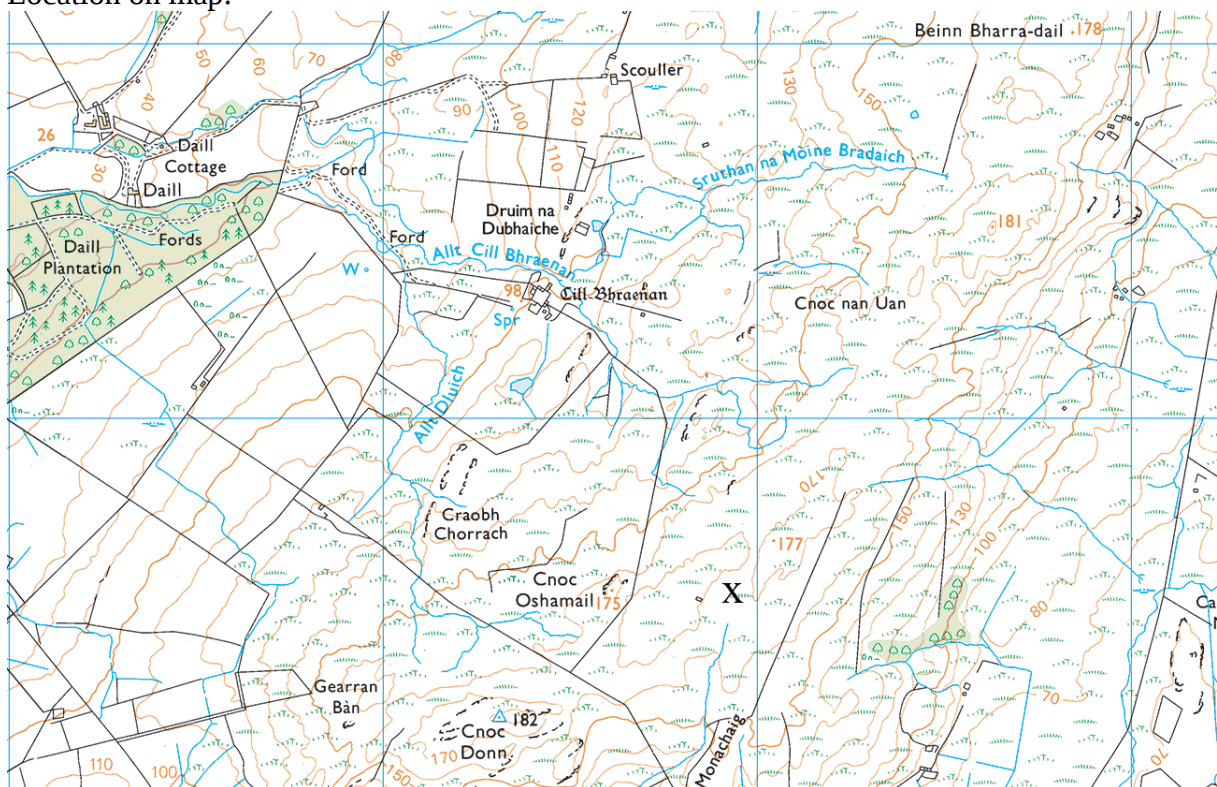
Measurements:

62/116	60/118	65/118	50/118	58/120
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Stereogram:



Location on map:

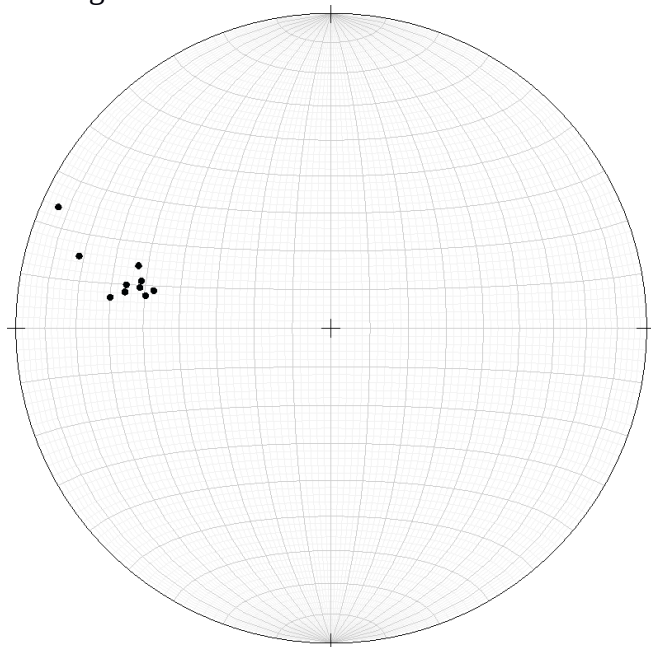


Locality 31:

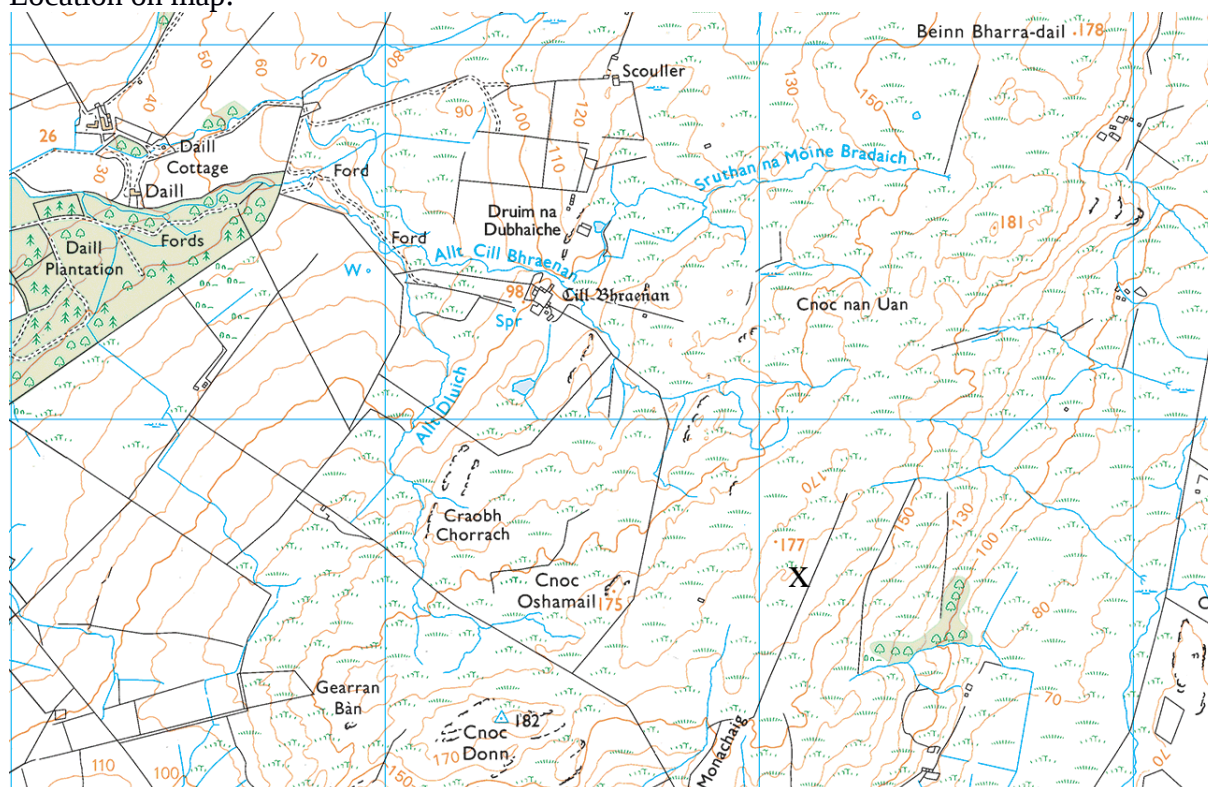
Measurements:

50/100	52/102	48/102	52/104	56/102	56/102
54/108	60/098	56/100	54/108	72/106	84/114

Stereogram:



Location on map:

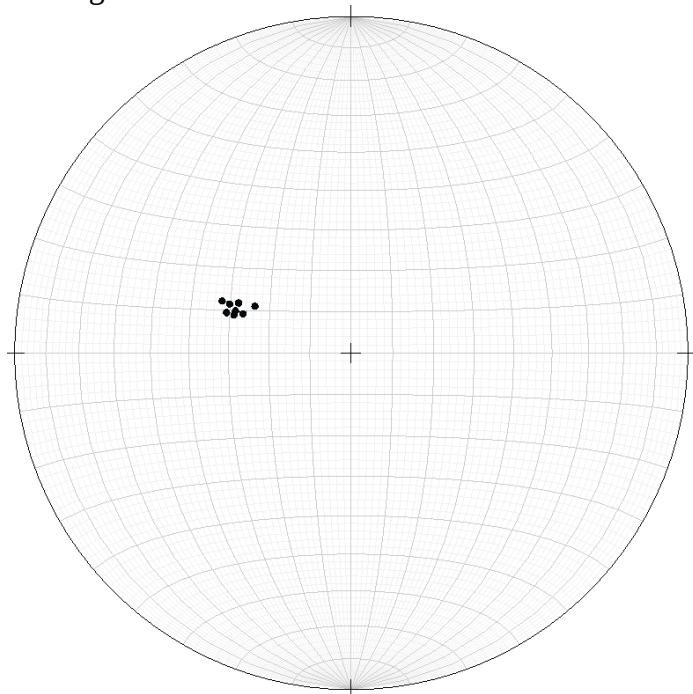


Locality 32:

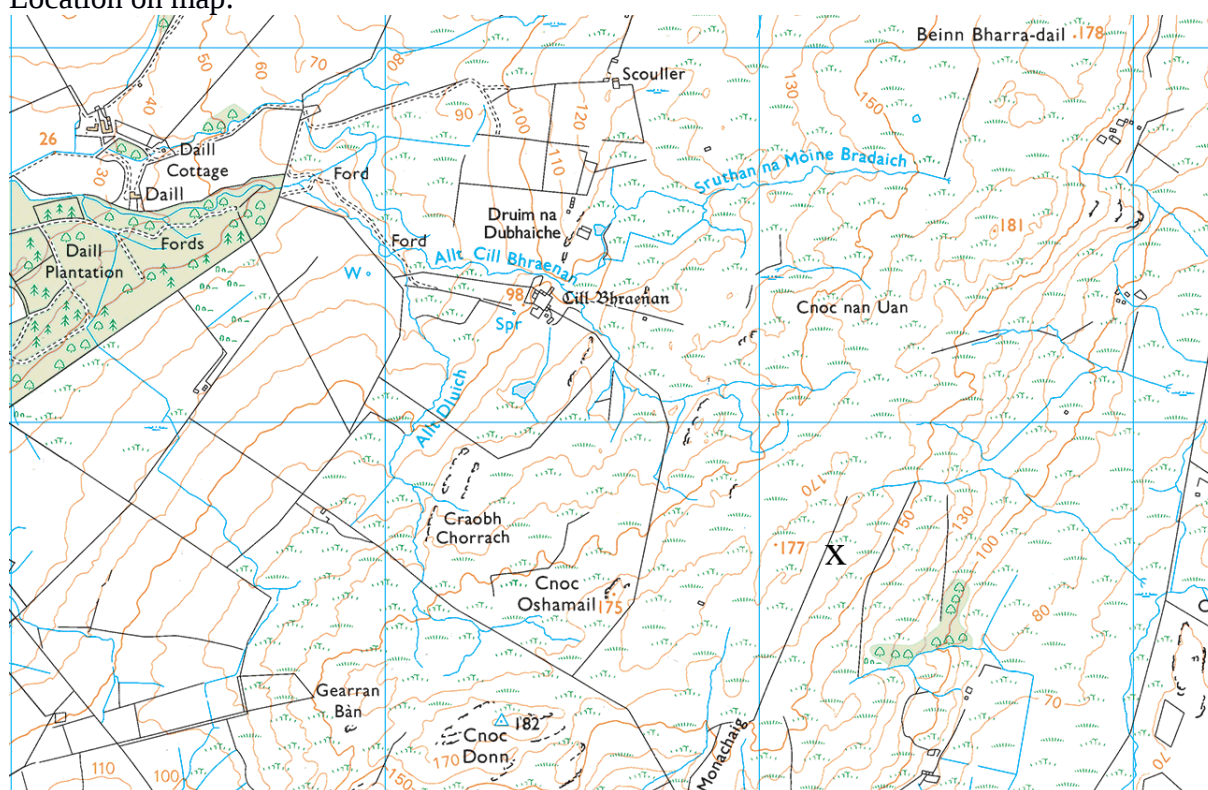
Measurements:

28/110	30/110	32/108	34/112	30/114
30/108	32/112	34/112	30/114	26/116

Stereogram:



Location on map:

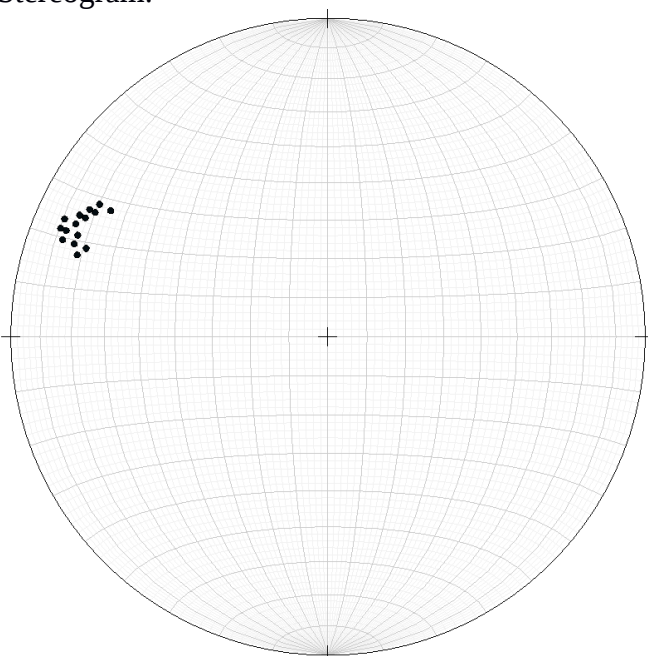


Locality 33:

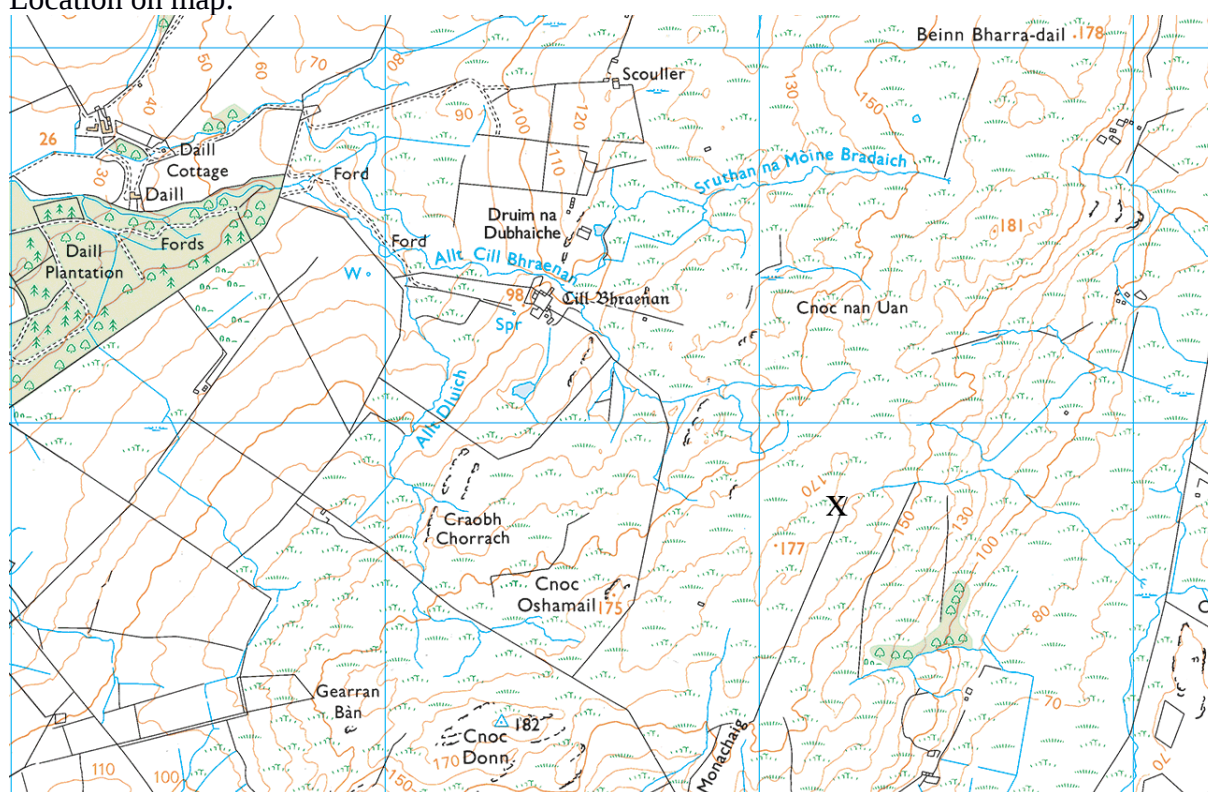
Measurements:

80/112	72/108	74/110	76/116	78/112
78/110	70/110	76/114	74/112	80/114
72/118	68/120	74/116	74/118	72/120

Stereogram:



Location on map:

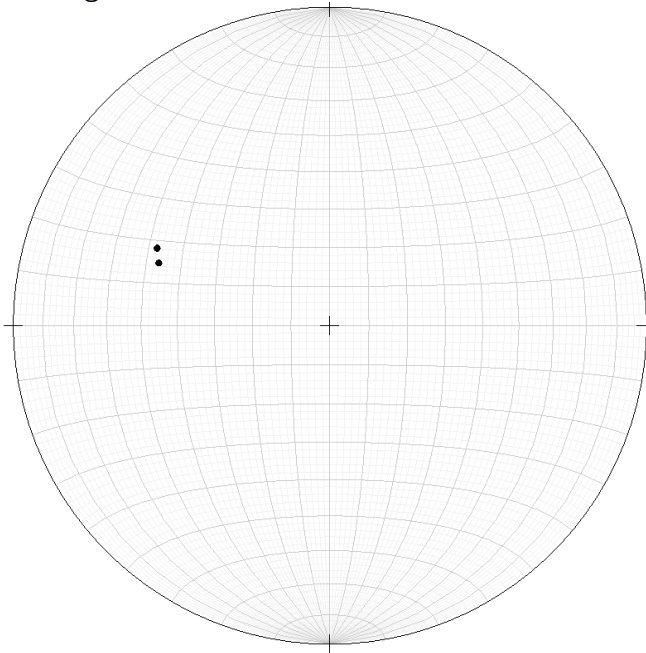


Locality 34:

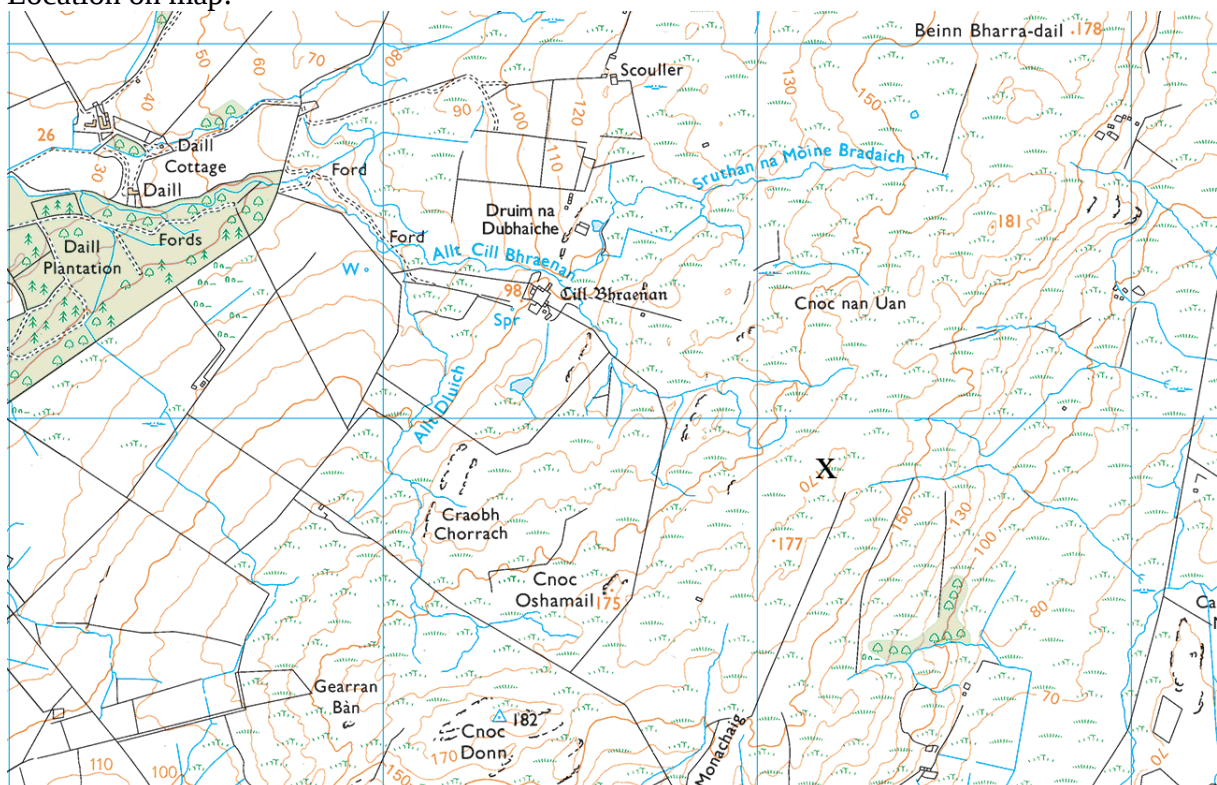
Measurements:

48/110	50/114
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Stereogram:



Location on map:

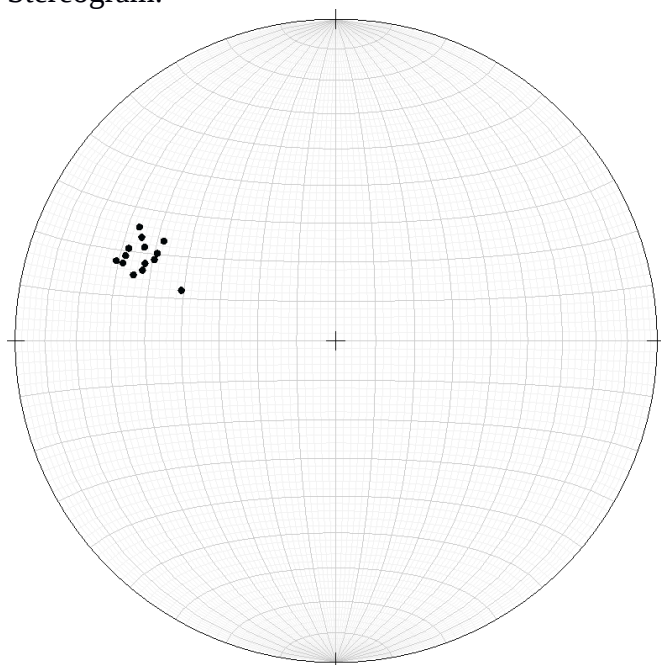


Locality 35:

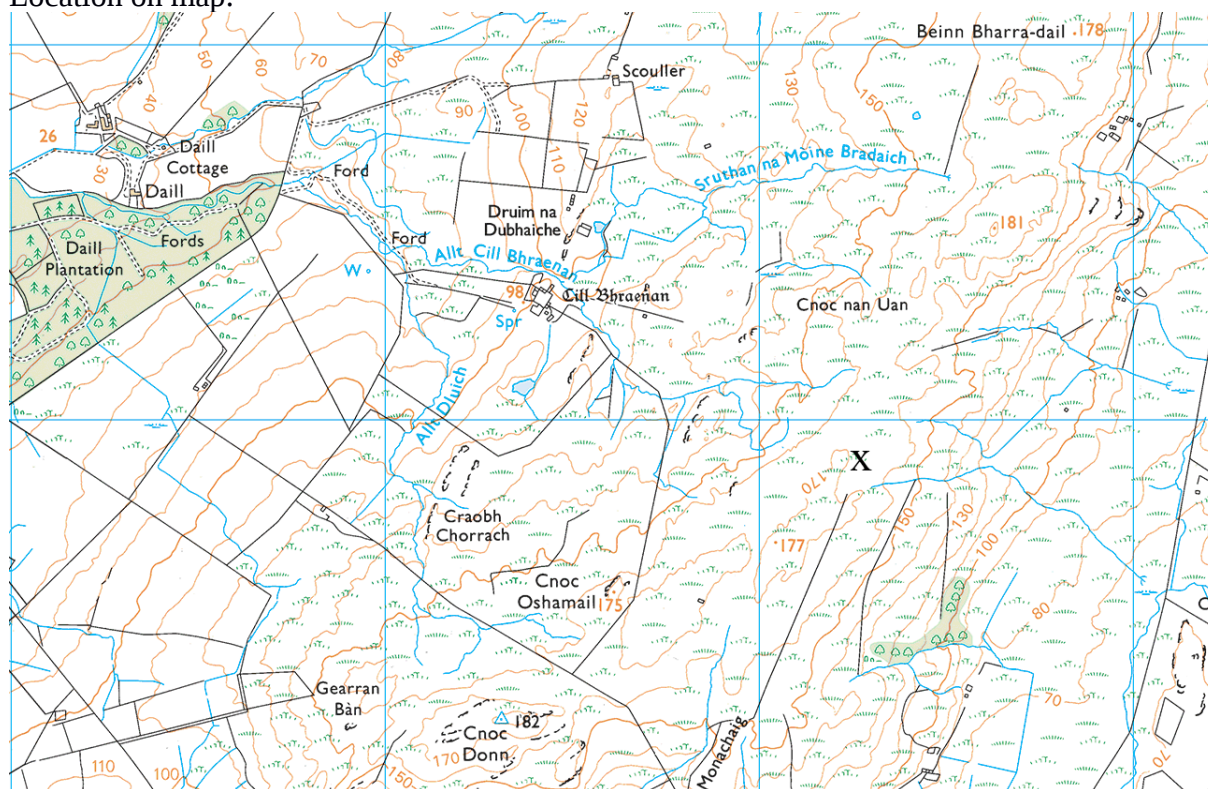
Measurements:

58/118	52/120	56/116	60/114	60/120
56/108	54/110	54/112	52/116	42/108
52/114	56/116	60/112	62/110	60/110

Stereogram:



Location on map:

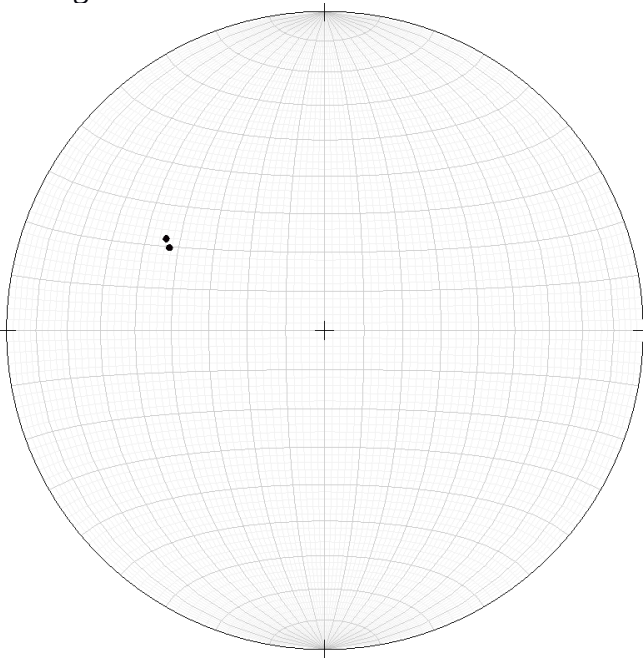


Locality 36:

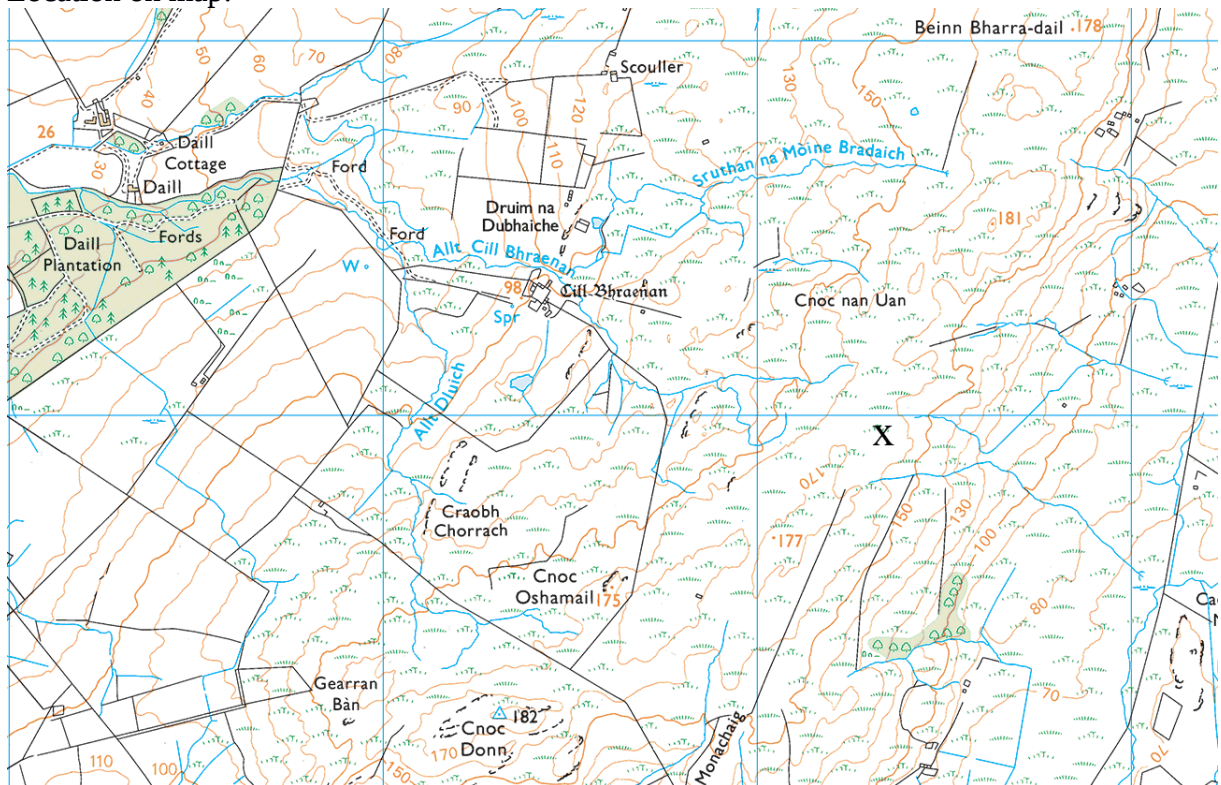
Measurements:

46/118	48/120
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Stereogram:



Location on map:

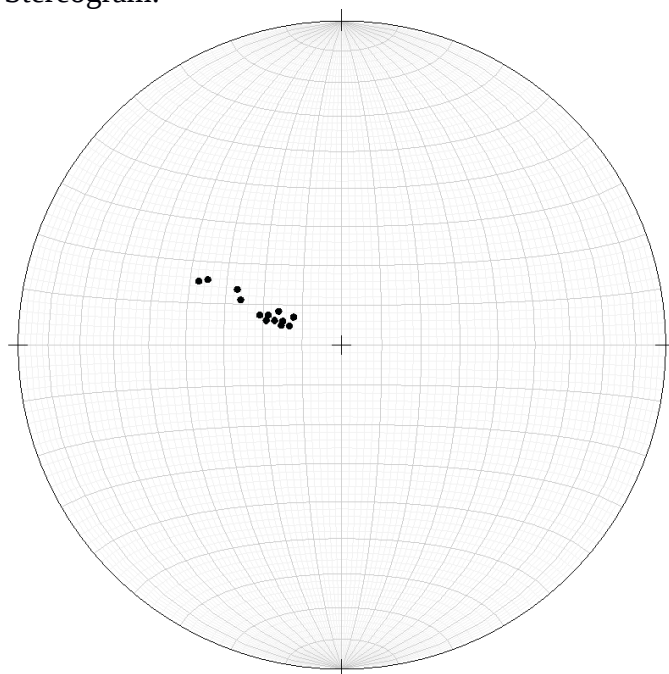


Locality 37:

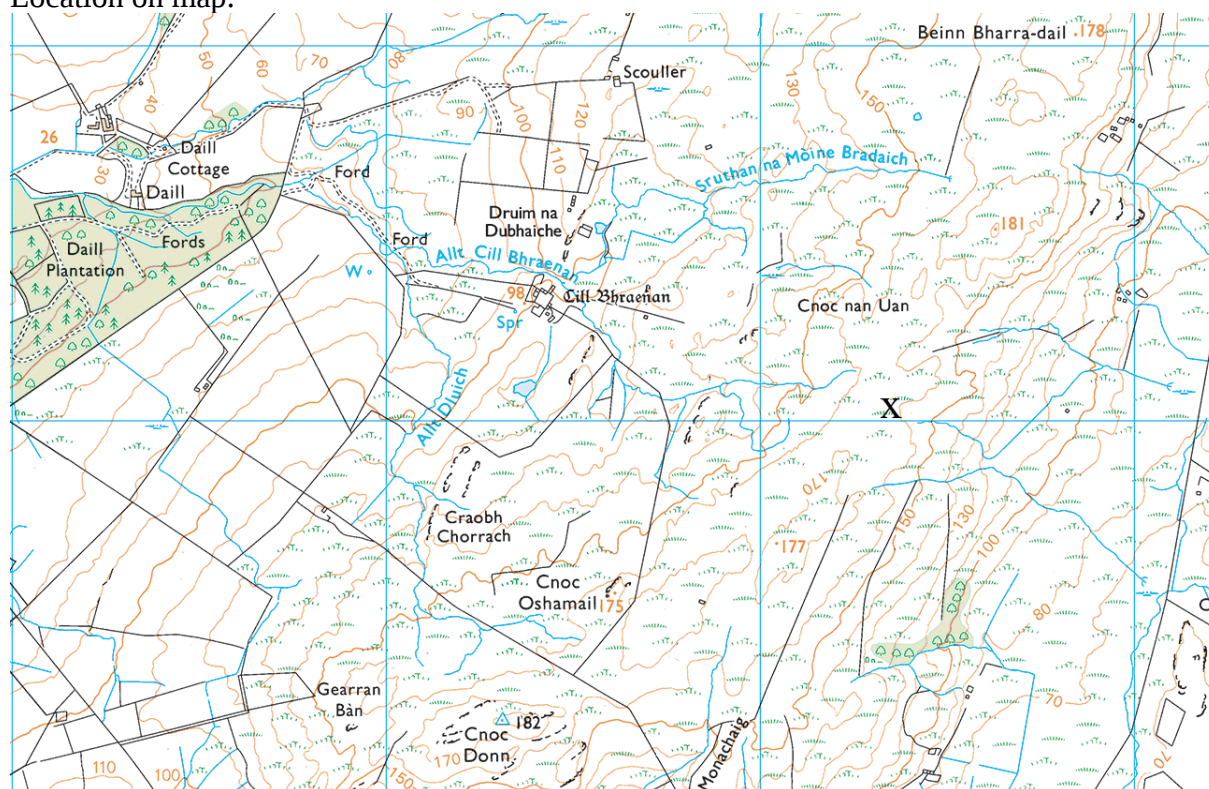
Measurements:

14/120	18/118	28/114	30/118	38/116
20/112	20/114	18/110	22/110	20/108
14/110	16/108	16/112		

Stereogram:



Location on map:

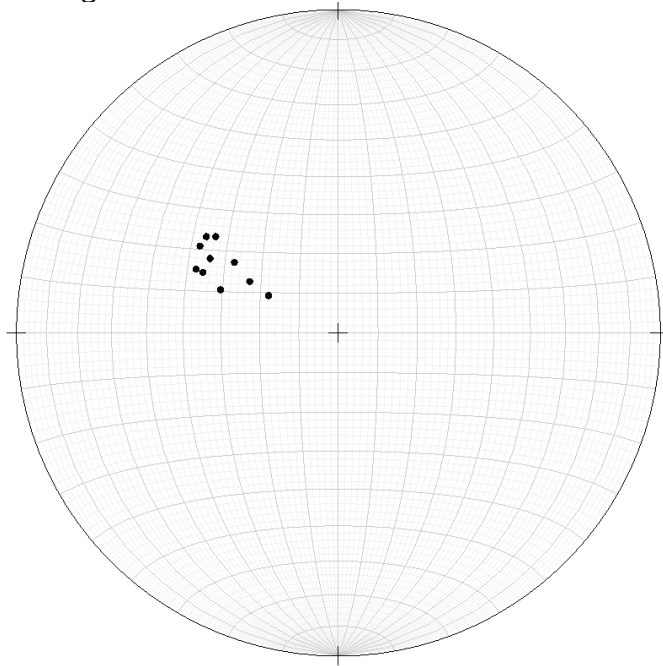


Locality 38:

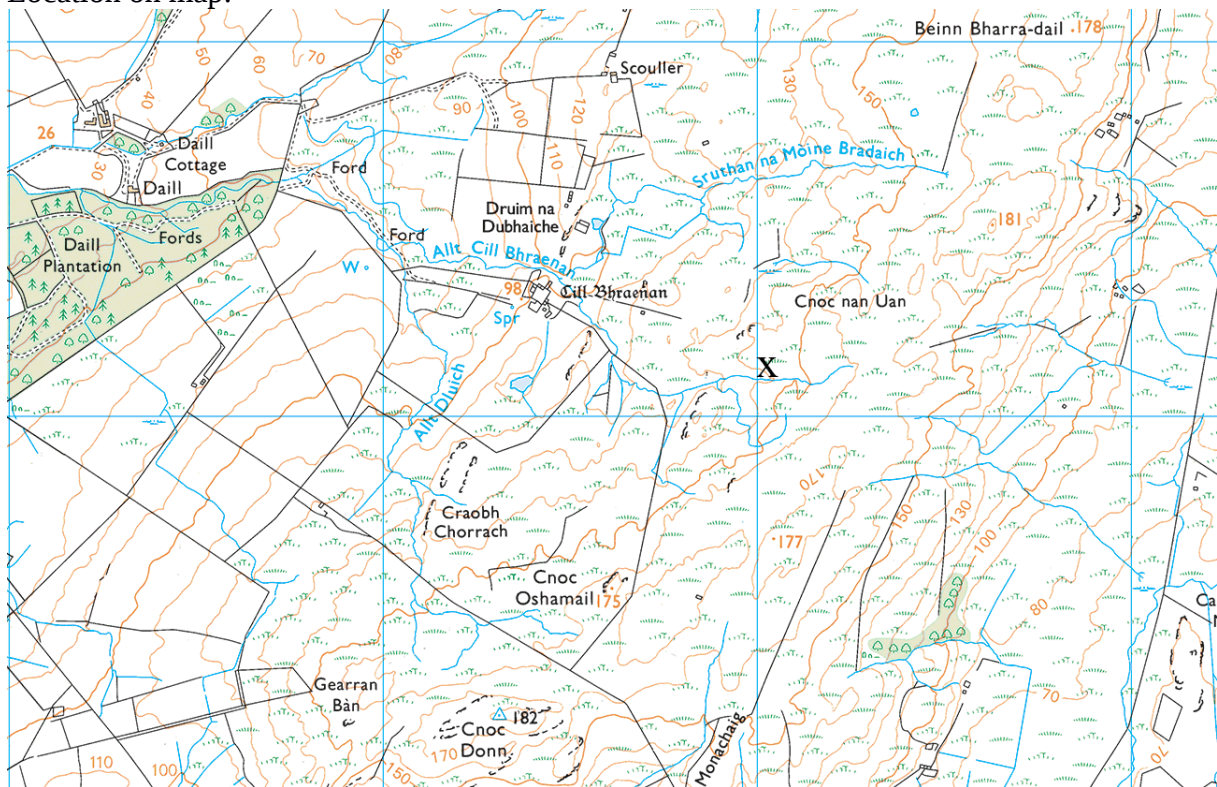
Measurements:

38/120	32/124	40/128	26/120	20/118	42/126
42/122	20/118	32/110	38/114	40/114	

Stereogram:



Location on map:

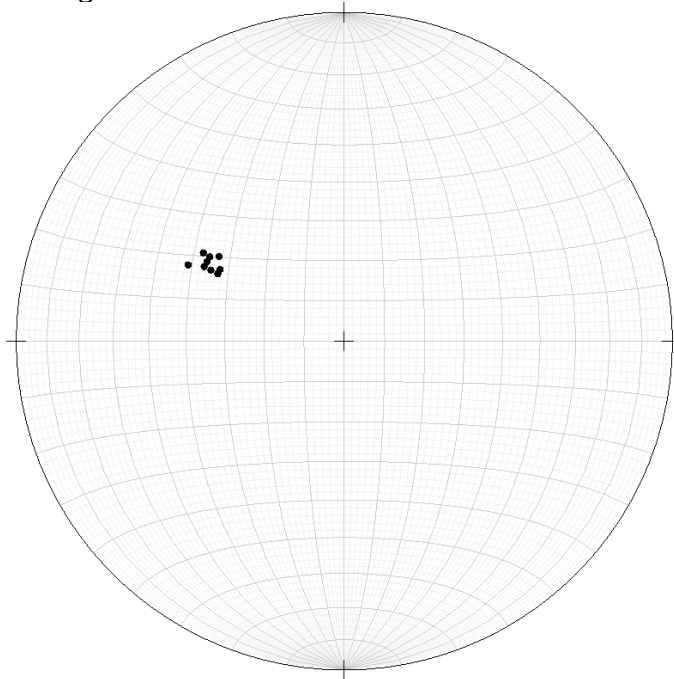


Locality 39:

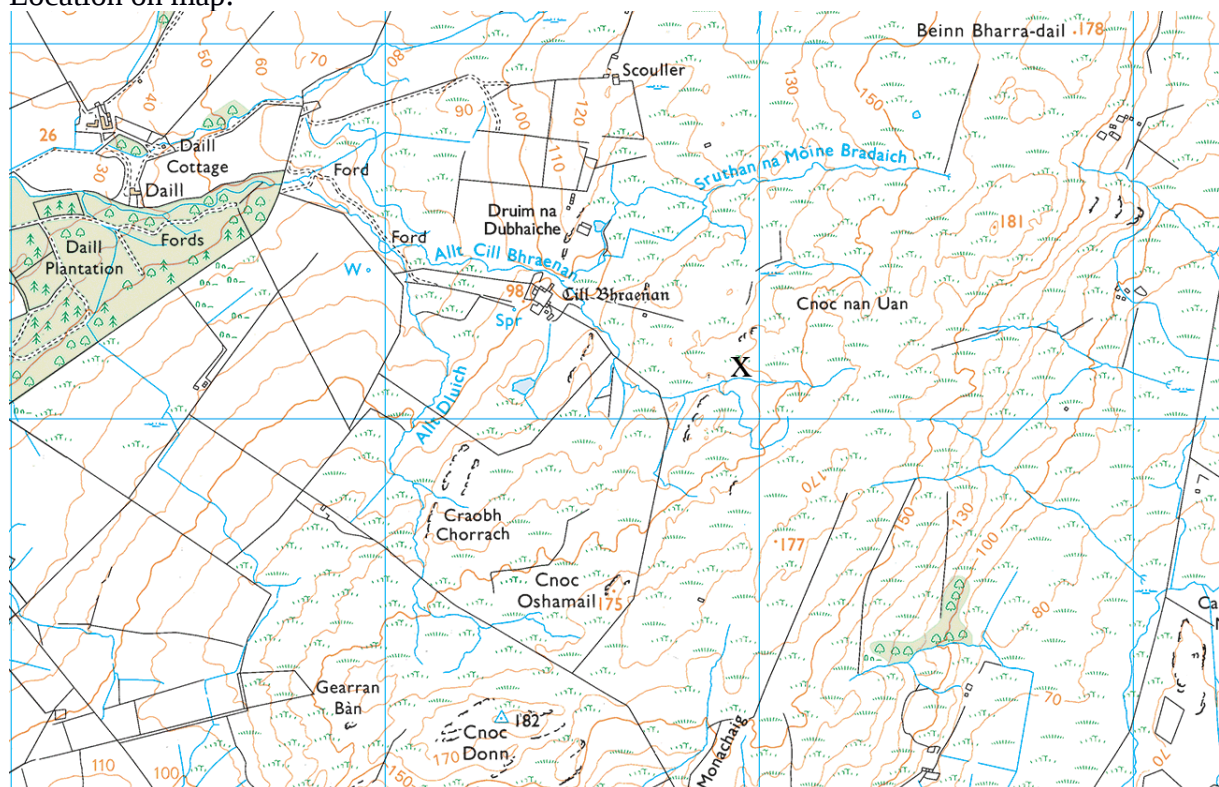
Measurements:

36/120	36/118	38/118	36/120	42/122	44/116
40/122	38/124	40/120	38/118	40/118	

Stereogram:



Location on map:

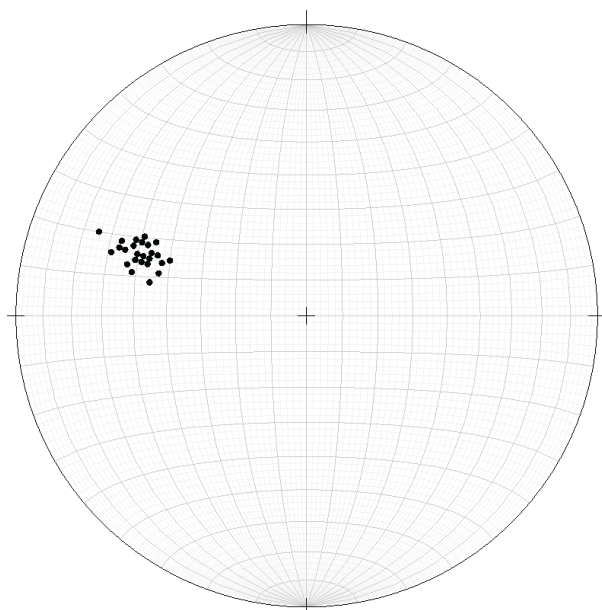


Locality 40:

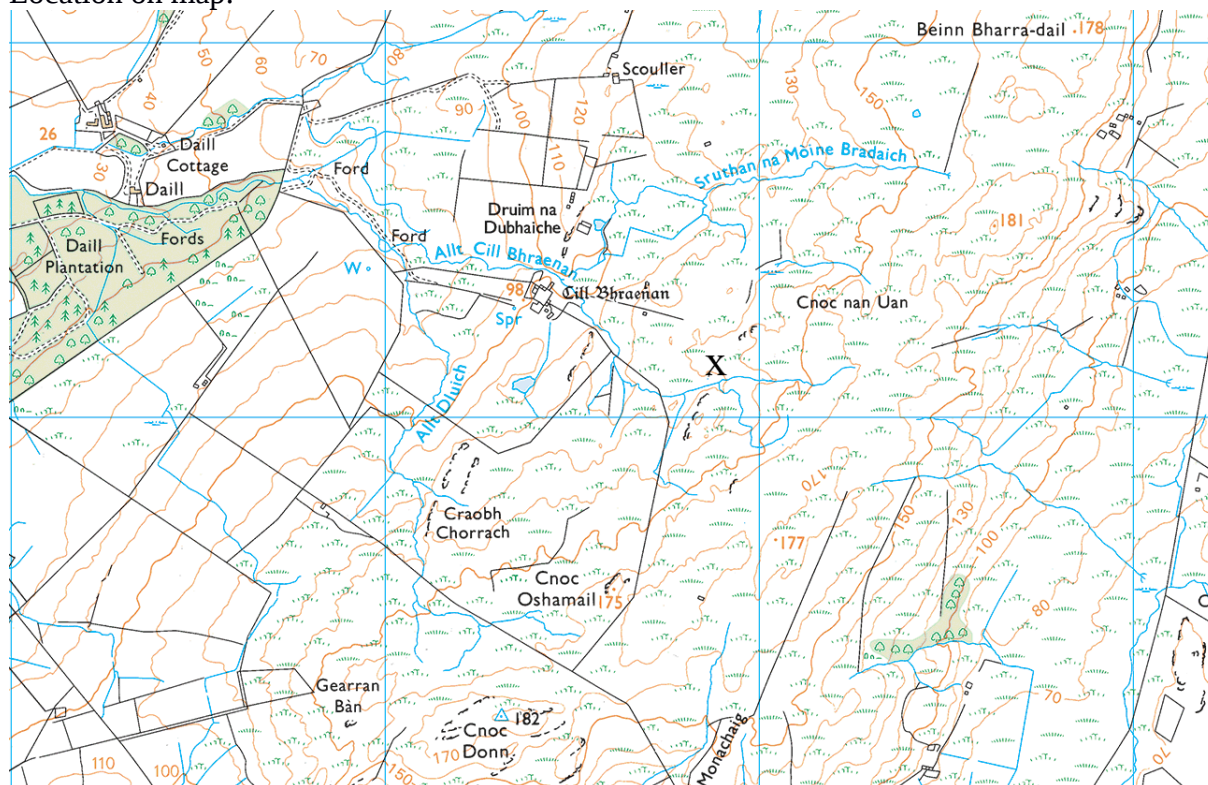
Measurements:

52/108	54/112	52/116	54/114	58/112	46/112
48/112	54/114	52/104	50/110	54/106	50/108
48/108	46/102	52/110	44/106	54/112	48/116
52/114	56/110	60/108	48/110	66/112	58/110
54/112	54/114	44/110	42/112	50/114	46/112

Stereogram:



Location on map:

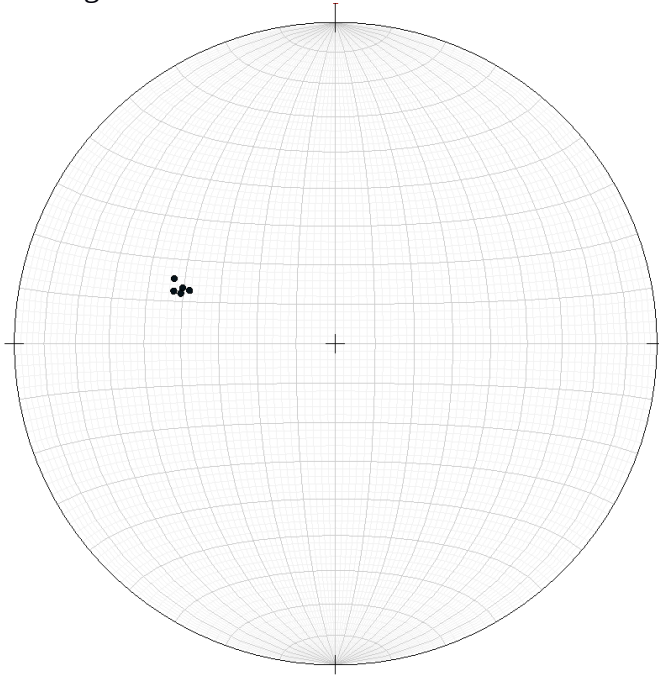


Locality 41:

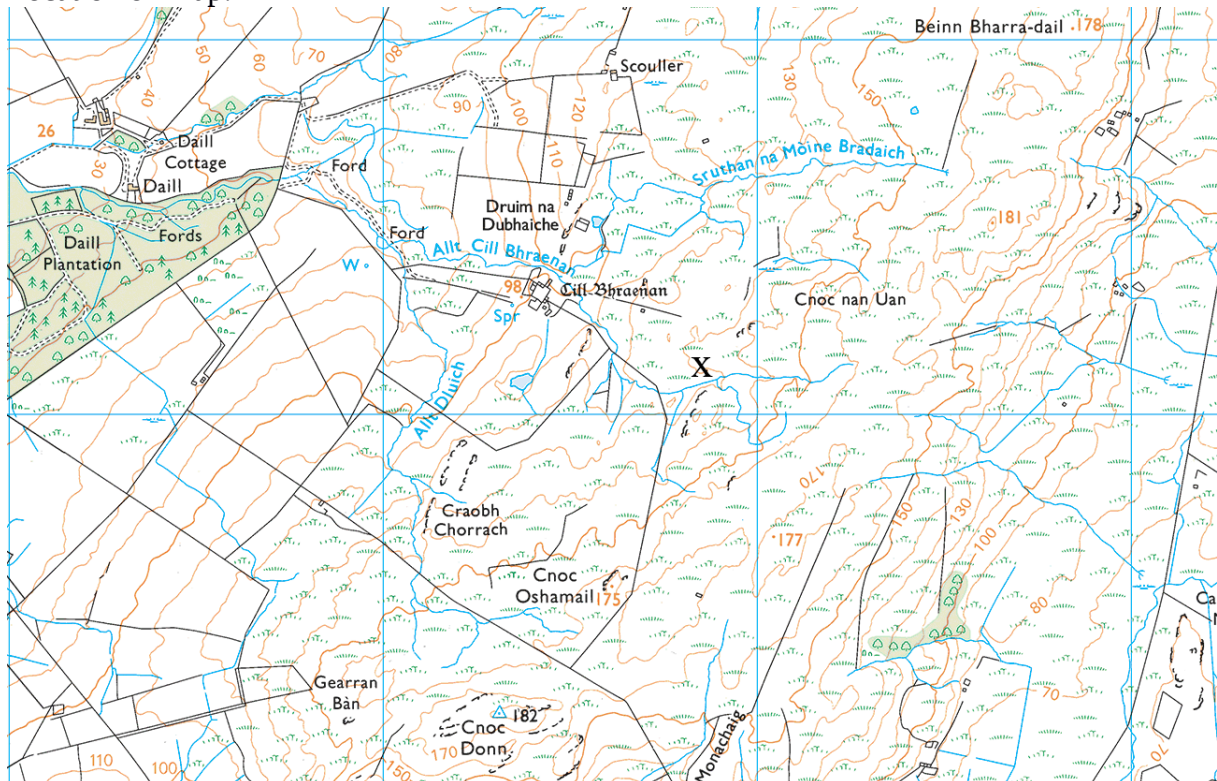
Measurements:

42/108	45/112	40/110	42/110	44/108
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Stereogram:



Location on map:

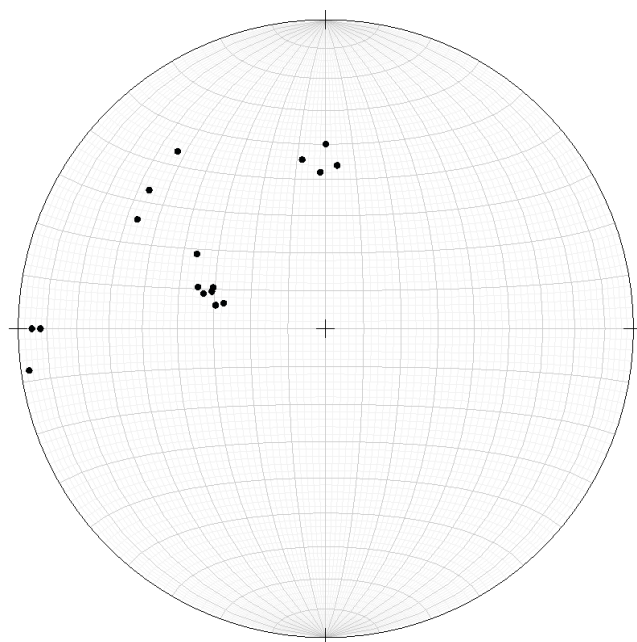


Locality 42:

Measurements:

60/120	64/140	62/128	40/120	32/110	36/108
30/102	34/106	32/108	28/104	50/180	46/172
42/178	44/184	85/090	87/082	82/090	

Stereogram:



Location on map:

