Bedrock Geology of Woodstock, Vermont, by Peter J. Thompson
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Introduction

This summary of the bedrock geology that underlies the town of Woodstock, Vermont, is meant to complement concurrent mapping of the surficial geology by David DeSimone. The mylar plates will be most meaningful when overlain on published 7 ½' quadrangle maps: Woodstock North, Woodstock South, Hartland, and small portions of Quechee and Plymouth. The next step in analysis will be to compare joint sets observed in the field with linear features observed on topographic maps and aerial photographs. Field work was accomplished by the author from May to November, 2005. Locations were determined by GPS and structural data were recorded using the right-hand-rule. Geology was adapted from Walsh (1998) for the portion of Woodstock that lies in the Hartland 7 ½' quadrangle. Reconnaissance work in adjacent towns sought to tie in my mapping with that of others.

Stratigraphy

The bedrock underlying Woodstock ranges in age from Ordovician to Devonian and, overall, the rocks are younger toward the east (Plate 1). Here and there much younger basalt dikes, probably associated with the igneous intrusion at Mt. Ascutney, cut across the older rocks. All the rocks other than the dikes experienced high enough temperatures and pressures to transform the original materials into the metamorphic rocks we see today. From west to east, the rock formations are as follows: Barnard Gneiss (in Curtis Hollow), phyllite of the Northfield Formation, schist and calc-silicate marble of the Waits River Formation, various rock types in the Standing Pond Volcanics, and schist and quartzite of the Gile Mountain Formation (in Taftsville). Much older Precambrian rocks, now exposed in Vermont only along the crest of the southern Green Mountains and in the Chester Dome, formed the leading edge of a continental mass referred to as "Laurentia", the ancient interior of North America.

Barnard Gneiss

The oldest rocks, exposed in Curtis Hollow in the southwest corner of Woodstock, are light-colored, very hard, felsic gneiss interlayered with dark amphibole and biotite gneiss (Figs.1 and 2). Chang and others (1965) mapped them as part of the Barnard Volcanic Member of the Mississquoi Formation. Whatever the name, these rocks were originally erupted in a volcanic island arc some distance from Laurentia during Ordovician time. U/Pb radiometric ages for samples from the Barnard Gneiss range from about 465 to 484 million years (Karabinos and others, 1998). The volcanic rocks were metamorphosed to gneiss and deformed as the arc collided with the Laurentian margin during the mountain-building episode referred to as the Taconian Orogeny, about 450 m.y. ago.

Northfield Formation

The Northfield Formation lies east of and on top of the Barnard Gneiss, but it was not deposited until several million years after the Taconian Orogeny. A period of erosion likely intervened, which resulted in what geologists refer to as an unconformity. The gneiss below this level suffered two orogenies, whereas the rocks to the east experienced only one. Layering in the Barnard Gneiss is tilted at steeper angles than the contact between the Barnard and the Northfield, and quartz pebble conglomerate is preserved at a few points along the contact, correlative with the Shaw Mountain Conglomerate, which has yielded Silurian fossils in Albany, Vermont (Boucot and Thompson, 1963). From the Reading town line the contact trends north-northeast to the Ottauquechee River, where it turns abruptly west. Less than a mile west of the town line it turns north again, continuing north to the type locality in Northfield, Vermont.

The Northfield Formation was deposited as mud into the "Connecticut Valley trough", which apparently formed in a basin between rocks of the Shelburne Falls arc and the Bronson Hill arc. The mud was eventually compacted to shale. In the Acadian Orogeny that followed, still higher pressure and temperature metamorphosed the shale to garnet-bearing phyllite and schist. (Phyllite is intermediate between slate and schist; it is shinier than slate but finer-grained than schist. All these rocks split relatively easily along the metamorphic foliation, which is caused by aligned flat minerals such as micas.) Rare, thin beds of sandy sediment in the Northfield were metamorphosed into tough gray quartzite layers, and limey beds less than 50 centimeters thick were metamorphosed into sandy calc-silicate blue-gray marble with distinctive garnet "carbuncles" in punky, brown-weathered outcrops. The phyllite, which makes up most of the formation, is dark gray to black and contains variable amounts of quartz, sericite (fine-grained white mica), biotite and garnet, with minor amounts of graphite and iron sulfides (photo WK-261). Biotite typically occurs as tiny flakes lying across the foliation, and garnet forms porphyroblasts about one to three millimeters across. Where the matrix is coarse enough to have visible micas, it should more properly be called schist rather than phyllite.

Waits River Formation

The Waits River Formation makes up the bedrock underlying better than two-thirds of the town of Woodstock. It consists of interlayered schist and calc-silicates (Fig.3). Different geologists have used different criteria to map the gradational contact between the Northfield Formation and the overlying Waits River Formation. The problem is that schist in the Waits River is identical to that of the Northfield, but thicker calc-silicate beds become more abundant toward the east (presumably higher in the section, although some geologists have found evidence that the Northfield might be younger than the Waits River; e.g. Westerman, 1987, Hatch, 1990). If one follows Chang and others' (1965) definition of the contact as the base of the first calc-silicate bed thicker than one foot (30 centimeters), the Northfield Formation would be restricted to a thickness of about 350 meters and the contact would lie west of Long Hill. However, if one allows a few thick calc-silicate beds into the Northfield, then the contact lies east of Long Hill, where a thick sequence of schist finally gives way to an area dominated by calc-silicates. The latter criteria, followed in this report, produce a map pattern closer to the depiction on Chang's original dissertation map (1950) and is more consistent with recent mapping by Hatch

(1987) to the north. The important thing is that Long Hill, Old Baldy, and the steep ledges north of the Ottauquechee River east of Bridgewater village are dominantly schist with only rare calc-silicate beds.

The dark gray schist in the Waits River Formation coarsens northeastward across Woodstock, reflecting increased metamorphic grade toward the Pomfret dome. Garnets increase in size from 2-3 mm near Fletcher Hill and Vondell Reservoir, up to 5-8 mm in West Woodstock and South Woodstock (Fig.4), and up to 1 cm in Prosper and Mt. Tom, where the higher-grade minerals staurolite and kyanite begin to appear.

The distinctive punky, brown-weathering calc-silicate layers contain abundant quartz grains, very apparent in weathered outcrops as a sandy texture (Fig.5). Unweathered blue-gray samples are hard and dense and they react to weak hydrochloric acid. Proportions of quartz sand to carbonate are about equal, meaning that the unmetamorphosed rock could be thought of as having been limey sandstone or sandy limestone. During metamorphism, some of the calcite in the limestone reacted with silica to form calcium-rich minerals such as zoisite, calcic almandine garnet and sprays ("fascicles") of calcic amphibole, which are common at contacts with schist (Chang and others, 1965). Amphibole fascicles can be seen at outcrops in Gulf Stream below a bridge about a mile downstream from Prosper (Fig.6).

Despite at least two phases of folding, primary sedimentary structures are preserved at many places in the Waits River Formation (Plate 2). Schist/calc-silicate contacts provide the most reliable bedding estimates. Bedding is rarely discernible in outcrops that are entirely schist and joints can easily be mistaken for bedding in thick calc-silicates. However, many calc-silicate beds contain delicate internal layering due to differing amounts of sand. Primary structures are particularly well exposed in a set of south-facing outcrops one mile west of South Woodstock, where intrastratal isoclinal folds and a wide, gentle trough are bounded by through-going, gently dipping bedding planes (Fig.7). Graded beds were observed at several localities (Fig.8). Near the top of the formation they are critical evidence for the topping direction of the map units (WK-477, 493). Graded beds are especially useful where the rock layers have been folded to the point that they are upside down.

I have roughly subdivided the Waits River Formation according to abundance of calc-silicate beds as follows: (1) a broad zone overlying the Northfield Formation where calc-silicates are 50% or more of most outcrops, (2) a mile-wide zone where calc-silicates are 10 to 50% of outcrops, trending northwest from Densmore Hill Road across Rt. 106 and passing east of West Woodstock, up Prosper Road and then swinging northeast to cross Rt. 12 south of Gilbert Hill, and (3) a zone also about a mile wide where calc-silicates are less than 10%, from Baylies Hill northwest to Mt. Tom and thence northeast toward the Cloudland Road. The third zone, which contains thin quartzite beds in many outcrops, was in part mapped out by Chang and others (1965) as unit DSws, but they show it pinching out northward before reaching the town line. I informally call this zone the Mt. Tom member of the Waits River Formation.

I have followed the Mt. Tom member north as far as the Appalachian Trail, where it is at most 800 feet thick. For a time I speculated that this uppermost member of the Waits River might correlate with the thinly bedded schist and quartzite in the Brownington syncline at Randolph, mapped by Ern (1963) as a western facies of the Gile Mountain Formation. This hypothesis now seems unlikely to me for two reasons: (1) the schist at the top of the Waits River pinches out northward and (2) the bedding character of the rocks at Randolph is really very different, with beautifully preserved, rhythmic graded beds. Further field work in Barnard might resolve the relationships between the Northfield Formation, my subunits of the Waits River, and rocks in the Brownington syncline.

<u>Standing Pond Volcanics</u>

The Standing Pond Volcanics define a tight fold through the village of Woodstock. They are well exposed on Mt. Peg and in the Ottauquechee River under Elm Street bridge, on the grounds of the Billings Mansion, and on the hill northwest of Cushing Cemetery. Although overall less than 500 feet thick, this unit is the most distinctive and variable in the town. I have not mapped out the different rock types separately, which include dark blackish green amphibolite, felty-textured feldspar-amphibole gneiss (Fig.9), felsic gneiss with sparse, small amphibole prisms, quartzose granofels, local calc-silicate horizons and, most distinctive of all, schist with giant amphibole fascicles and garnets up to 5cm across ("garbenschiefer", Fig.10-11). Walsh (1998) separated some of the different rock types on his map of the Hartland quadrangle, especially where the formation is exposed over a wide area south of Hartland Hill due to folding.

The Standing Pond Volcanics were erupted in a rift environment perhaps related to roll-back above a west-directed subduction zone, or perhaps in a pull-apart basin along a left-lateral strike slip system on the southern flank of the St. Lawrence promontory (Rankin and others, in press). Some of the metavolcanic layers were likely deposited as pyroclastic materials, whereas others may represent volcanics that were eroded, "reworked" by ocean currents and mixed with sedimentary material. A layer of felsic rock in Springfield, Vermont, variously interpreted as a volcanic layer or as a dike, was dated at 423 +/- 4 Ma (Aleinikoff and Karabinos, 1990), at the boundary between Lower and Upper Silurian. Thus the main belt of Standing Pond Volcanics must be at least that old. Other metavolcanic layers not directly connected to the main belt could be older or younger horizons within Waits River or Gile Mountain. All these rocks were metamorphosed during the Acadian Orogeny. Boxwell and Laird (1987) reported evidence for two prograde phases of metamorphism in presumably correlative amphibolites from southeastern Vermont and concluded that the higher grade, equilibrium assemblage formed at the same time as the spaced schistosity.

Traditionally the Standing Pond was defined as the uppermost member of the Waits River Formation and as such it marked the boundary with the overlying Gile Mountain Formation, with the understanding that both formations contain similar lithologies in different proportions (Doll, 1944; Lyons, 1955). Defining the contact farther north, where the volcanics are absent, proved more difficult (Hall, 1959). Hueber and others (1990) reviewed the long history of confusion over the relative ages of units in the

Connecticut Valley trough. Thompson and others (1997) observed that the Waits River/Gile Mountain contact is likely a time-transgressive boundary between laterally equivalent facies. Walsh (1998) went even farther by considering the volcanics and limestone-bearing portions of the Gile Mountain as members of the Waits River, and placing the contact much farther east. This argument rested partly on incorrect correlation of limestone layers above and below the Standing Pond (see discussion in structure section).

I have chosen for this report to accept the Standing Pond Volcanics, at least in Woodstock, as a time-stratigraphic marker and to assign rocks below it to the Waits River and those above it to the Gile Mountain. It follows that the Waits River Formation can be no younger than 423 Ma, and is thus Silurian. According to Walsh (1998), it could be in part Devonian. I prefer to think of calc-silicate layers above the Standing Pond as horizons within the Gile Mountain, just as the schist-rich Mt. Tom member is part of the Waits River.

Gile Mountain Formation

The Gile Mountain is exposed only in the easternmost part of Woodstock, on Blake Hill and in Taftsville. It is composed of schist similar to that of the upper Waits River Formation, but with much more abundant quartzite beds. The quartzite beds range in thickness up to more than a meter thick (Fig.12). Some contain appreciable biotite and feldspar. Only one punky-weathering limestone horizon was found, parallel to the continuation of a hornblende-fascicle horizon, perhaps a pyroclastic layer, mapped by Walsh (1998) in Hartland.

Based on the lithologies in the limited area I have mapped, I see no reason not to call these rocks Gile Mountain Formation, following the usage of Lyons (1955), Doll and others (1961) and Chang and others (1965). The discontinuous hornblende-fascicle schist that serves as a marker horizon to outline an overturned syncline on Blake Hill was also mapped by Lyons (1995) around the south end of the Pomfret dome. Graded beds in Woodstock confirm topping south and east for the whole sequence across the Standing Pond (Plate 2). Detailed mapping in the Quechee 7 ½-minute quadrangle might help assess the extent of limestone beds east of the Standing Pond, the presence of which, in the Hartland quadrangle, led Walsh (1998) to reassign rocks immediately above the Standing Pond to the Waits River Formation.

The formation was originally deposited as alternating shale and sandstone. Correlative rocks in Quebec, the Compton Formation, contain late Early Devonian plant fossils (Hueber and others, 1990). Hatch (1987, 1990) presented a review of the problem of a sediment source for the Connecticut Valley trough sediments. The Gile Mountain may have been the leading edge of a wedge of sediments that was deposited westward from an advancing deformational front during the early stages of the Acadian orogeny, which eventually overcame and deformed the rocks of the trough.

Intrusive rocks

Two granite sills intrude schist roughly parallel to foliation, one in the Northfield Formation north of Rt. 4 (WK-233) and the other north of South Woodstock, west of south Randall Road (WK-635 and 637). They are lighter-colored than the schist and contain both biotite and muscovite. The sill at WK-233 is deformed by a D2 fold. Similar granite at Black Mountain, West Dummerston, Vermont, has been dated at 373 +/- 4 m.y. If the sills are the same age, this implies that D2 folding is younger than 373 m.y., consistent with Acadian deformation.

Basalt dikes occur in at least two places: near Biscuit Hill and southeast of South Woodstock (WK 618). They are tan-weathering, dark gray basalt, with feldspar phenocrysts. Both dikes are roughly vertical and about two meters thick. The first one is exposed south of Biscuit Hill (WK 460) and strikes about N22E. Loose float blocks of basalt were found 500 meters and 1800 meters to the NNE. The second dike strikes N05W. Both are likely Mesozoic in age, related to the intrusions at Mt. Ascutney.
The two basalt dikes found in Woodstock are oriented almost at right angles to the dominant east-west joint direction in the rocks. In his compilation of post-metamorphic dikes McHone (1984) reported that dikes in eastern Vermont typically have a wide array of orientations, whereas east-west dikes are more common in the Champlain Valley and northeast trending dikes are more common in the Taconic Mountains and in New Hampshire.

Quartz dikes or veins are common throughout Woodstock. Loose white quartz boulders, conspicuous in the till and stone walls, are often referred to by locals as “marble”. They are not intrusive in the strict sense of the word, since they probably formed by precipitation of silica derived from fluids being driven off during metamorphism, rather than by solidification of molten rock. Thinner quartz veins are apt to be deformed along with the dominant foliation, indicating that they formed earlier than D2. Some of the wider veins have very planar margins and can be followed for tens of meters across the countryside. Good examples can be seen along the North Peak trail on Mt. Tom (WK 78) and at the North Peak itself, where the veins strike N80W, parallel to spaced cleavage. Three preferred orientations are indicated by my limited data (Appendix II, Folder B).

Ductile Structures

No detailed study has been made for this report of structures in the Barnard Gneiss, other than to observe that foliation in the gneiss generally dips more steeply than the unconformity and the foliation in rocks above it. In the Silurian-Devonian rocks evidence for three phases of deformation are present: D1, D2 and D3. Equal-area stereonets for each phase, prepared using *GEOrient version 9.2* (Holcombe, 2005), are presented in Appendix I.

I have divided the town into seven structural domains as follows (see Plate 4):

Domain 1: upright, SE-dipping limb of D2 syncline on SW shoulder of Pomfret dome
Domain 2: axial region of D2 anticline west of Pomfret dome
Domain 3: upright limb of D2 anticline in D3 saddle
Domain 4: upright limb of D2 anticline deformed by N-plunging folds
Domain 5: axial region of D2 anticline on N shoulder of Chester dome
Domain 6E: overturned limb of D2 anticline on S shoulder of Pomfret dome
Domain 6W: axial region of D2 anticline in D3 saddle

Early Foliation (Plate 3)
A strong foliation (S1 or Sn) is well developed in the schists as a closely spaced alignment of platy minerals, chiefly muscovite and biotite. In the metavolcanic rocks the pervasive foliation is defined by aligned biotite and/or amphibole. Foliation is also apparent to varying degrees within the calc-silicates and quartzites, depending on their mica content. The pervasive foliation is oriented approximately parallel to schist/calc-silicate contacts in most exposures, except in the hinges of rare isoclinal folds, where it crosses bedding. Many isoclinal folds seem to be restricted to certain zones that are bounded above and below by undeformed bedding planes (Fig.13). Whether these earliest folds (D1) might be the result of soft-sediment deformation or early folding coeval with the development of foliation surfaces (S1) is unknown; the folds do not seem to affect the map distribution of rock units and thus do not seem to have regional structural significance.

Further investigation is warranted to determine whether the eastward-opening early syncline at Woodstock village, which I equate with the syncline in West Windsor (see below), might be a D1 structure, refolded by D2. Minor folds that deform S1 show a reversal across the axial traces of these folds, so I have concluded that they are D2 folds. One key area to resolve this question would be east of Happy Valley in Taftsville, across Kent Hill to Rt. 12 in Hartland, with particular attention to mapping out the hornblende fascicle schist that serves as a marker horizon across Blake Hill. Hopefully that horizon is continuous enough to define the fold interference pattern across the crest of the Pomfret dome. If the Woodstock syncline is a D1 structure, is it also continuous with the Proctorsville syncline, which lies between the Chester dome and Green Mountain anticlinorium (Townshend-Brownington Syncline, TBS-F1 on Fig.14)?

Overturned, intermediate-age folds (Plate 1)
The dominant foliation, early quartz veins and bedding are deformed by asymmetrical, open to tight folds (D2) in most outcrops throughout Woodstock (Fig.15). The folds range in amplitude from a few centimeters to meters. Weakly developed, gently to moderately-dipping spaced cleavage (S2 or Sn+1) lies parallel to the D2 axial planes in many outcrops. In the more phyllitic rocks the axial planar foliation may be more penetrative and difficult to differentiate from S1. The axial trace of a major overturned D2 anticline passes through South Woodstock. In the western part of town the minor folds are inclined to overturned and east-verging, on the upright limb of the anticline. Long limbs of the minor folds have gentle to moderate dips. To the east on the

overturned limb, the folds are west-verging and long fold limbs are steep (Fig.16). All of these structures are deformed by the domes; the saddle between the domes also passes near South Woodstock, but it trends more to the NW, oblique to the D2 anticlinal zone. The overturned long limbs flatten out in domain 5 north of the Chester dome (Fig.17).

The axial zone of the major D2 anticline was not readily apparent during initial mapping in South Woodstock because dips measured on bedding planes tend to dip gently east or west in the area. It appeared that dips get progressively less steep from the overturned limb along Rt.106 (domain 6E) westward to Meetinghouse Hill. However, in the axial zone (domain 6W) the gentle dips are actually on the short limbs of neutral folds, and the enclosing larger-scale contact is close to vertical. Key outcrops north of Kedron Brook Stables (WK 624-633) and along Randall Road (WK-641A) demonstrate that schist/calc-silicate contacts are vertical, folded by accordion-style folds. Well driller George Spear (2005, pers. comm.) reported that in several low-yield wells in South Woodstock, the well stayed in schist to depths of 200 or more feet without encountering any "sandstone" or "limestone" layers (calc-silicates). The axial trace of the anticline across the map has been estimated by noting where the vergence of minor folds changes from west-over-east to east-over-west; its continuation into adjacent towns north and south remains unknown.

The Z-shaped box fold outlined by the Standing Pond in Woodstock village is a D2 syncline, plunging SSW at 24 degrees. It is part of a series of folds related to the major eastward-opening syncline depicted by Lyons (1955, cross-section A-A') draped over the Pomfret dome. Because of the dome's south plunge, other folds on the overturned limb, above the fold through Woodstock, intersect the earth's surface farther southeast in Hartland (Lyons, 1955, cross-section B-B'). Walsh (1998) incorrectly shows the Hartland folds as minor folds on an upright limb, an interpretation that demands the connection of calc-silicate layers that are structural above and below the volcanics. The still deeper, upright, limb is exposed around the Pomfret dome and on the south limb of the West Windsor syncline north of the Chester dome, as shown by Doll and others (1961) in their cross-section D-D' through Woodstock.

The S-shaped fold in the Barnard/Northfield contact east of Bridgewater village is an anticline plunging NNE at about 10 degrees. Walsh and Ratcliffe (1994) and Walsh (1998) referred to this fold as a D2 structure, but its style and the orientation of minor fold axial planes suggest that if so, it has been modified by D3 folds.

<u>Later, dome-stage structures</u>
The Pomfret and Chester domes (D3) deform the moderately-dipping S_2 spaced cleavage such that it strikes NW in the eastern part of Woodstock, E-W in the central part, and NE in western Woodstock. This array was predicted by Walsh (1998), who mapped bedrock in the Hartland quad to the east and the Plymouth quad to the west (Walsh and Ratcliffe, 1994). S_2 data gathered in the present study partially closes the data gap in Walsh's (1998) figure 2 (See figure 14, this paper). The dip of S2 is much flatter in Woodstock than in adjacent quadrangles due to the saddle between the Pomfret and Chester domes. Equal area nets of poles to bedding, poles to S1 and poles to S2 all show an east-west girdle due to the doming (Appendix I).

Minor structures related to the domes are not very apparent in most outcrops. Open, upright, symmetrical folds with axial planes striking north were assumed to be D3 folds. Steep spaced cleavage striking roughly north was assumed to be S3 rather than S2, although this can be said with certainty only where intersecting cleavages can be observed. Undeformed quartz veins, some of which are meters thick, are parallel to S2 in some places and parallel to S3 in others. Ratcliffe (2000) differentiated late upright folds at the north end of the Chester dome according to the strike of spaced cleavage and axial planes: those striking NNW are older, D3 folds, and those striking NNE are D4. These two sets also appear in Woodstock, but I did not observe proof of their relative ages.

<u>Linear Features</u> (Plate 5)
Lineations of all sorts show preferred orientations depending on their locations relative to the domes: in domain 1 closest to the Pomfret dome lineations mostly plunge south, in domains 4 and 5 they mostly plunge north, whereas a mix of north and south plunges is observed in between (domains 2, 3 and 6). The lineations include minor fold axes, quartz rods, crenulations on foliation surfaces, intersection lineations and mineral lineations. In the saddle between the domes intersecting lineations are commonly observed, sometimes plunging in opposite directions.

Brittle Structures

<u>A. Introduction</u>
Geologists refer to cracks in bedrock, many of which may be potential conduits for groundwater, as "joints". The most interesting ones for water transmission are the long through-going joints and the shorter joints that cross or abut bedding-plane joints. (It should be mentioned here that many joints within the calc-silicates and quartzites in Woodstock follow bedding planes, and that the analysis below does not take into account these joints.) Joints are far less common parallel to foliation within the schists than parallel to bedding, nor are they always present along schist/calc-silicate contacts. A truer picture of the water-bearing joint system might be achieved by combining joint and bedding information. Figure 18 shows post-like features due to weathering along bedding and an intersecting joint set.

The strike and dip of joints were measured at each outcrop, along with additional information such as spacing, exposed length, mineralization, number of parallel joints, and whether the joint was open or closed, planar or curved. Some attempt was made to characterize the context of each joint as through-going (across the entire outcrop), blind, en echelon, crossing other joints, or abutting other surfaces. Of course some of these characterizations depend in part on the size of the outcrop. Rose diagrams (Appendix II) were created using the program *GEOrient version 9.2* (Holcombe, 2005) so as to compare the orientations of different styles of joints and also to compare joints in different rock units and in different structural domains. The diagrams are arranged in the appendix in the same order as in the text.

The most obvious conclusion from this study is that almost every outcrop contains at least one steep joint oriented roughly east-west (between N80E and S70E). This is apparent even with only a cursory glance at the rose diagrams, almost all of which show a strong preferred orientation around east-west. A second common joint orientation strikes toward the northeast (N40-50E). It is possible that the course of the Ottauquechee River, zigzagging as it does from northeast to east, might be following zones of closely spaced joints, although outcrops in the river itself do not have a noticeably higher density of joints.

Out of 1603 joints, 38% strike from N80E to S70E and 90% lie between N20E and S60E. Joints dipping 65 degrees and steeper (88% of total) show a similar distribution to that of the total, whereas those that dip more gently than 65 have orientations all around the compass with no clear pattern. (See first three rose diagrams in Appendix II, Folder A. These are plots of <u>total joints</u> rather than measured joint directions - - see following discussion.)

It should be noted that for outcrops exposing parallel joints, the azimuth was measured on only one joint and the number of parallel joints was recorded in the database. Although I measured a total of 678 joints, because many of them represent parallel joints, the total number of joints represented is 1603. There is a difference of opinion in the literature as to the most objective way to present the data for bedrock aquifer studies (Walsh, 2000). I have chosen to use rose diagrams of <u>joint directions measured</u> in Sections B and C below, and diagrams of <u>total joints represented</u> for Section D (joints by structural domain).

<u>B. Analysis relative to joint style and context</u>

Planar joints (n=561) are more likely to be east-west than curved joints (n=103), probably because the latter tend to abut other pre-existing surfaces. Through-going joints (n=286) are also dominantly east-west. Abutting joints (n=173) have a wide range of orientations, but those that abut bedding (n=58) are less likely to strike NE than those abutting other joints or foliation. Short joints (less than 2 meters, n=68) show a pattern of orientations similar to that for all steep joints, whereas joints longer than 4 meters tend to be either near E-W or toward the NE. Not surprisingly, joints observed to cross each other in an outcrop (n=70) show several sets of orientations, as do en echelon joints.

One of the more interesting outcomes of this study is that closed, mineralized joints tend to have orientations very different (N10-20E and S60-80E) from the open, unmineralized joints. For calcite especially, this might indicate that water is not currently flowing in these directions, or at least at a much slower rate, allowing precipitation of minerals rather than dissolution. Other common joint-fillings are quartz and iron-oxides. In some instances mineralization along joints has made the joint surfaces more resistant to weathering (Fig.19). The wide bull quartz veins, in contrast to the thin joint coatings, are mostly oriented parallel to S2 or S3.

<u>C. Analysis of joints relative to rock type</u>

The calc-silicates contain more joint directions than the schists. On a plot of 316 joints in schist, regardless of formation (Northfield, Waits River or Gile Mountain), a strong east-west preferred orientation is obvious. Joints in calc-silicates of the Waits River Formation (n=177) show a much wider array of orientations. It is important to reiterate here that bedding-parallel joints are also common in calc-silicate beds, providing better interconnections for water flow. Furthermore, because the calc-silicates are more susceptible to chemical weathering, many joints have been widened through solution, especially at and above the water table. Miniature karst features such as caves can be seen in some outcrops (Fig.20). Topographic sinkhole-like depressions also seem quite common in the Waits River calc-silicates, for example near WK-350, where two linear valleys intersect. Some of these depressions are important ecologically as vernal pools.

Joints in schist are most commonly developed perpendicular to the dominant foliation (Fig.21). Intersecting joint sets result in rectangular blocks that break away from the outcrop. This is also true of joints in the Barnard Gneiss, which seem to be widely spaced but through-going. Some of the highest yielding bedrock wells in Woodstock are found in areas of Curtis Hollow underlain by gneiss. Whether this is due to characteristics of fractures in the gneiss or to the structure in the area is unknown. The rose diagram for joints in the gneiss is very similar to that for all of domain four (dominantly striking WNW), which includes both the gneiss and the younger rocks as well.

D. Analysis of total joints relative to structural domain

Very little variation is apparent geographically across the town of Woodstock. The mean joint azimuths range from N83E to S85E, a difference of only 12 degrees. The most frequent joint azimuth in each domain varies more widely (N60E to S60E), and the N40-50E, secondary direction, is stronger in some domains than others.

Domain	Total joints (n)	Mean joint azimuth	Most frequent joint azimuth
1	786	85	90-100
2	199	95	100-110
3	269	87	110-120
4	694	84	80-90
5	198	88	90-100
6	320	83	60-70

Many joints strike perpendicular to bedding (Plate 2) and S1 foliation (Plate 3), and this can be seen in the rose diagrams from the different domains. The joints are younger than the bedding and foliation. They may have formed during arching of the domes or more likely during Mesozoic extension. Regardless of the exact timing, the orientation of bedding and the dominant foliation may have controlled in part the orientation of joints. The implication for water flow is that many joints strike parallel to the maximum dip direction of bedding planes. The flow direction, however, would be toward lower hydraulic head, which might be either in the down-dip or up-dip directions (generally west or east).

References Cited

Aleinikoff, J.N. and P. Karabinos, 1990, Zircon U-Pb data for the Moretown and Barnard Volcanic Members of the Mississquoi Formation and a dike cutting the Standing Pond Volcanics, southeastern Vermont, *in* Slack, J.F., ed., Summary Results of the Glens Falls CUSMAP Project, New York, Vermont and New Hampshire: U.S. Geological Survey Bulletin no.1887, p.D1-D10.

Boucot, A.J. and J.B. Thompson, Jr., 1963, Metamorphosed Silurian brachiopods from New Hampshire: Geological Society of America Bulletin, v.74, p.1313-1334.

Boxwell, M. and J. Laird, 1987, Metamorphic and deformational history of the Standing Pond and Putney Volcanics in southeastern Vermont, *in* Westerman, D.S., ed., Guidebook for Field Trips in Vermont, New England Intercollegiate Geological Conference 79th Annual Meeting, Montpelier, Vermont, Trip A-1, p.1-20.

Chang, P.H., 1950, Structure and metamorphism of the Bridgewater-Woodstock area, Vermont: Doctoral thesis, Harvard University, 76 p., scale 1:62,500.

Chang, P.H., E.H. Ern, Jr., and J.B. Thompson, Jr., 1965, Bedrock geology of the Woodstock quadrangle, Vermont: Vermont Geological Survey Bulletin no.29, 65 p., scale 1:62,500.

Doll, C.G., 1944, A preliminary report on the geology of the Strafford quadrangle, Vermont: Vermont State Geologist 24th biennial report, 1943-1944, p.14-28.

Doll, C.G., W.M. Cady, J.B. Thompson, Jr. and M.P. Billings, 1961, Centennial Geologic Map of Vermont: Vermont Geological Survey, scale 1:250,000.

Ern, E.H., Jr., 1963, Bedrock geology of the Randolph quadrangle, Vermont: Vermont Geological Survey Bulletin no.21, 96 p., scale 1:62,500.

Fisher, G.W. and P. Karabinos, 1980, Stratigraphic sequence of the Gile Mountain and Waits River Formations near Royalton, Vermont: Geological Society of America Bulletin, Part I, v.91, p.282-286.

Hall, L. M., 1959, Geology of the St. Johnsbury quadrangle, Vermont and New Hampshire: Vermont Geological Survey Bulletin no.13, 105 p., scale 1:62,500.

Hatch, N.L., Jr., 1987, Lithofacies, stratigraphy and structure in the rocks of the Connecticut Valley trough, eastern Vermont, *in* Westerman, D.S., ed., Guidebook for Field Trips in Vermont, New England Intercollegiate Geological Conference 79th Annual Meeting, Montpelier, Vermont, Trip B-3, p.192-212.

Hatch, N.L., Jr., 1990, Revisions to the stratigraphy of the Connecticut Valley trough, eastern Vermont: U.S. Geological Survey Bulletin v.1935, p.5-7.

Holcombe, R.J., 2005, GEOrient Version 9.2, Holcombe, Coughlin & Associates, University of Queensland, Australia.

Hueber, F.M., W.A. Bothner, N.L. Hatch, Jr., S.C. Finney and J.A. Aleinikoff, 1990, Devonian plants from southern Quebec and northern New Hampshire and the age of the Connecticut Valley trough: American Journal of Science, v.290, p.360-395.

Karabinos, P., S.D. Samson, J.C. Hepburn and H.M. Stoll, 1998, The Taconian orogeny in New England Appalachians: Collision between Laurentia and the Shelburne Falls arc: Geology, v.26, no.3, p.215-218.

McHone, J.G., 1994, Mesozoic igneous rocks of northern New England and adjacent Quebec: Summary, description of map, and bibliography of data sources: Geological Society of America Map and Charts Series MC-49, p.1-5, scale 1: 690,000.

Rankin, D.W., R.A. Coish, R.D. Tucker, Z.X. Peng, S.A. Wilson and A.A. Rouff, in press, Silurian extension in the upper Connecticut Valley, United States and the origin of Middle Paleozoic basins in the Quebec embayment: American Journal of Science.

Ratcliffe, N.M., 2000, Bedrock geologic map of the Cavendish quadrangle, Windsor County, Vermont: U.S. Geological Survey Geologic Quadrangle Series Map GQ-1773, 19 p., scale: 1:24,000.

Walsh, G.J., 1998, Digital bedrock geologic map of the Vermont part of the Hartland quadrangle, Windsor County, Vermont: U.S. Geological Survey Open-File Report 98-123, 17 p., scale: 1:24,000.

Walsh, G.J., 2000, Geologic controls on remotely sensed lineaments in southeastern New Hampshire: Geological Society of America, Northeastern Section, Abstracts with Programs, vol.32, no.1, p.81.

Walsh, G.J., T.R. Armstrong and N.M. Ratcliffe, 1996, Preliminary bedrock geologic map of the Vermont part of the 7.5X15-minute Mount Ascutney and Springfield quadrangles, Windsor County, Vermont: U.S. Geological Survey Open-File Report 96-733-A, 36p., scale 1:24,000.

Westerman, D.S., 1987, Structure in the Dog River fault zone between Northfield and Montpelier, Vermont, *in* Westerman, D.S., ed., Guidebook for Field Trips in Vermont, New England Intercollegiate Geological Conference 79th Annual Meeting, Montpelier, Vermont, Trip A-6, p.109-132.

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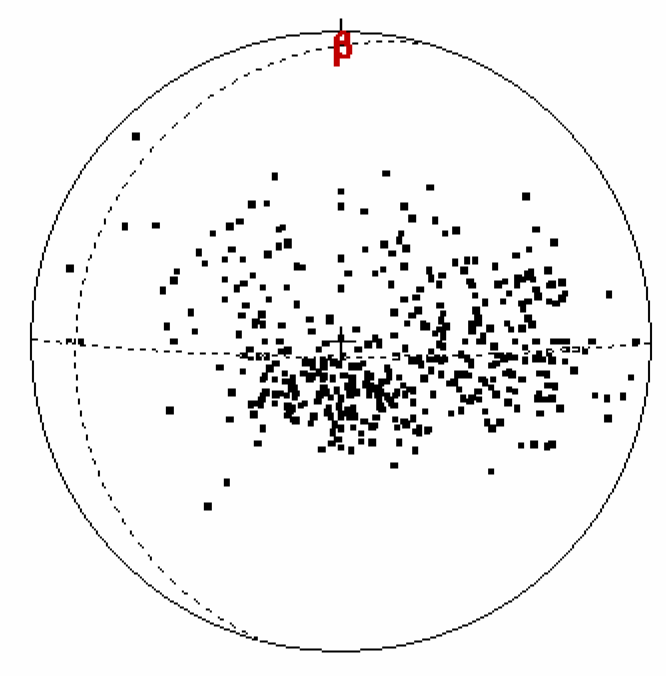
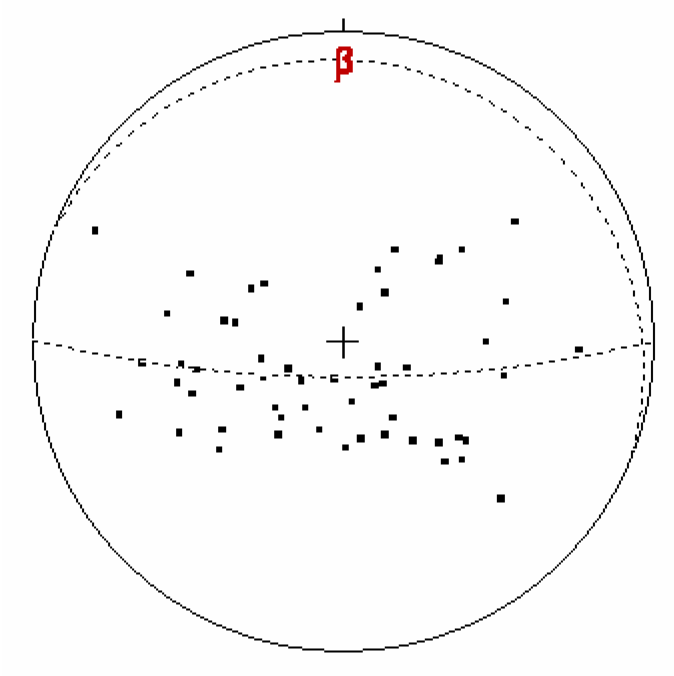


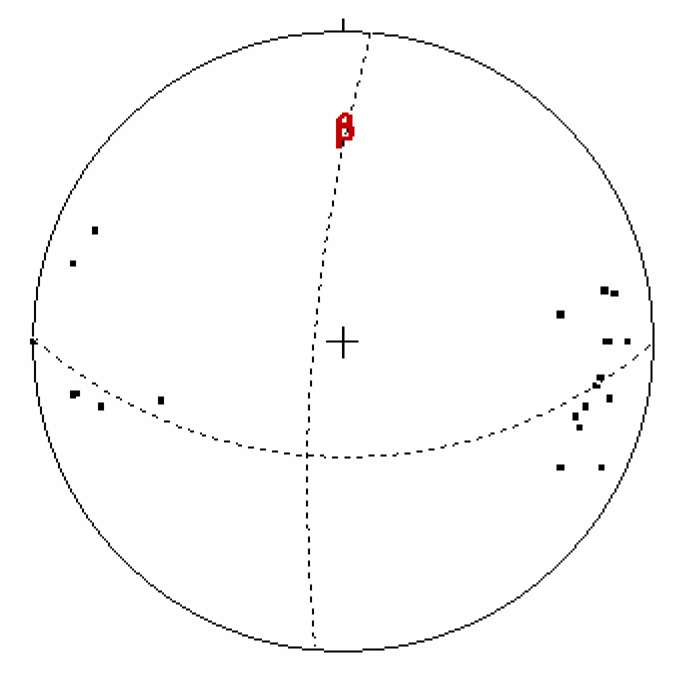
Poles to selected dominant schistosity Sn
(all domains) n=434

Mean Principal Orientation = 195/16
Mean Resultant dir'n = 15-281
Mean Resultant length = 0.84
(Variance = 0.16)
Calculated. girdle: 090/86
Calculated beta axis: 4-000



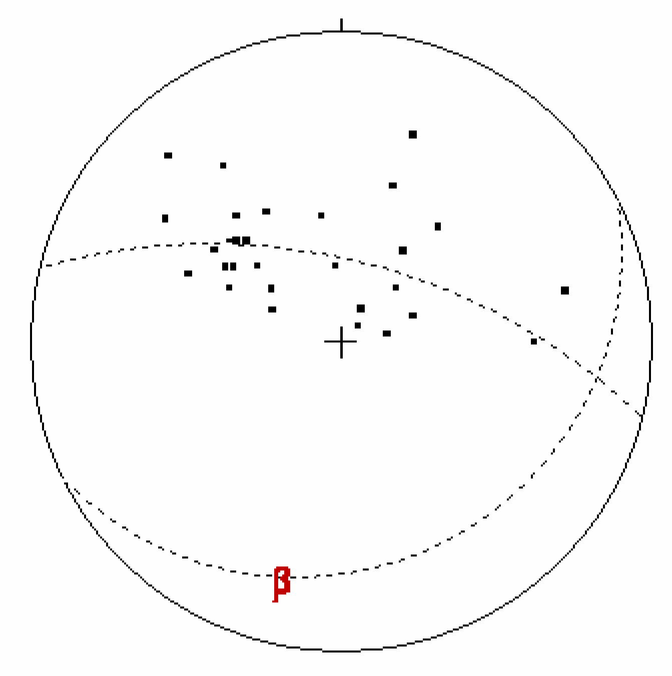
Poles to selected spaced cleavage S2
N=56

Mean Principal Orientation = 291/10
Mean Resultant dir'n = 9-021
Mean Resultant length = 0.82
(Variance = 0.18)
Calculated. girdle: 090/81
Calculated beta axis: 9-000

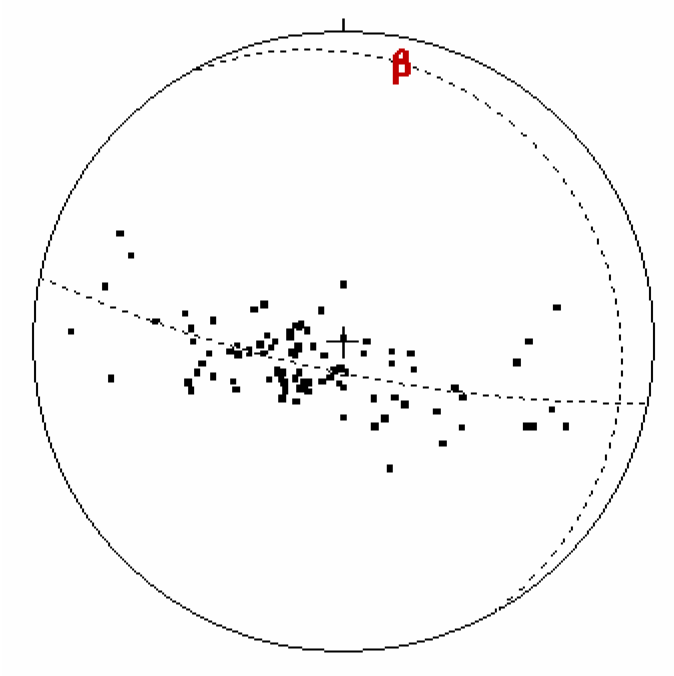


Poles to spaced cleavage S3 n=21

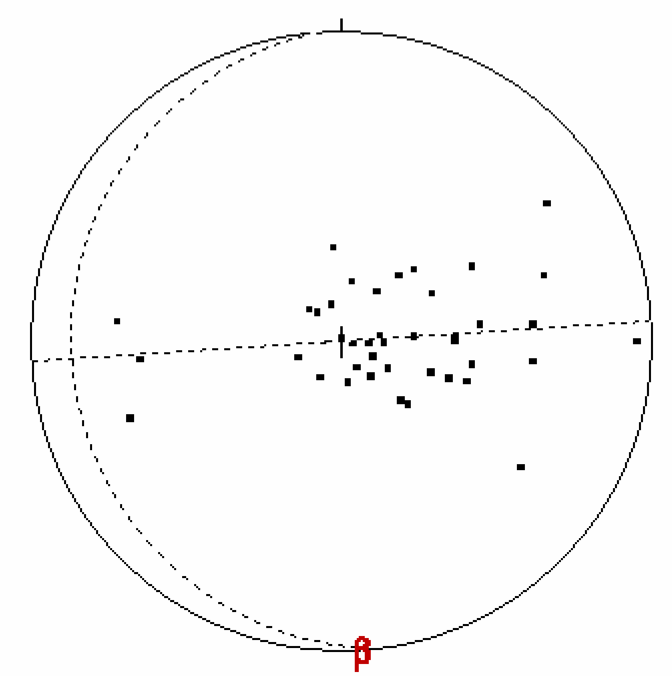
Mean Principal Orientation = 185/82
Mean Resultant dir'n = 49-287
Mean Resultant length = 0.43
(Variance = 0.57)
Calculated. girdle: 091/59
Calculated beta axis: 31-001



Domain 1 poles to bedding   n=29



Domain 2 poles to bedding n=95



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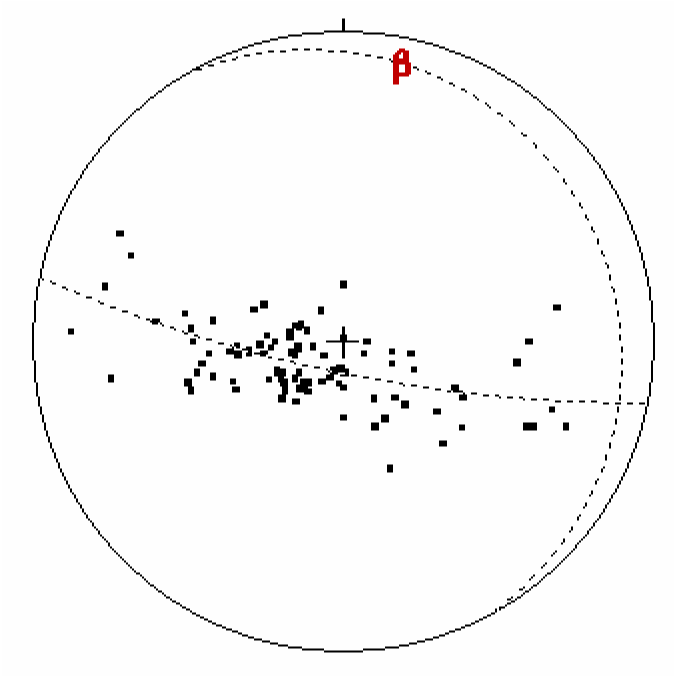
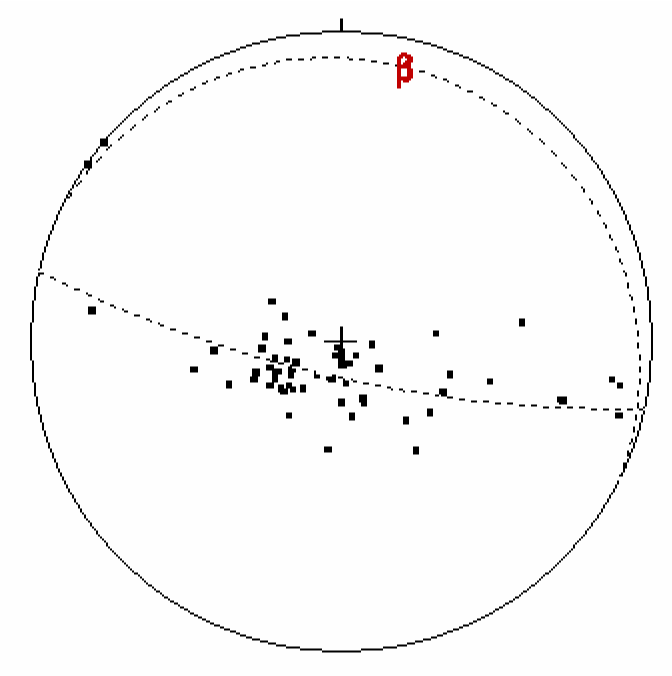
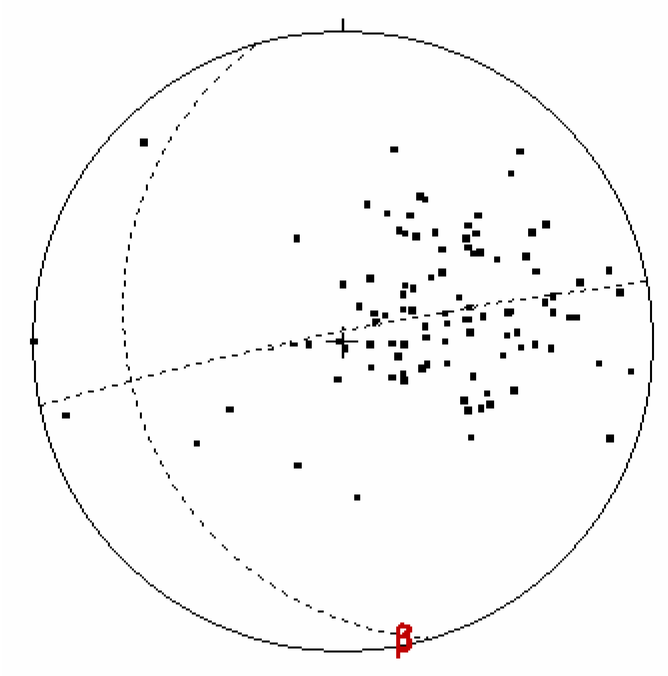


Domain 4 poles to bedding   n=94



Domain 5 poles to bedding   n=62

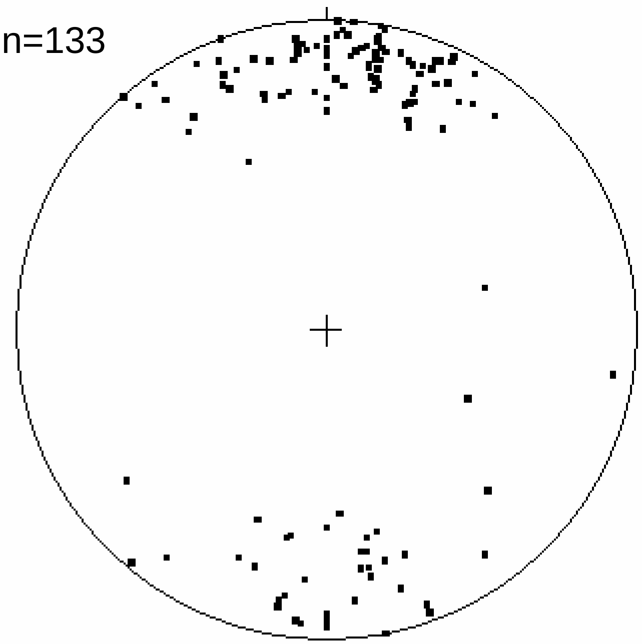


Domain 6 poles to bedding   n=104

Linear data

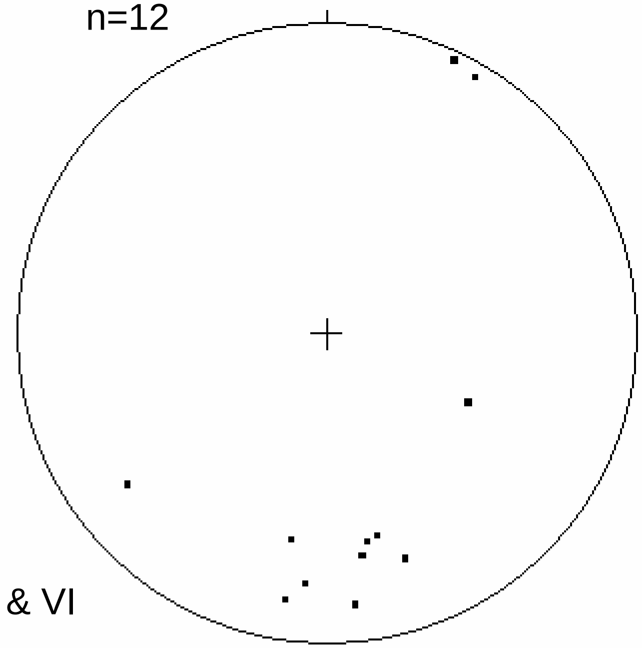
All lineations

n=133



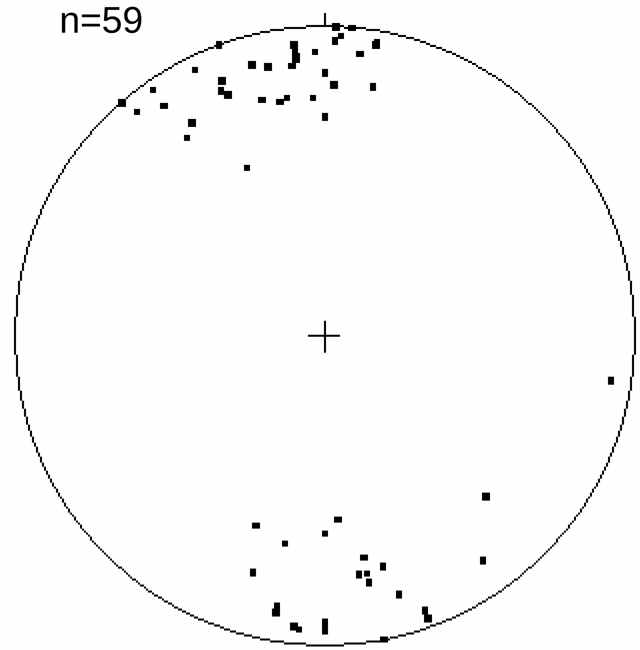
Domain I

n=12



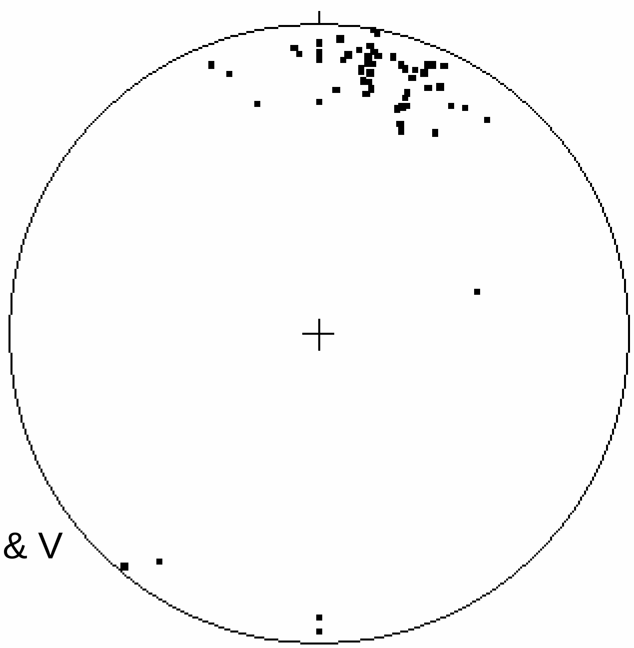
Domains II, III & VI

n=59

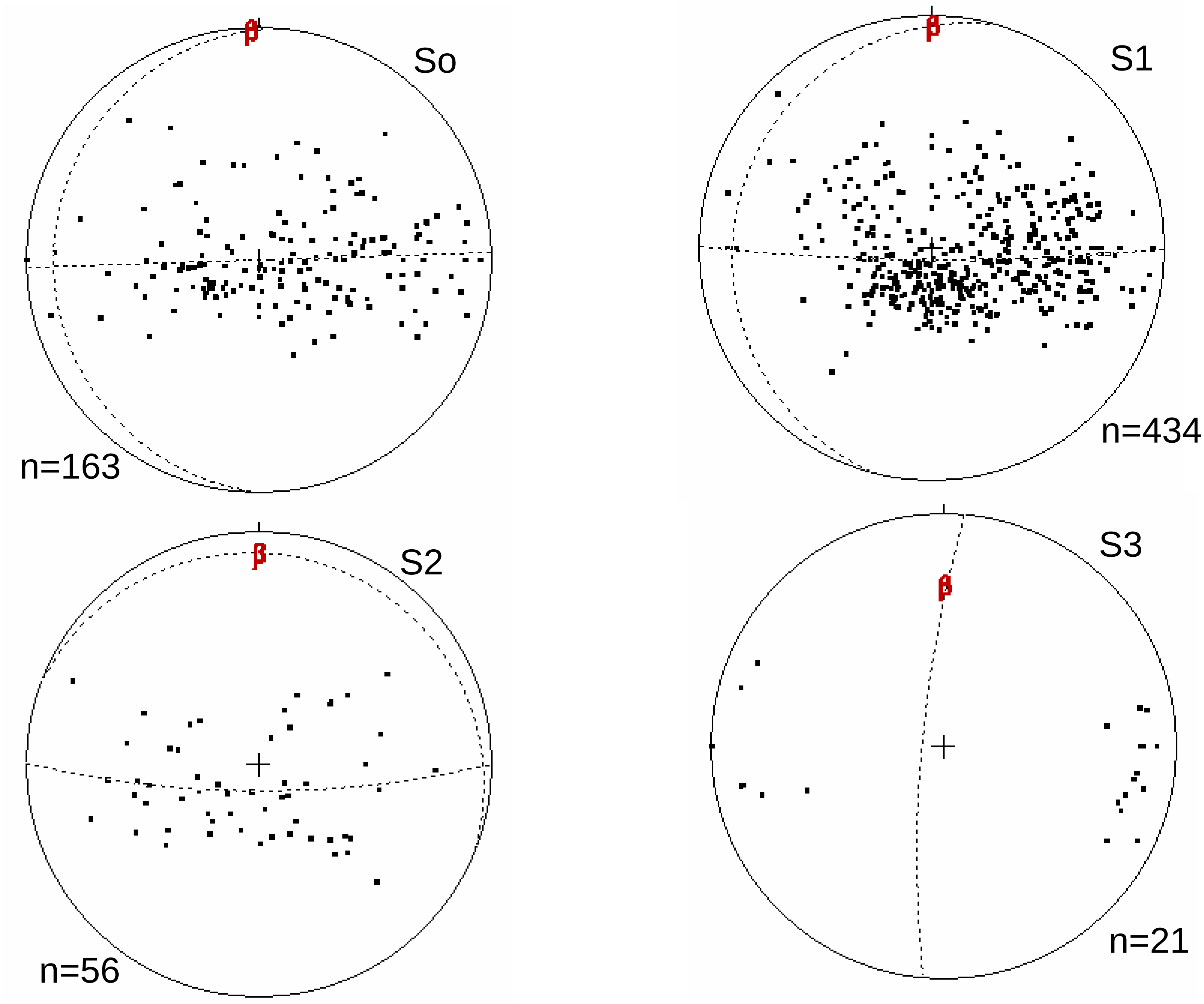


Domains IV & V

n=61

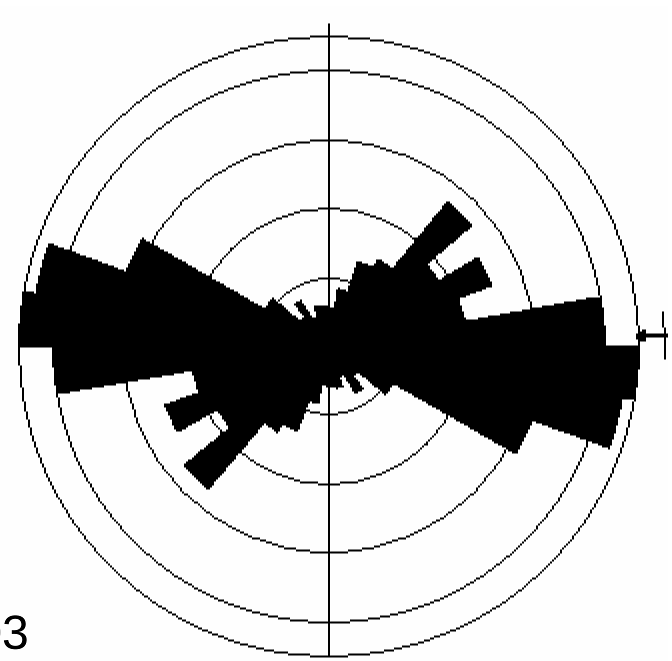


Ductile: poles to planar features



Total joints, Woodstock, Vermont
All joint directions measured multiplied by
number of joints in each direction

All joints

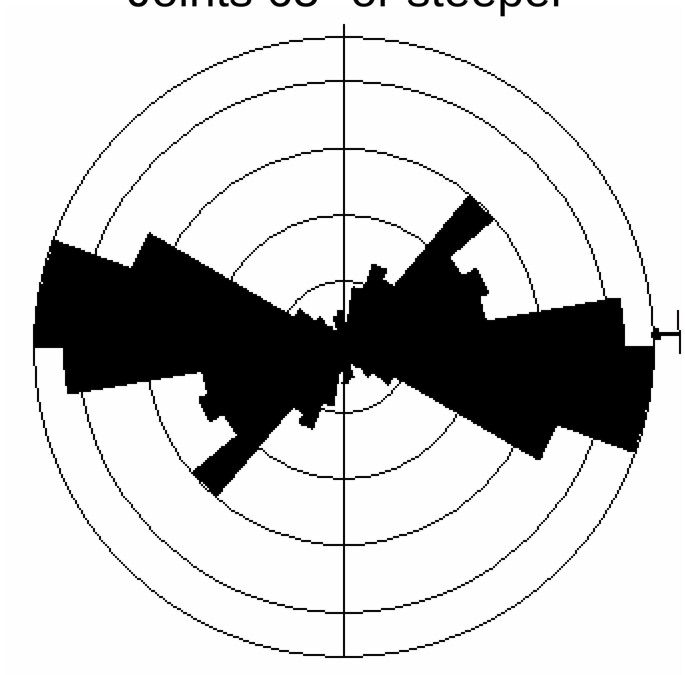


n=1603

Sector angle = 10°
Scale: tick interval = 3% [48.1 data]
Maximum = 13.5% [216 data]
Mean Resultant direction = 088-268
[95% Confidence interval = ±4°]

Total joints, Woodstock, Vermont
Steep compared to gentler-dipping joints

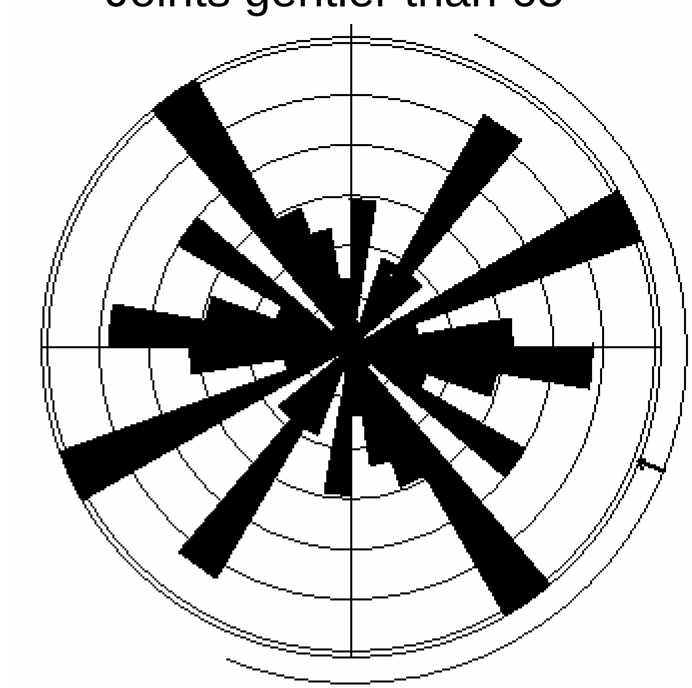
Joints 65º or steeper



n=1415

Sector angle = 10°
Scale: tick interval = 3% [42.5 data]
Maximum = 14.0% [198 data]
Mean Resultant direction = 088-268
[95% Confidence interval = ±4°]

Joints gentler than 65º

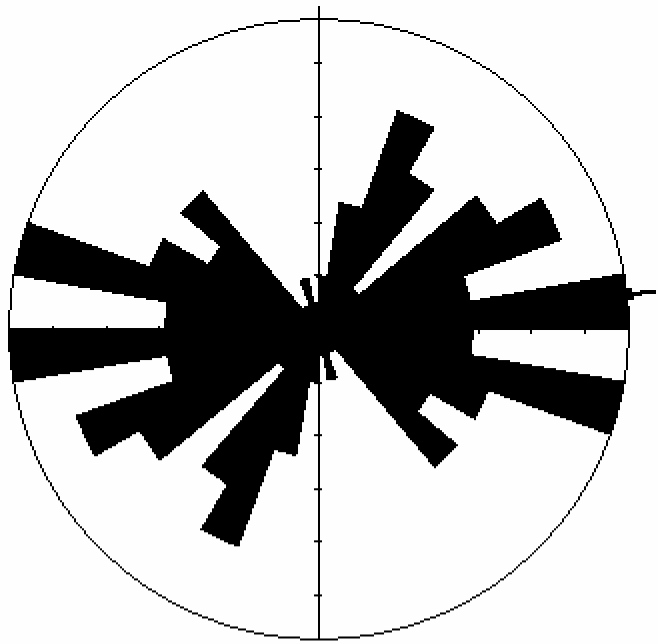


n=188

Sector angle = 10°
Scale: tick interval = 2% [3.8 data]
Maximum = 12.2% [23 data]
Mean Resultant direction = 112-292
[95% Confidence interval = ±90°]

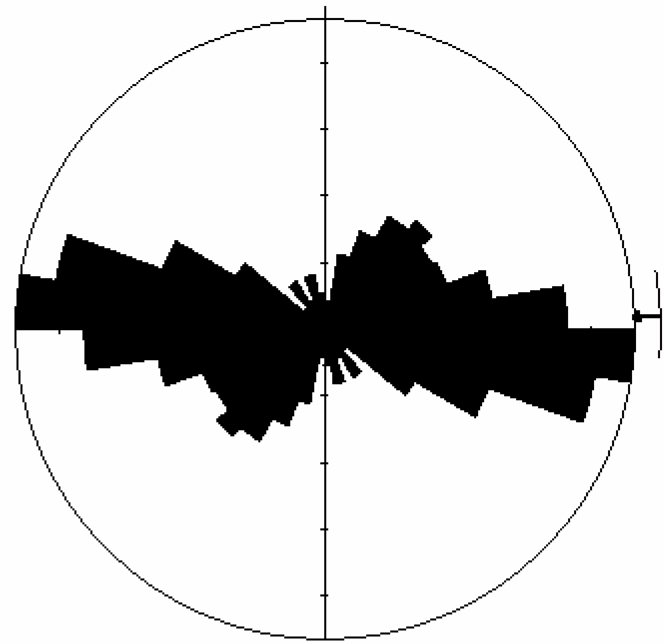
Measured joint directions, Woodstock, Vermont
Curved compared to planar

Curved joints

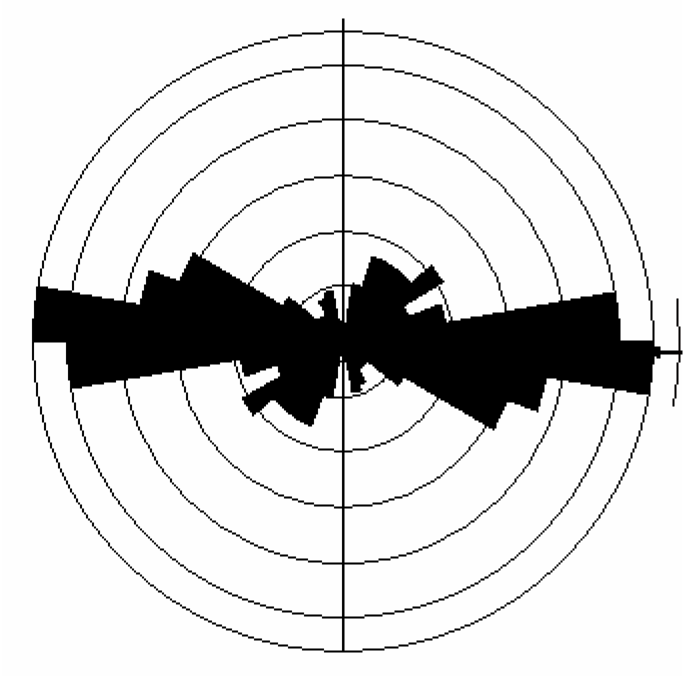


n=103
Mean resultant azimuth=264, 84
95% confidence for mean=+/-23 degrees

Planar joints

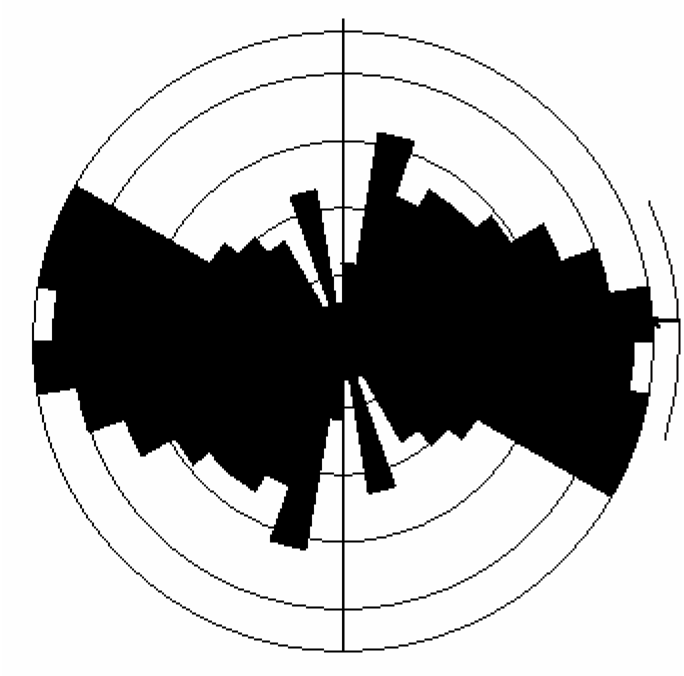


n=561
Mean resultant azimuth=267, 87
95% confidence for mean=+/-25 degrees



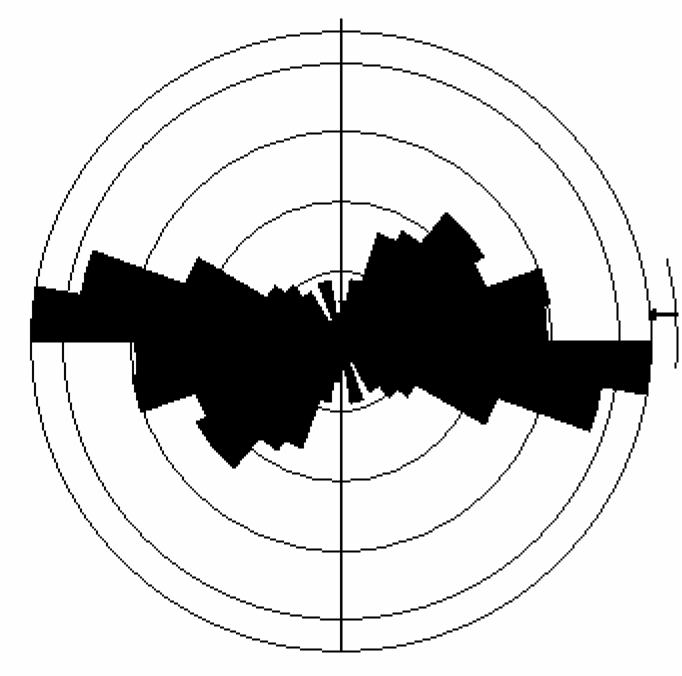
Through-going joints n=286

Sector angle = 10°
Scale: tick interval = 3% [8.6 data]
Maximum = 16.8% [48 data]
Mean Resultant direction = 092-272
[95% Confidence interval = ±9°]



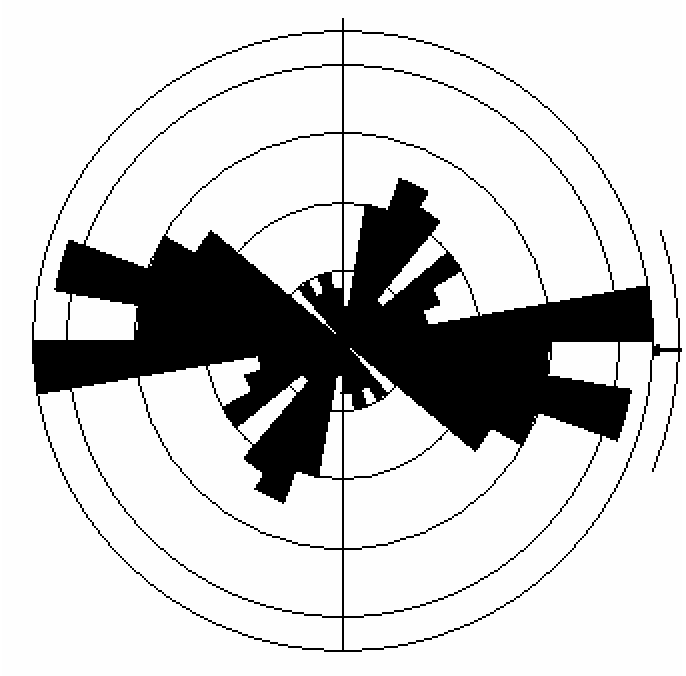
Abutting joints n=173

Sector angle = 10°
Scale: tick interval = 2% [3.5 data]
Maximum = 9.2% [16 data]
Mean Resultant direction = 086-266
[95% Confidence interval = ±21°]



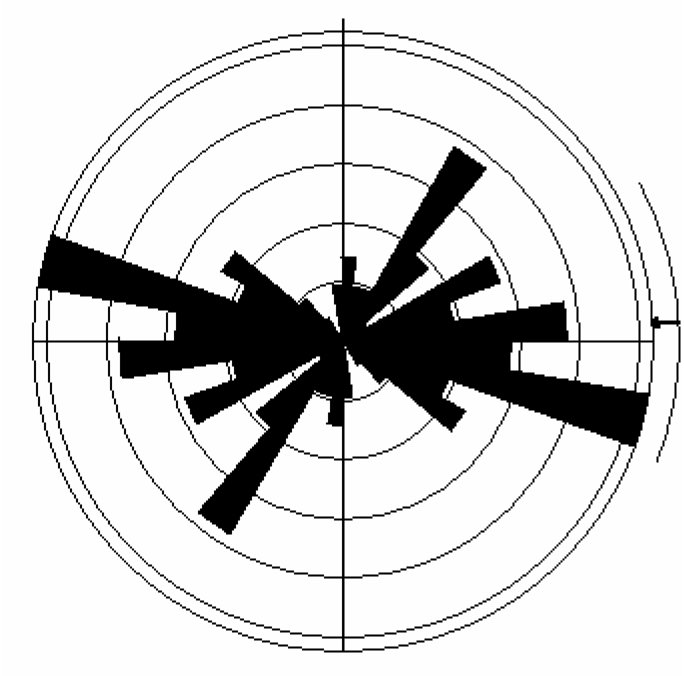
Joints 2 meters and shorter n=406

Sector angle = 10°
Scale: tick interval = 3% [12.2 data]
Maximum = 13.3% [54 data]
Mean Resultant direction = 085-265
[95% Confidence interval = ±9°]



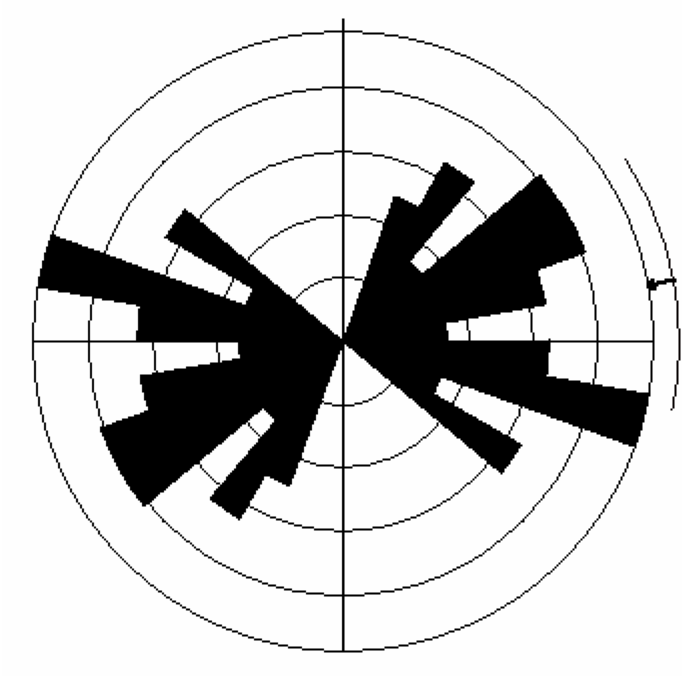
Joints 4 meters and longer   n=134

Sector angle = 10°
Scale: tick interval = 3% [4.0 data]
Maximum = 13.4% [18 data]
Mean Resultant direction = 092-272
[95% Confidence interval = ±21°]



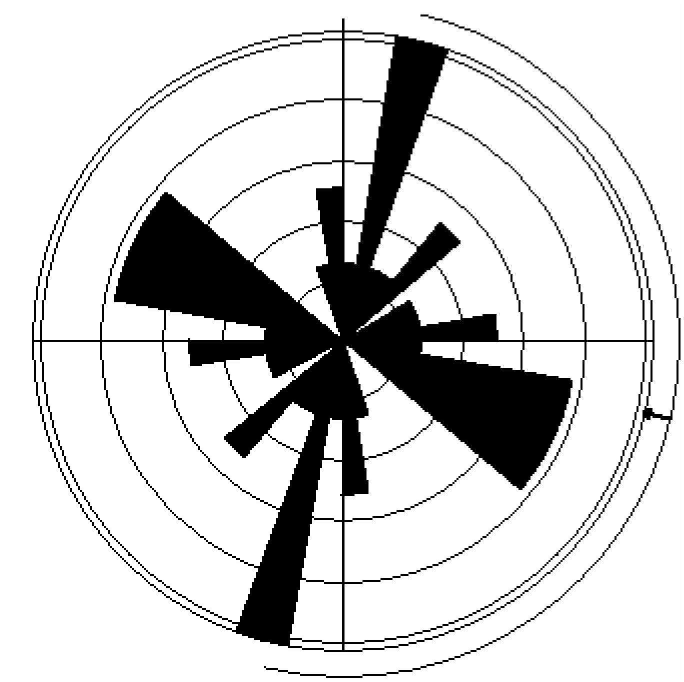
Crossing joints n=70

Sector angle = 10°
Scale: tick interval = 3% [2.1 data]
Maximum = 15.7% [11 data]
Mean Resultant direction = 087-267
[95% Confidence interval = ±25°]



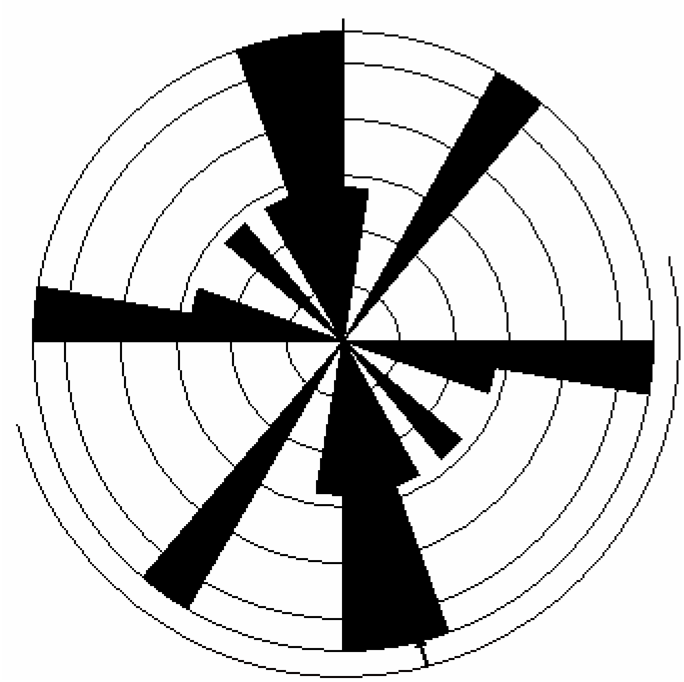
En echelon joints n=41

Sector angle = 10°
Scale: tick interval = 3% [1.2 data]
Maximum = 14.6% [6 data]
Mean Resultant direction = 080-260
[95% Confidence interval = ±22°]



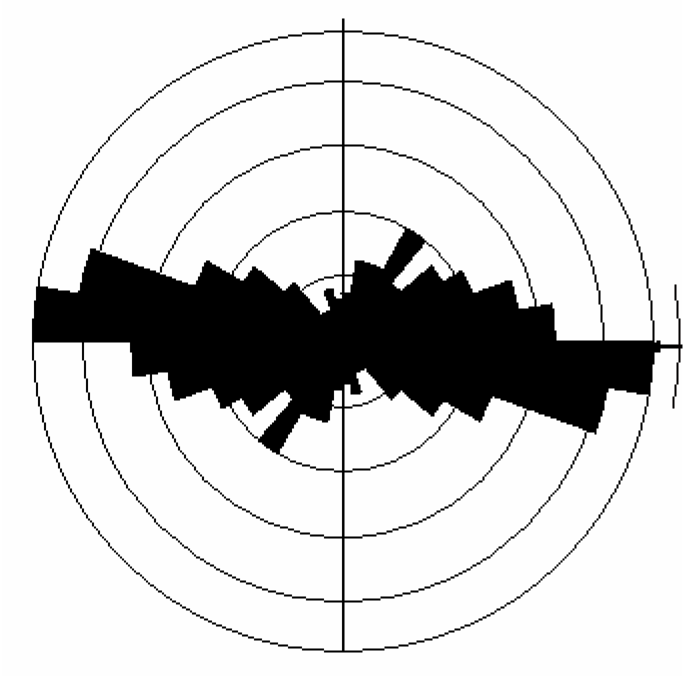
Mineralized joints n=26

Sector angle = 10°
Scale: tick interval = 3% [0.8 data]
Maximum = 15.4% [4 data]
Mean Resultant direction = 104-284
[95% Confidence interval = ±90°]



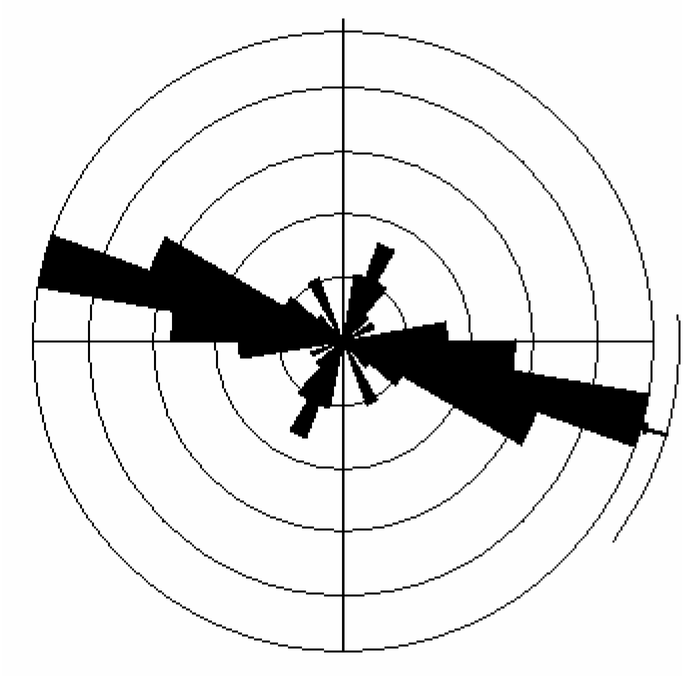
Bull quartz dikes (wide veins)   n=12

Sector angle = 10°
Scale: tick interval = 3% [0.4 data]
Maximum = 16.7% [2 data]
Mean Resultant direction = 166-346
[95% Confidence interval = ±90°]



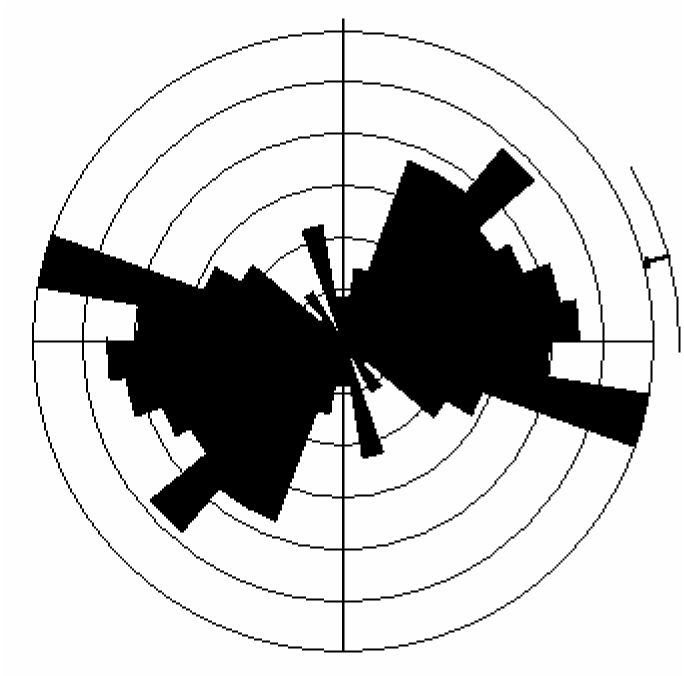
Joints in schist n=316

Sector angle = 10°
Scale: tick interval = 3% [9.5 data]
Maximum = 14.2% [45 data]
Mean Resultant direction = 091-271
[95% Confidence interval = ±11°]



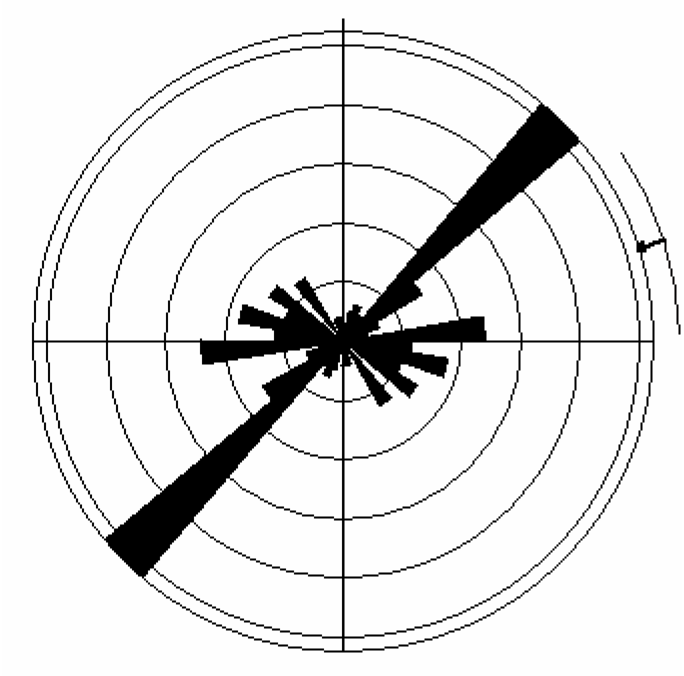
Joints in Barnard Gneiss n=37

Sector angle = 10°
Scale: tick interval = 5% [1.9 data]
Maximum = 24.3% [9 data]
Mean Resultant direction = 106-286
[95% Confidence interval = ±21°]



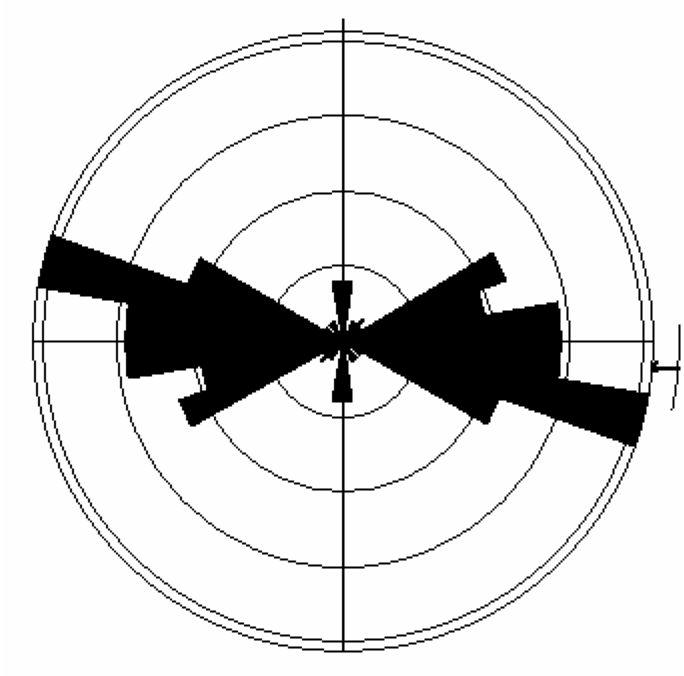
Joints in Calc-Silicates n=177

Sector angle = 10°
Scale: tick interval = 2% [3.5 data]
Maximum = 11.9% [21 data]
Mean Resultant direction = 075-255
[95% Confidence interval = ±17°]



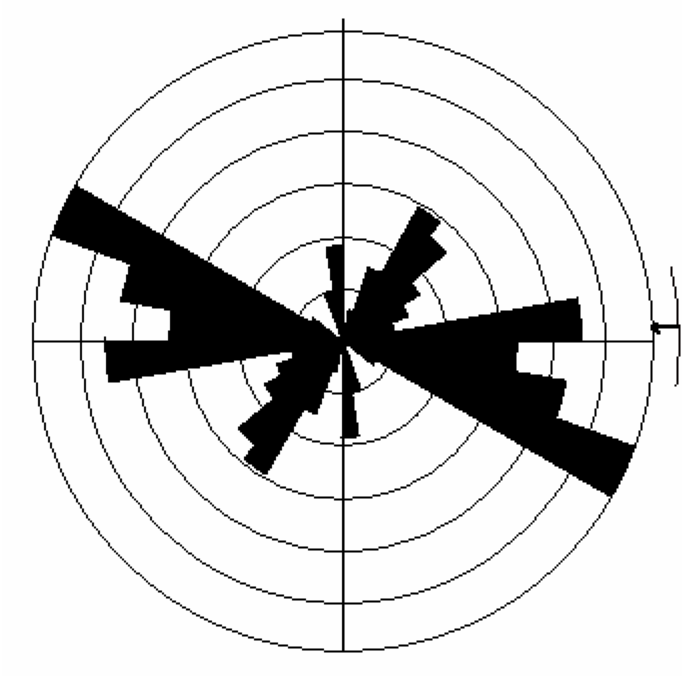
Domain 1 total joints n=191

Sector angle = 10°
Scale: tick interval = 5% [9.6 data]
Maximum = 26.2% [50 data]
Mean Resultant direction = 073-253
[95% Confidence interval = ±16°]



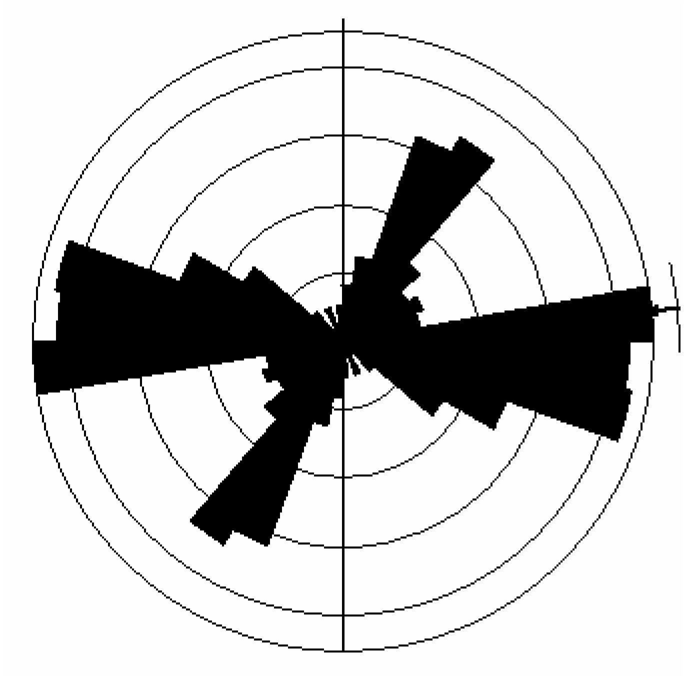
Domain 2 total joints n=199

Sector angle = 10°
Scale: tick interval = 5% [10.0 data]
Maximum = 20.6% [41 data]
Mean Resultant direction = 095-275
[95% Confidence interval = ±7°]



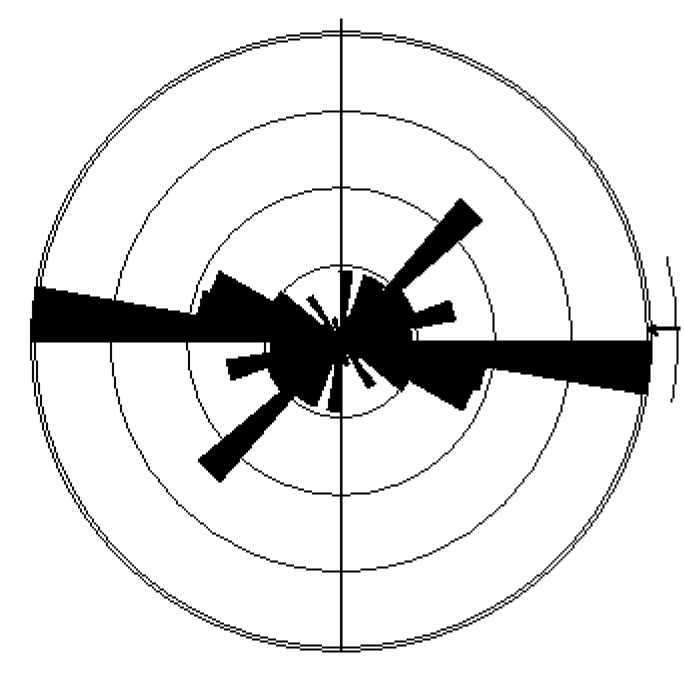
Domain 3 total joints n=271

Sector angle = 10°
Scale: tick interval = 3% [8.1 data]
Maximum = 17.7% [48 data]
Mean Resultant direction = 087-267
[95% Confidence interval = ±10°]



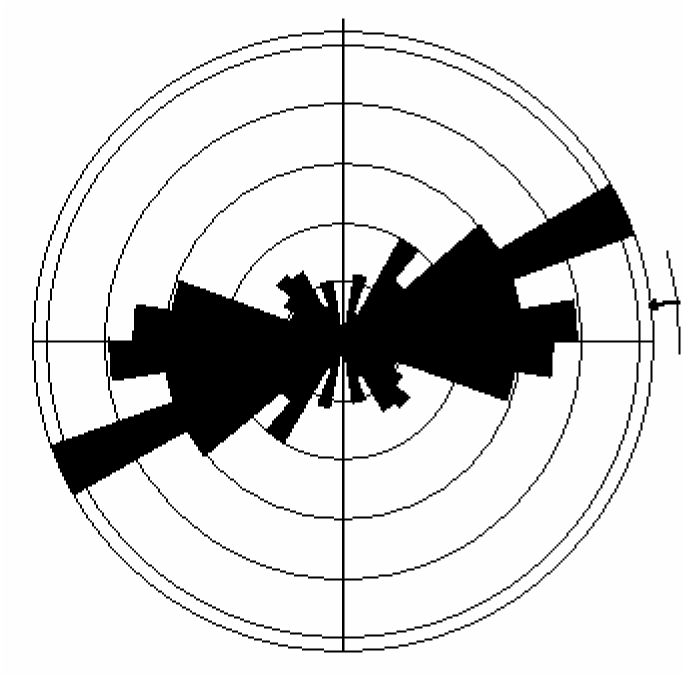
Domain 4 total joints n=694

Sector angle = 10°
Scale: tick interval = 3% [20.8 data]
Maximum = 13.5% [94 data]
Mean Resultant direction = 084-264
[95% Confidence interval = ±8°]



Domain 5 total joints n=198

Sector angle = 10°
Scale: tick interval = 5% [9.9 data]
Maximum = 20.2% [40 data]
Mean Resultant direction = 088-268
[95% Confidence interval = ±13°]



Domain 6 total joints n=320

Sector angle = 10°
Scale: tick interval = 3% [9.6 data]
Maximum = 15.6% [50 data]
Mean Resultant direction = 083-263
[95% Confidence interval = ±9°]

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LIBERTY

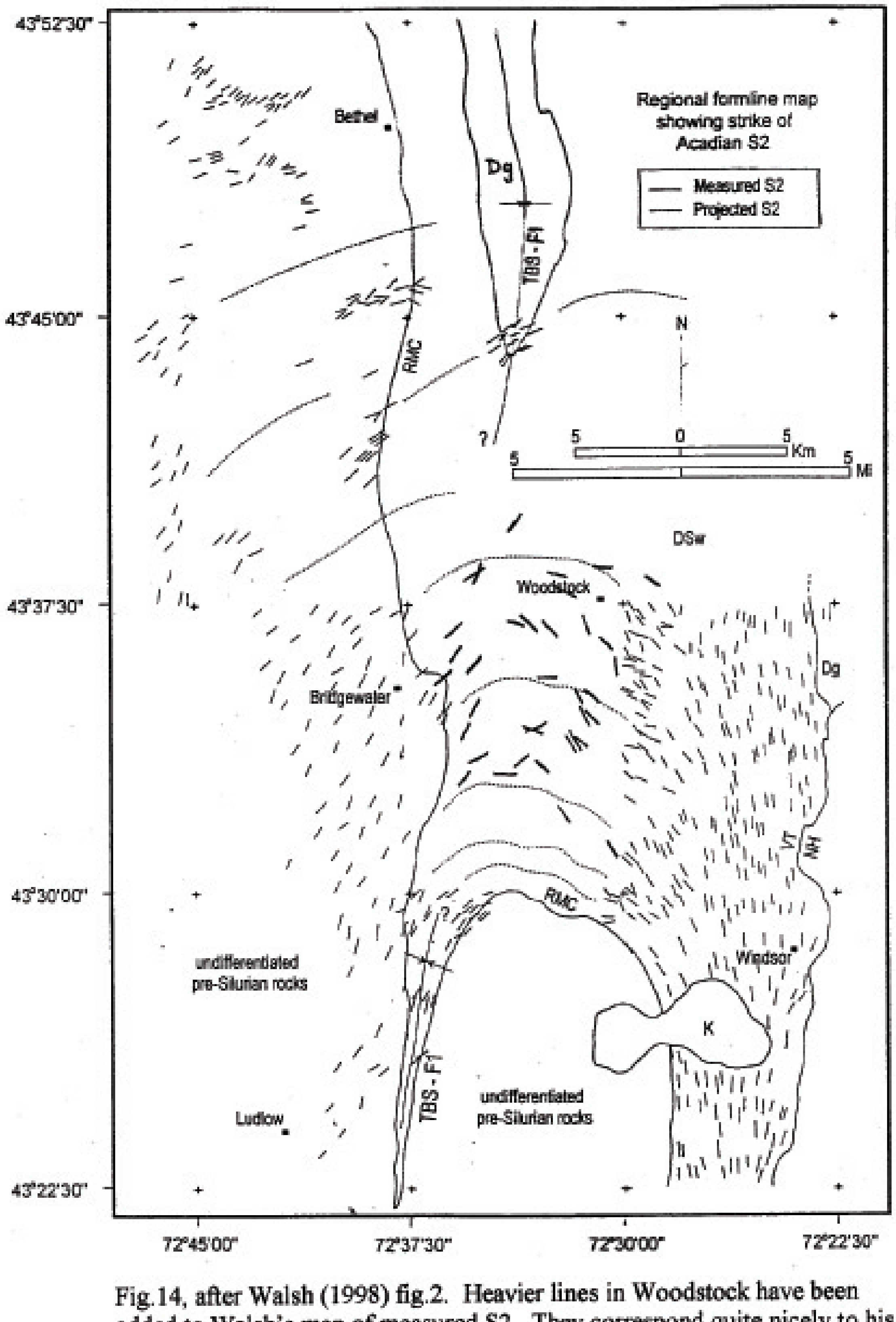

Fig.14, after Walsh (1998) fig.2. Heavier lines in Woodstock have been added to Walsh's map of measured S2. They correspond quite nicely to his projected S2 formlines (dotted lines).